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Deformation mechanisms accommodating faulting of quartzite under upper crustal conditions

GEOFFREY E. LLOYD and ROBERT J. KNIPE

Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, U.K.

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Abstract—Analysis of the deformation microstructures associated with a high-level fault in quartzite (Skiag Bridge, Assynt, NW Scotland) reveals a complex variation in the deformation mechanisms active during faulting. The different mechanisms have been identified using an integrated study involving optical, cathodoluminescence and electron (both SEM and TEM) microscopy. The specific mechanisms identified include: intragranular cleavage fracture (types 1, 2 and 3), brittle intergranular fracture (types 1 and 2), low-temperature ductile fracture, diffusion mass transfer and low-temperature crystal plasticity. Fracturing dominates the deformation (faulting), initially via intragranular extension cleavage fractures due to stress concentrations at grain contacts (although many of these may be healed by quasi-simultaneous diffusive mass transfer processes). These eventually link and are then exploited as shear fractures, leading to the development of microbreccia-cataclasite zones which define a three-dimensional fracture array. Quasi-simultaneous diffusive mass transfer processes may heal these through-going fractures. Continued fault zone deformation involves the development of a damage ('wake') zone along the displacement zone borders where low-temperature plasticity and subsequent low-temperature ductile fracture processes aid the expansion of the fault zone.

This study emphasizes that the evolution of the Skiag Bridge fault zone has involved three main categories of deformation mechanisms: fracture, crystal plasticity and diffusion mass transfer. The interrelationship between these categories, and the transition between individual fracture mechanisms, are significant aspects of this evolution. The examples presented demonstrate the complex interrelationships which exist between a group of deformation mechanisms and emphasize the potential importance of low-temperature plasticity and low-temperature ductile fracture processes during faulting under upper crustal conditions.

INTRODUCTION

ALTHOUGH the recognition and identification of the deformation processes involved in natural fault zone evolution is far from complete, there is a growing awareness of the value of both the fracture mechanics and damage mechanics approaches to the problem. Fracture mechanics attempts to define material parameters important to the fracture process (Griffith 1921, Irwin 1957, Knott 1973, Lawn & Wilshaw 1975, Ghandi & Ashby 1979, Lawn 1983), whilst damage mechanics takes account of the various stages of crack evolution and interaction during progressive deformation (Costin 1987, Meredith 1990). Together these approaches provide important frameworks which can aid the interpretation of experimental and natural faulting processes (Atkinson 1987a, Pollard & Aydin 1988). However, the experimental determination of parameters crucial to fracture mechanics of minerals and rocks often remains difficult (see Lawn *et al.* 1980, 1983, Kirby 1983, 1984, Kirby & McCormick 1984, Tullis & Tullis 1986, Ferguson *et al.* 1987).

In this paper we demonstrate the potential of applying fracture and damage mechanics to the interpretation of the microstructures preserved in natural fault zones. Previous research (e.g. Aydin 1978, Aydin & Johnson 1983, Blenkinsop & Rutter 1986; see also Rutter *et al.* 1986, Wang 1986, Scholz 1989) has recognized that a three stage sequence, involving the development of isolated fractures, the linkage of fractures and the localization of displacement to form breccias and cataclasites, is often involved in the development of a fault zone. In order to investigate the detailed deformation processes involved and the interaction between different processes during this sequence we have studied the microstructures within a small thrust fault from the Moine thrust zone of NW Scotland (Knipe 1990). This microstructural characterization has involved combining optical, cathodoluminescence (Marshall 1988), scanning electron (Lloyd 1985, 1987, Lloyd *et al.* 1991) and transmission electron (Barber 1985, White 1985) microscopy. The first part of the paper presents a critical assessment of the mechanisms which may be involved in the development of fault zones at high levels in the crust. The second part discusses the origin of the fault-induced microstructures in the particular fault studied and also the application of our observations to high-level faulting in general.

DEFORMATION MECHANISMS ASSOCIATED WITH HIGH-LEVEL FAULTING

Three broad categories of deformation mechanisms have been recognized which may be pertinent to faulting at high (typically less than 15 km depth) crustal levels (see Sibson 1986a,b, Mitra 1988, Knipe 1989): fracture, diffusive mass transfer and low-temperature crystal plasticity. Each of these categories is now assessed.

Fracture processes

There are several mechanisms (see Ashby *et al.* 1979, Ghandi & Ashby 1979, Ewalds & Wanhill 1989) by which a crystalline material such as quartz can fracture at low temperatures (i.e. <0.3 melting temperature, T_m). These mechanisms are influenced by confining pressure, effective stress, temperature, chemical equilibrium, pre-existing and induced microstructures, residual strain energy and internal stress. The fracture mechanisms which need to be considered are as follows.

Fracture at the ideal strength occurs at the stress required to break atomic bonds in an ideal or perfect crystal. However, it is assumed to be unlikely in nature because of the presence of material flaws.

Dynamic fracture occurs at large applied stresses and is driven by the propagation of elastic waves.

Intragranular cleavage fracture occurs by one of three possible mechanisms when the resistance to plastic shear is greater than the cohesive strength of cleavage planes. Cleavage 1 involves fracture where there is no general plasticity in the specimen and is usually associated with stress concentrations and crack propagation from existing flaws. Cleavage 2 occurs where the stress concentration is large enough to reach the value needed for crystal slip or twinning and leads to up to 1% bulk plastic strain. This plasticity may induce other internal stresses which are able to nucleate cracks (e.g. at dislocation pile ups). If the yield stress exceeds the fracture stress a crack nucleated by plasticity will propagate as soon as it forms, but if the fracture stress is greater than the plastic yield stress then propagation is arrested and will only continue if the stress is raised even further. Cleavage 3 involves a higher degree of general plasticity (i.e. 1–10%) accommodated either by crystal slip or by grain boundary sliding and is favoured by higher temperatures than the other cleavage mechanisms or a small grain size. The plasticity acts to blunt existing cracks and increases the resistance to fracture. It is worth emphasizing that cleavage fracture can occur even in compression because cracks oriented at an angle to the axis of compression have adjacent tension and compression regions at their tips. However the fracture stress in compression is 8–15 times greater than in tension and in general the stress needed to cause cleavage fracture increases with confining pressure.

Brittle intergranular fractures (*BIF, types* 1, 2 *and* 3) exploit grain boundaries and are dependent upon the strength of the boundaries. A delicate balance exists between the stress required for BIF fracturing and that necessary for the equivalent intragranular cleavage mechanisms; whichever has the lowest fracture stress will dominate. Grain boundary impurities (e.g. inclusions, voids) are important to the strength in low porosity rocks, while the presence and distribution of cement bridges are important in porous rocks.

Low-temperature ductile fracture occurs when significant ($>10\%$) crystal plasticity precedes fracture. Voids are often the damage microstructure, and their nucleation, growth and coalescence leads to the formation of cracks and failure. Void development is controlled either by diffusional processes or by strain incompatibilities between grains with different slip system activities. Cracks may be either intragranular or intergranular depending on whether voids nucleate within grains or along grain boundaries.

Several other fracture mechanisms are generally recognized, such as transgranular creep fracture, intergranular creep fracture, rupture (see Ghandi & Ashby 1979), but they are favoured by temperatures in excess of those considered to occur in the upper crust (i.e. $>0.3T_m$).

The competition between different fracture mechanisms in rocks has been assessed by Atkinson (1982) (see also Mitra 1984, Atkinson 1987a). By assuming low tensile stresses, a grain size of 100 μm and less than 1% general plasticity, Atkinson suggested, on the basis of a fracture deformation mechanism map for quartz, that the upper 20 km of the Earth's crust is dominated by cleavage 1 and BIF 1 mechanisms. However, if the whole tensile stress range shown on this map is considered, all three types of cleavage and BIF mechanisms, as well as dynamic fracture, are possible. Each of these mechanisms assumes that cracks propagate (either stably or unstably) at some critical value of a particular fracture mechanics parameter (such as K_c, the critical stress intensity factor). Unfortunately, such parameters do not provide sufficiently general fracture criteria to account for crack growth during longer term loading typical of deformation in the Earth's crust. Such conditions encourage a variety of time-dependent phenomena known collectively as *subcritical crack propagation* (e.g. Atkinson 1982, 1987b, Atkinson & Meredith 1987, Costin 1987).

Subcritical crack propagation involves fracturing at stresses below the critical values of fracture mechanics parameters (such as K_c) and thus deviates from the classical Griffith-type fracture mechanics (Rice 1978, Atkinson 1980, 1982, 1984, Atkinson & Meredith 1987). A range of processes can be involved (e.g. diffusion, dissolution, ion-exchange and microplasticity) which induce episodic crack extension into a damage or process zone ahead of a propagating crack tip. Subcritical crack growth is therefore linked to, and dependent upon, a host of deformation processes, particularly diffusive mass transfer and crystal plasticity, and also allows for crack-healing.

It is therefore clear that a delicate and complex interaction between the different fracture mechanisms, and also other deformation processes, can take place during natural faulting events. For example, the dominance of intragranular or intergranular fracture may change during a deformation event as damage induces changes in the microstructure. We now consider the potential relevance of other deformation processes to fault evolution.

Diffusive mass transfer mechanisms

Diffusive mass transfer is now recognized as an important deformation mechanism in low-temperature ($<0.3T/T_m$) environments, particularly in fine-grained rocks where the diffusion path length is short and differential stress levels are low enough to inhibit crystal plastic deformation mechanisms (e.g. Rutter 1976, 1983, Kerrich 1978, Robin 1978, Beach 1979, Poirier 1985, Groshong 1988, Knipe 1989). Diffusive mass transfer is also an important diagenetic process which promotes compaction and cementation (Houseknecht 1984, 1988, Hicks *et al.* 1986, James *et al.* 1986). The driving force for diffusive mass transfer depends upon chemical potential gradients, which can be controlled by stress variations (Wheeler 1987), fluid pressure gradients (Etheridge *et al.* 1984) and the internal strain energy of individual grains (Wintsch 1985, Wintsch & Dunning 1985, Bell *et al.* 1986). The deformation depends on three processes: first, solution of material at a source; second, migration or diffusion of the material along some mass transfer pathway; and third, precipitation of material at a growth site or sink (Knipe 1989). These three processes determine the specific nature of the diffusive mass transfer deformation and consequently there are a number of different constitutive flow laws possible for this type of deformation (Spiers & Schutjens 1990).

There is a common association of fractures filled with material generated by diffusive mass transfer (see Ramsay & Huber 1983, 1987), which suggests some link between fracture and diffusive mass transfer mechanisms. However, the exact timing and interrelationship between these mechanisms and their rate-controlling parameters remain unclear. For example, whilst dilation at fracture sites may be sufficient to induce thermodynamic instability and local solution and mass transfer of material, the converse argument that dissolution and migration of material from a source to a precipitation site in a sink can influence fracture, is also possible. Furthermore, many tectonic fractures are tension fractures developed when the tensile stresses at depth, plus any associated fluid pressure, exceed the confining pressure by an amount equal to the local tensile strength. There is now little doubt that many extension fractures are filled by minerals crystallized from the aqueous fluid contained in the resulting crack, but the quantities of fluid involved in the generation of specific structure remains poorly constrained. Due to the low solubility of minerals such as quartz in water (Weill & Fyfe 1964) such fracture in-fill requires the transportation of hundreds of thousands of crack volumes of water through the fracture. This suggests, therefore, either the existence of an external water reservoir (which must still move through the rock) or the crack-filling material is derived via local diffusive mass transfer processes.

Diffusive mass transfer often results in cementation and can be considered as a microstructural strengthening process which promotes strain hardening. In contrast, fracturing is generally a weakening process. An important consequence of this is that strengthening can occur locally because of localized precipitation. The result may be a partitioning of the deformation into domains which change in size and location progressively or in a cyclic fashion during straining (see Knipe 1989). In the case under consideration here, the cyclic deformation may involve high strain-rate fracture events alternating with low strain-rate diffusive mass transfer periods.

Intracrystalline plasticity mechanisms

Crystal plasticity, where strain is accommodated by the glide and/or climb of dislocations, is usually associated with high-temperature (i.e. $T/T_m > 0.3$) deformation (e.g. Martin & Durham 1975, Tullis & Yund 1980). However dislocations can be active at lower temperatures, particularly at the slow strain rates expected during geological deformations, resulting in such ubiquitous intracrystalline microstructures as undulose extinction and deformation lamellae (Groshong 1988, Knipe 1989). In general, this low-temperature plasticity is achieved by dislocations gliding on slip planes (Ashby & Verrall 1977), although dislocation climb controlled by diffusion along dislocation cores may also be possible (Atkinson 1977). Glide is controlled by the resistance induced by the lattice or by obstacles (e.g. impurity atoms, solute, precipitates, other dislocations, planar defect structures, etc.). Lattice-resistance appears to provide the greatest opposition to dislocation glide only at the lowest absolute temperatures, and therefore in most cases of low-temperature plasticity obstacle-resistance determines the deformation rate.

Dislocation glide can only occur if the resistance produced by the lattice and/or any other obstacles to dislocation motion are overcome. This might initially suggest that there exists a threshold stress level below which low-temperature plasticity does not occur and dislocations are inactive. However, the probable time dependency of yield stress must mean that the threshold stress is also time dependent and will decrease as the duration of the deformation increases, even where the overall applied stress level remains low. Whichever mechanism is operating, low-temperature plasticity is characterized by a long transient involving progressive work-hardening ('cold working'), associated with the development of dislocation tangles, which should in theory continue until the saturation flow stress (i.e. steady-state) is reached. However, steady-state low-temperature plasticity is unlikely to be achieved in practice. A tensional low-temperature plasticity deformation is likely to result in fracture because the applied stress eventually exceeds the fracture stress. In contrast, a compressional low-temperature plasticity deformation requires very large strains to develop before steady-state is attained. Thus, continued deformation by dislocation movement eventually becomes impossible as dislocations are pinned and the material therefore fractures.

Fracture induced by the motion of dislocations (low-temperature plasticity) is synonymous with the low-temperature ductile fracture mechanism described earlier and can involve up to 100% bulk plasticity prior to fracture. However, since both cleavage 3 and BIF 3 fracture mechanisms can also involve up to 10% bulk plastic deformation, they are also potential terminations for low-temperature plasticity. Where low-temperature ductile fracture has occurred we expect the microstructure to consist of microcracks with adjacent low-temperature plasticity 'process zones' or 'wake zones' (Lawn 1983).

DEFORMATION PROCESSES ACTIVE DURING FAULTING

To investigate the interaction between the different deformation mechanisms reviewed above during the development of upper crustal fault zones, we have studied in detail the evolution of an individual fault zone. The fault is a minor back-thrust in a pure quartzite (Cambrian Pipe-Rock) located at Skiag Bridge, in the Assynt Region of the Moine thrust zone, NW Scotland. The deformation mechanisms associated with other thrust faults in the Moine thrust zone have been described by Knipe (1990). The fault chosen for this study has a displacement of approximately 1 m. This allows the continuous monitoring of the microstructural changes which occur in individual sedimentary units through the fault zone. The fault is considered to have developed under temperatures of 200–250°C, pressures of 200–300 MPa and a depth of 7–10 km (see Johnson *et al.* 1985, Knipe 1990).

In the sections which follow we have chosen some representative microstructures preserved in the fault zone which allow discussion of the active deformation processes associated with the fault evolution sequence noted earlier (Aydin 1978, Aydin & Johnson 1983, Blenkinsop & Rutter 1986): (1) origin of intragranular microfractures; (2) linkage of isolated microfractures; and (3) development of microbreccia or cataclasite, initially in narrow displacement zones. By combining the observations of intragranular microfracture microstructures with the characteristics of possible fracture mechanisms we can infer which mechanisms were active and hence are responsible for these microstructures. We emphasize that the microstructures described here are not necessarily common to all faults but are used to highlight, first, the role of integrated microstructural analysis in the identification of fracture processes, and second, the important platform that fracture and damage mechanics provides for the interpretation of preserved microstructures. With these objectives in mind, we present a brief description and interpretation of the microstructures observed.

Origin of intragranular microfractures

In the Skiag Bridge fault zone, intragranular cracks are characteristic of low strain areas located either away from the main displacement zone or in relict low deformation zones present throughout the entire fault zone. Intragranular (e.g. cleavage) rather than intergranular (e.g. BIF) fracture mechanisms have therefore dominated deformation in the Skiag Bridge fault zone. For most microfractures to be intragranular rather than intergranular the grain fracture strengths must have been less than the grain boundary fracture strengths.

It has been suggested (Schneibel *et al*, 1981, Wilson & McBride 1988) that where the original grain arrangement tends to be poorly sorted, the preferred orientation of intragranular extension microfractures is expected to be low. The Pipe Rock quartzite in the Skiag Bridge fault zone is commonly poorly sorted and no obvious preferred orientation of intragranular microfractures has been detected.

The intragranular microfractures tend to link grain contacts (Fig. 1). This geometry is exactly that suggested by the experiments of Gallagher *et al.* (1974) and Berka (1982). Stress concentrations due to 'point-loading' across grain–grain contacts dictate that microfractures follow the stress trajectories which connect the most highly stressed contacts. We therefore interpret the intragranular microfractures as simple extension cracks, particularly as they show no significant displacements either parallel to or normal to the fracture trace.

In most cases, there is no bulk plasticity associated with the intergranular extension microfractures (e.g. Figs. 1a–c), which we therefore interpret as cleavage 1 fractures. A small proportion of cleavage 2 fractures may also be present. However, many of these microfractures are preserved as healed fractures (e.g. Fig. 1d). Where they are healed by the same material as the host grain (i.e. quartz), we assume local derivation by quasi-simultaneous diffusive mass transfer processes. It is possible that these microfractures did not develop by a single fracturing event, but represent the cumulative effect of many small increments of crack extension, which would also explain intragranular microcracks which terminate within grains. As a sharp flaw develops into a crack in an aqueous environment, the almost instaneous increase in volume leads to a sudden loss of fluid pressure which arrests crack propagation ('blunting' of crack-tips by localized crystal plasticity in the region of the tip can also arrest crack propagation). Thus, many of the 'intragranular extension microfractures' recognized may never have existed as continuous fractures, and hence individual grains may never have had through-going fractures.

There is evidence within the Skiag Bridge fault zone for significant syn-faulting intracrystalline plasticity (i.e. low-temperature plasticity) and related fracture (i.e. low-temperature ductile fracture). Undulose extinction (Fig. 2a) and deformation lamellae or bands (Fig. 2b) are concentrated in the fault zone relative to the country rock. These and other low-temperature plasticity features (e.g. subgrains) are often exploited by intragranular fractures (Figs. 2c & d). TEM examination of the vicinity of these fractures (Fig. 2e) reveals the presence of a concentrated dislocation substructure adjacent to the fracture trace. Such microstructures represent clear evidence for low-temperature ductile fracture.

The development of concentric arrays of subgrains at grain contacts (Fig. 2f) provides further evidence of fault related low-temperature plasticity. An obvious analogy can be drawn between these features and the develop-

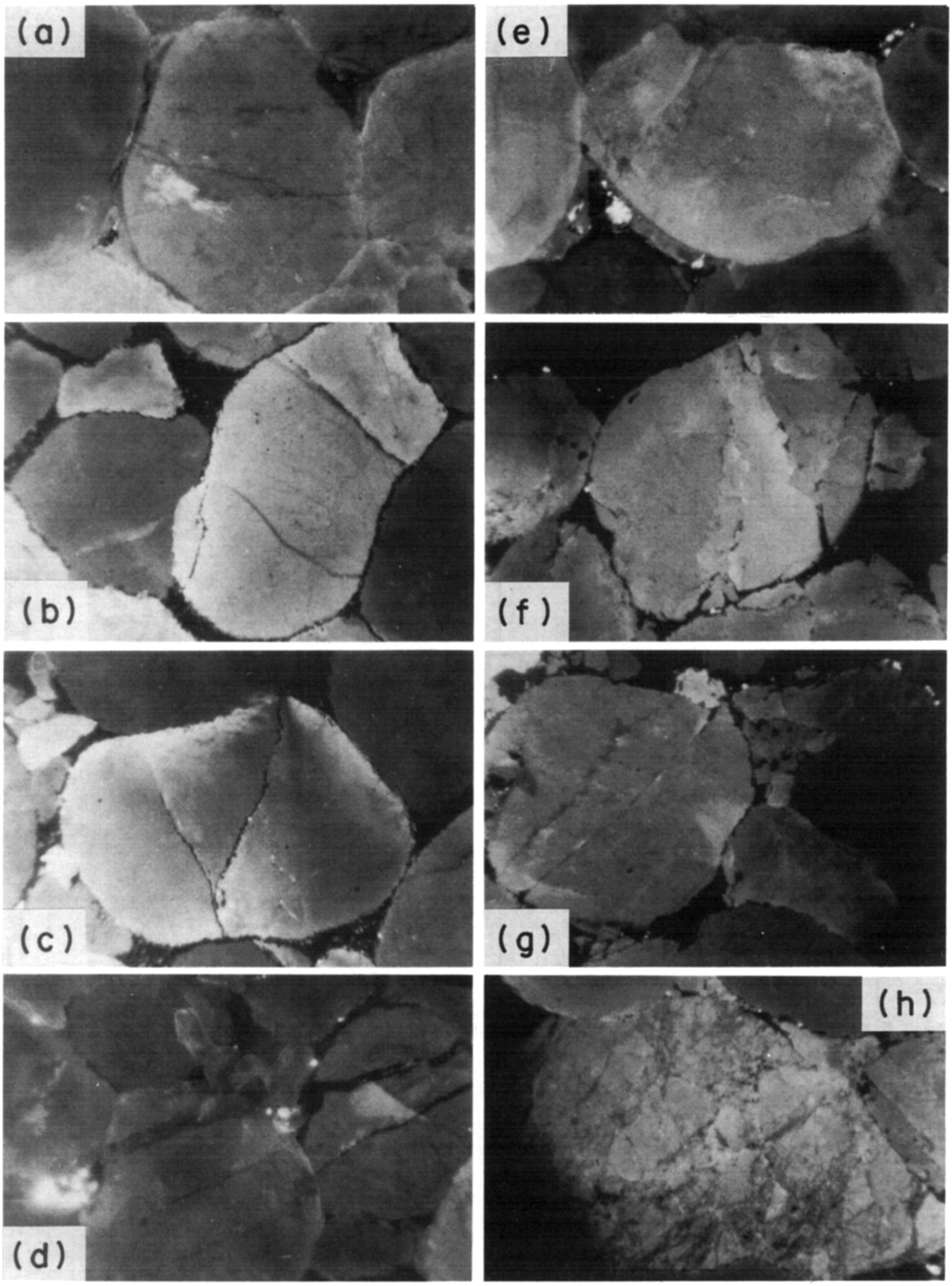


Fig. 1. Examples of intragranular extension fractures observed in the Skiag Bridge fault zone, particularly in relatively undeformed parts away from the main fault movement zone or in relict low deformation areas throughout the entire fault deformation zone. Note tendency for fractures to originate at grain contact points. (Black and white reproductions of original colour optical cathodoluminescence images; width of view approximately 2 mm.) (a) Single fracture. (b) Pair of parallel fractures. (c) Bifurcating fracture. (d) Open fracture subsequently healed by diffusive mass transfer processes. (e)–(h) Intragranular microbreccia-cataclasite 'zones' due to complex intragranular (extension?) fracturing.

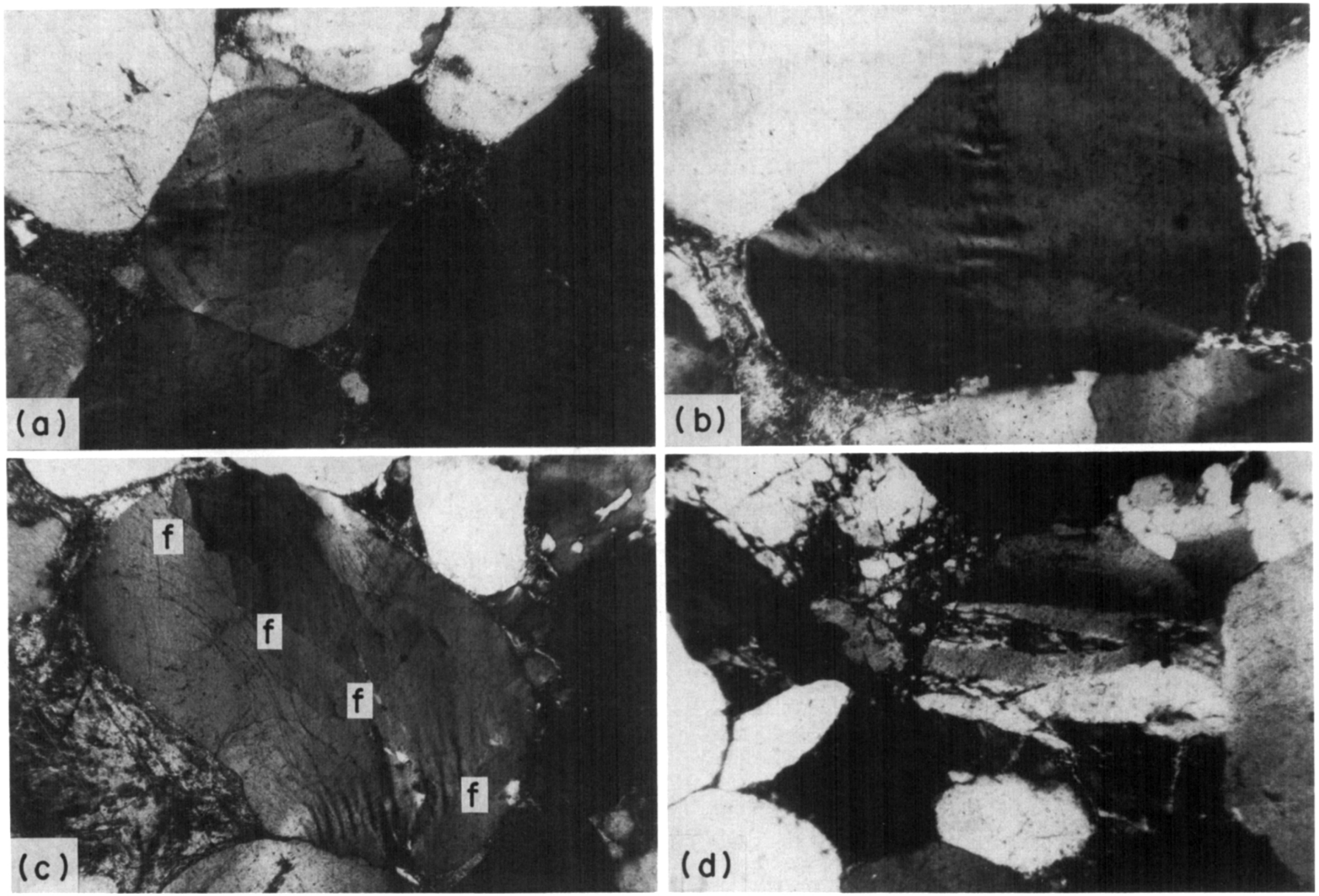


Fig. 2. Microstructures indicative of low-temperature plasticity (LTP) and low-temperature ductile fracture (LTDF) during faulting. (a)–(d) Optical photomicrographs crossed nicols, 2 mm width-of-view. (a) LTP microstructure: undulose extinction and deformation bands, note the 'flame-like' feature adjacent to the actual grain contacts, due to stress concentrations at the contacts. (b) LTP microstructure: deformation lamellae/bands, also due to stress concentrations at grain contacts. (c) Early LTP microstructures (deformation lamellae/bands and subgrains) subsequently exploited by fractures, f, due to LTDF. (d) LTP microstructures (enlarged 'flame-like' features, including subgrains) subsequently exploited by fracturing due to LTDF; note also the LTP undulose extinction and/or deformation bands/lamellae.

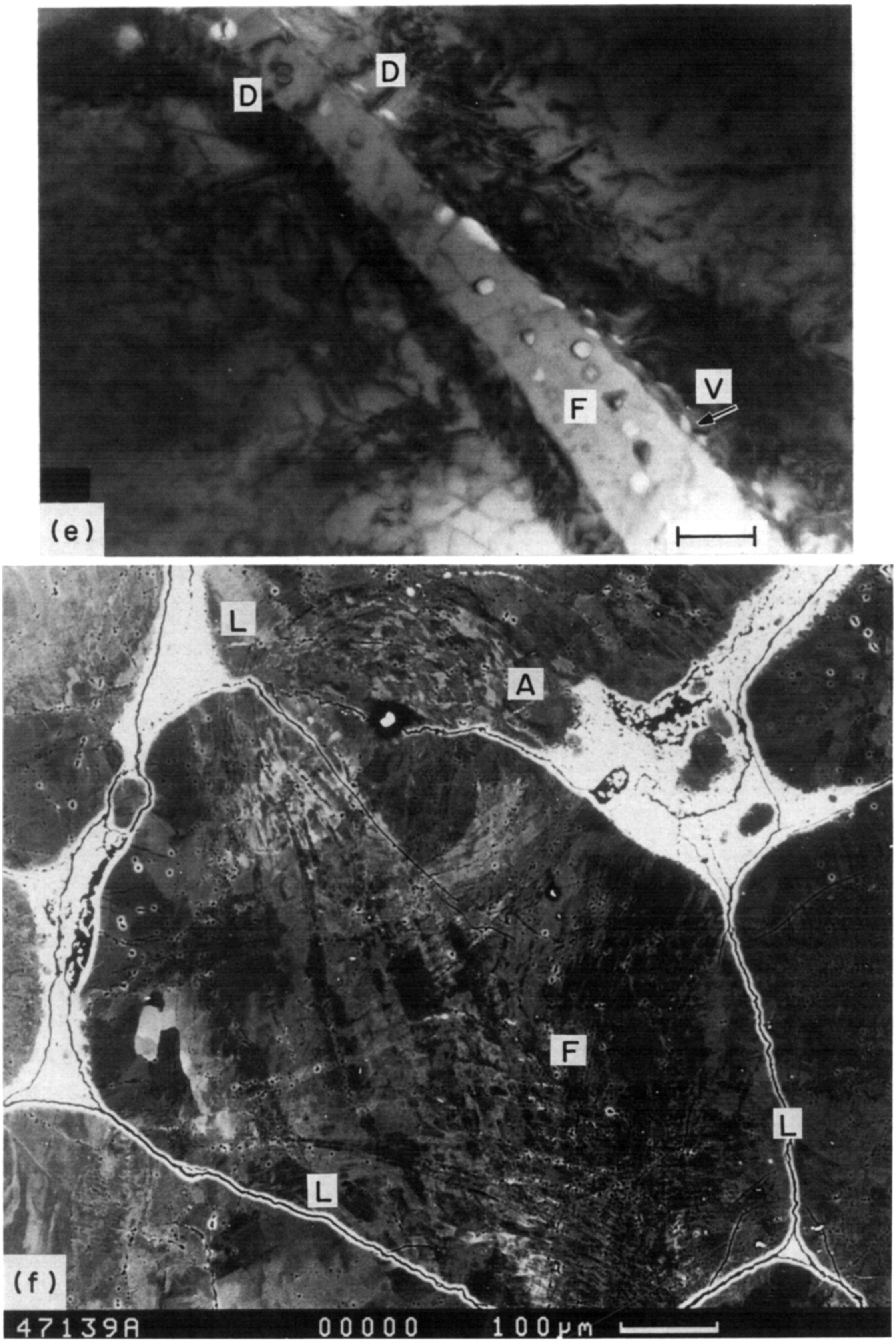
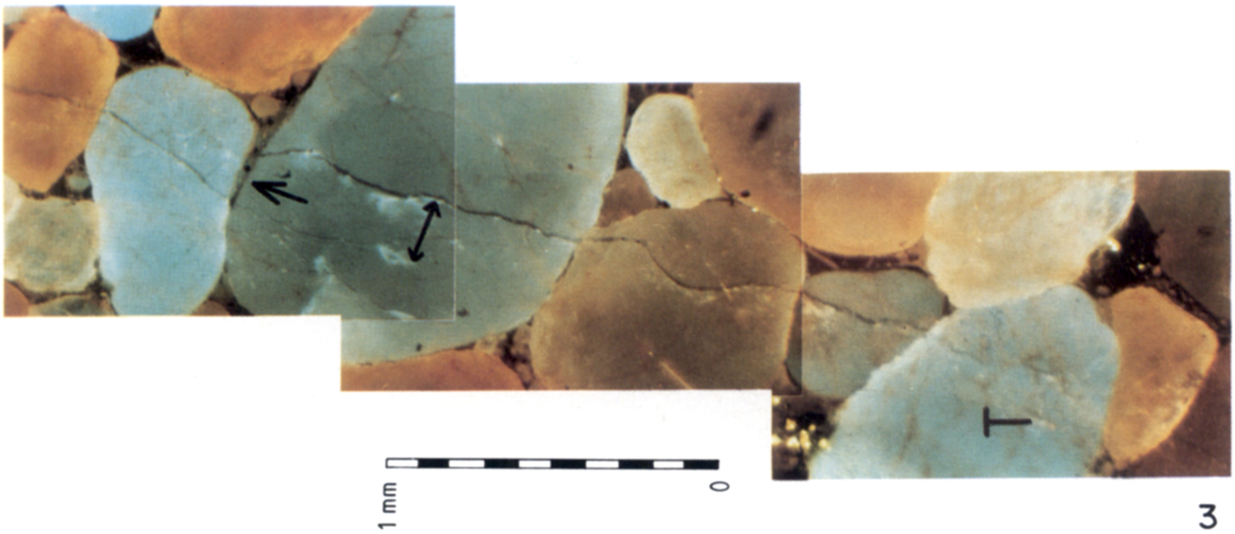


Fig. 2. (e) TEM image of an intragranular quartz-filled extension fracture, F. Note: concentration of bubbles inside the fracture; voids, V, along the fracture margin; and concentration of lattice distortion, D, adjacent to the fracture. Scale bar 1 μm. (f) SEM electron channelling image of LTP and LTDF microstructures. Arcuate array of subgrains, A, develop at grain contacts due to LTP caused by 'soft indentation'. LTP deformation lamellae, L, overprint both the arcuate subgrain and inherited microstructures (large subgrains). These in turn are overprinted by healed fractures, F (now represented as bubble trails), due to LTDF.



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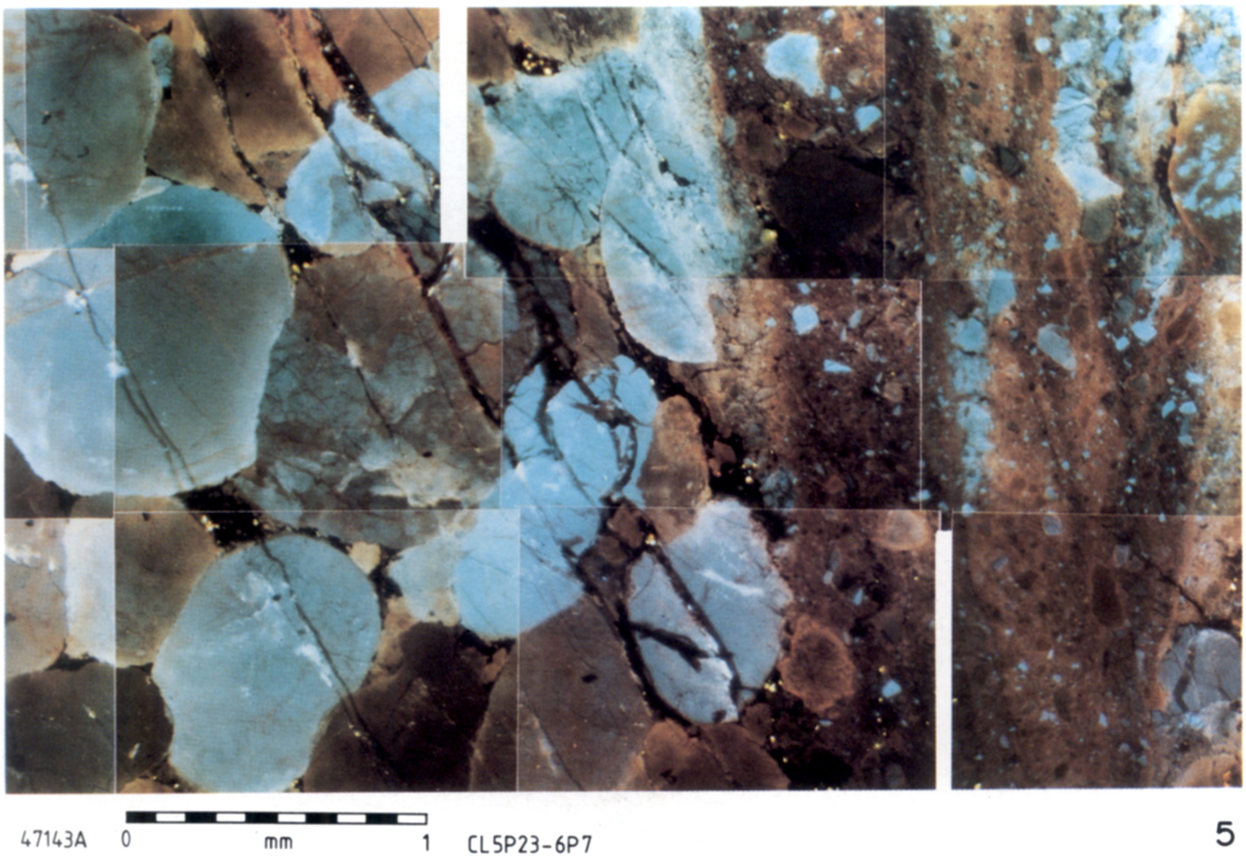

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Fig. 3. Optical cathodoluminescence image of a linked through-going intragranular extension fracture. There has been no displacement either parallel or perpendicular to the fracture path. However, the effective fracture width (represented by the double-headed arrow) is irregular on the scale of the grain size. Note the relatively short grain-boundary component (arrowed) and also the suggestion of fracture termination in the lower grain (T), suggestive of crack-tip low-temperature plasticity (crack blunting?).

Fig. 5. Optical cathodoluminescence image of foliated quartz microbreccia-cataclasite zone (right) and relict low-deformation quartzite block (left). Note: (1) colour cathodoluminescence signatures in the microbreccia-cataclasite zone indicate the allegiances of the different foliated regions in terms of their parental grains; (2) intragranular and through-going extension and displacement fractures in the relict block, many showing evidence of diffusive mass transfer healing processes; (3) displacement sense is uniquely sinistral (i.e. relict block downwards), indicated by the fractures in the relict block and the colour of trailing edges of grain fragments in the foliated microbreccia-cataclasite zone; (4) relict block grains are incorporated into the zone by extensional 'spalling' (see Fig. 10), involving intragranular fractures which develop subparallel to the zone; and (5) the presence in the microbreccia-cataclasite zone of larger fragments (including whole grains).

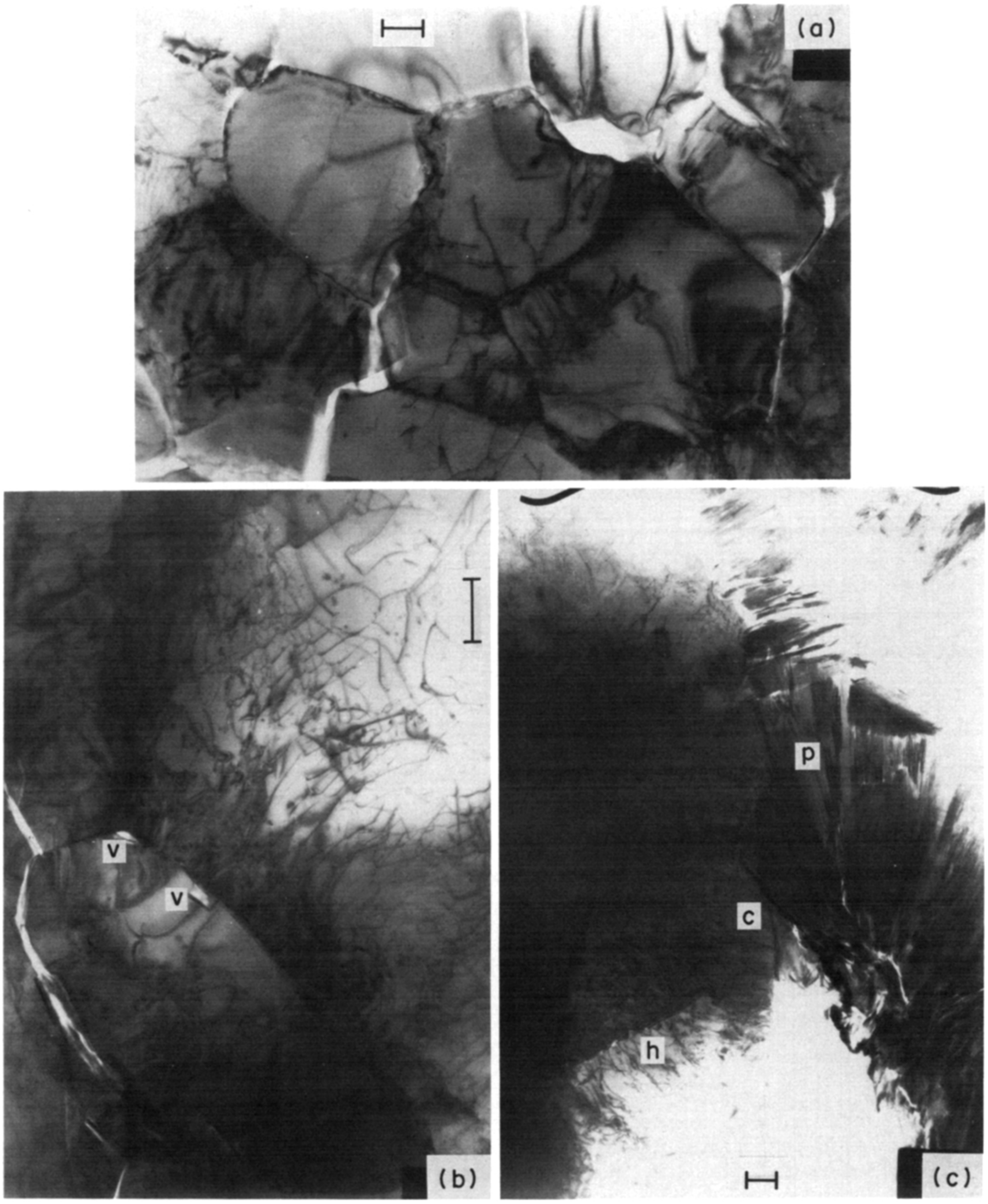
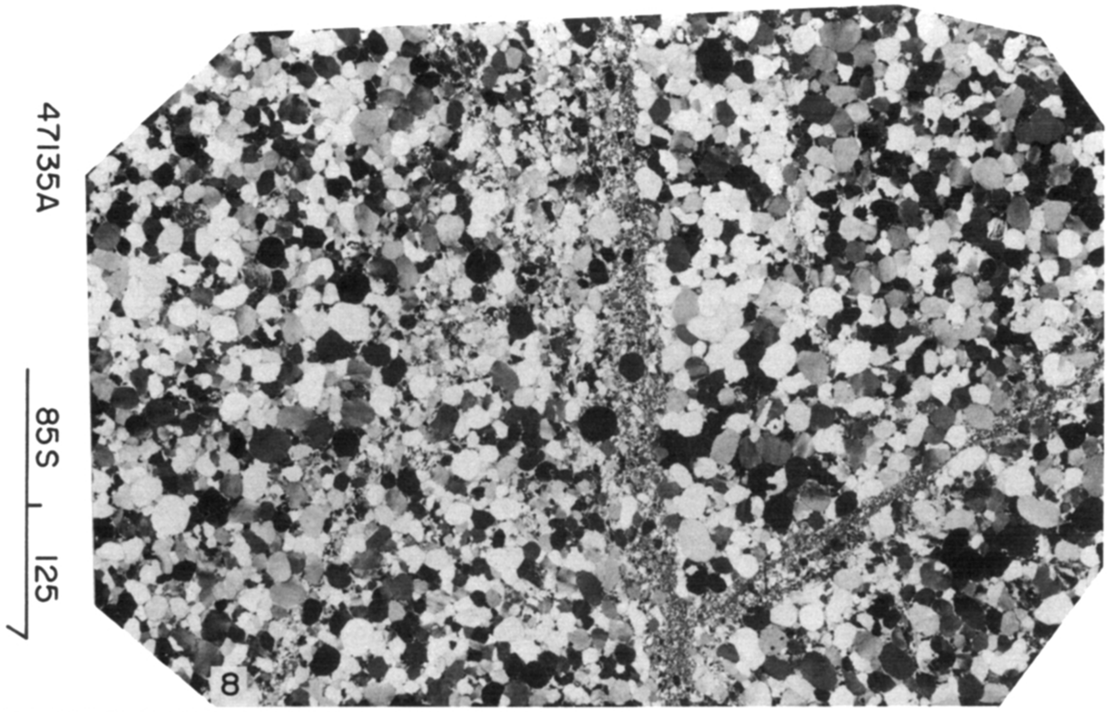


Fig. 6. TEM micrographs of microbreccia-cataclasite zone microstructures (all scale bars 1 μm). Note that similar features have also been observed in quartz fault rocks by Hippler & Knipe (1990). (a) Fine-grained nature of the matrix and associated dislocation sub-structure present within the grains. (b) Sub-structure within a clast incorporated into a microbreccia-cataclasite zone; note the dense dislocation arrays and tangles, as well as voids, present along subgrain walls. (c) Quartz cement, c, and phyllosilicate growth, p; note also the interface between the quartz cement and a host grain fragment, h.



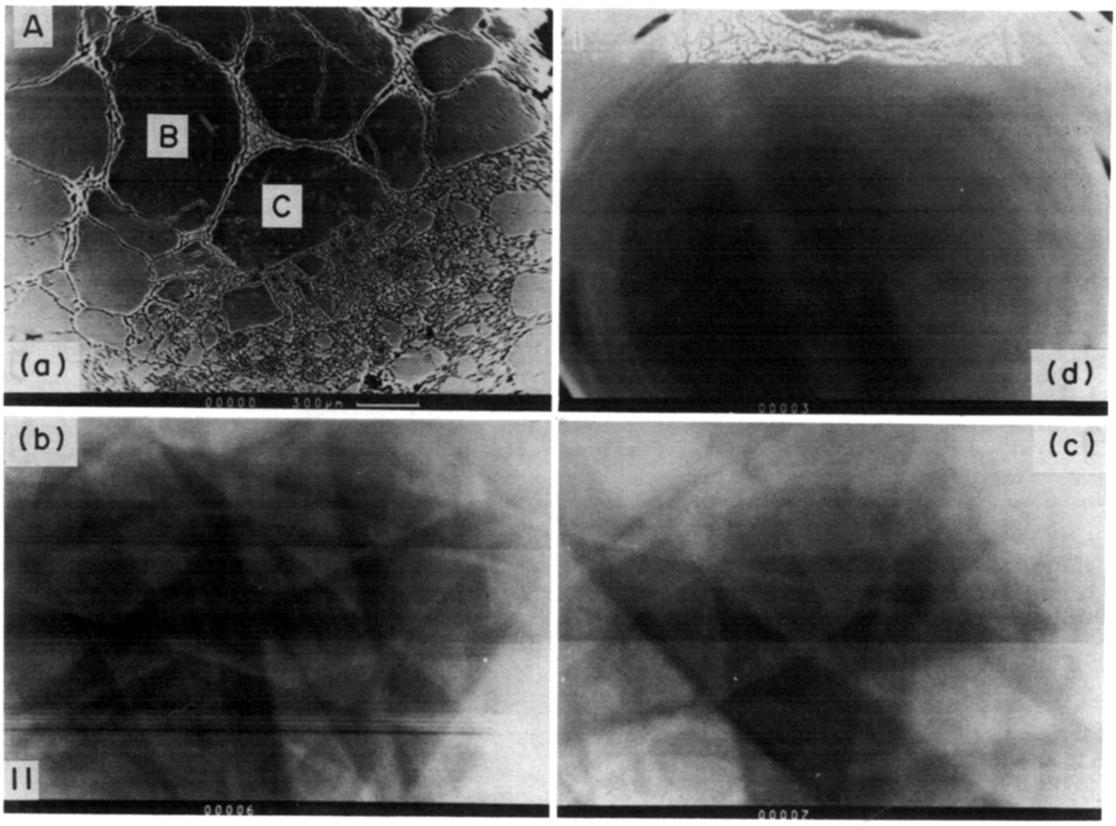


Fig. 8. Photomicrograph of a whole thin-section (width of view approximately 4.5 cm) showing the development of a blocky microstructure, comprising relict blocks of original quartzite separated by narrow microbreccia-cataclasite filled displacement fracture zones, resulting in the partitioning of the bulk deformation into regions dominated by different deformation mechanisms. The evolution of this microstructure is shown schematically in Fig. 9.

Fig. 11. SEM electron channelling analysis of wall rock adjacent to a microbreccia-cataclasite zone suggests a narrow ('wake') zone of work-hardening (cold-working) due to low-temperature plasticity deformation (LTP). (a) Wall rock region adjacent to the fracture zone showing the relative positions of three grains, A–C, from which electron channelling patterns (ECP) were obtained. (b) ECP from grain A; note the good quality (correct band width and high contrast) typical of low/zero work-hardening/LTP. (c) ECP from grain B; note decrease in quality (broadening of band width, lower contrast) relative to grain A, due to LTP. (f) ECP from grain C is almost completely obscured by the effects of pervasive LTP.

ment of the extensional microfractures (e.g Fig. 1) associated with 'point loading' and stress concentrations at grain contacts. We therefore suggest the operation of a similar but much slower process for the formation of the arcuate subgrain arrays, namely the 'slow indentation' of one (harder) grain into an adjacent (softer) grain. The stress levels which developed at these contacts were either sufficiently high or existed long enough (i.e slow strain rate) to cause dislocation glide. Teufel & Logan (1978) suggested a similar process for inelastic deformation of asperity contacts between grains. This microstructural development may also be important to subsequent deformation as the large number of low-angle grain boundaries reduce the local diffusion path length and may localize diffusive mass transfer processes (see also Meike 1990, for a theoretical analysis of this type of behaviour). This relationship between microstructures induced by dislocation processes (low-temperature plasticity) and deformation accommodated by diffusive mass transfer provides an additional example of the interdependency of deformation during faulting.

The faulting induced low-temperature plasticity and low-temperature ductile fracture microstructures are complex and there is evidence that the early formed microstructures are overprinted and obliterated by later low-temperature plasticity features which have a different character. Examples are shown in Fig. 2(f), where long and typically very narrow lamellae are superimposed on an arcuate subgrain microstructure. This suggests that lamellae development occurs later in the deformation history. The low-temperature plasticity microstructures are themselves overprinted by intragranular extension fractures (e.g. bubble trails in Fig. 2f), indicating that these low-temperature plasticity processes also culminate in fracture.

The development of the crystal plastic microstructures within the Skiag Bridge fault zone prompts us to suggest that low-temperature ductile fracture represents a significant but hitherto unappreciated geological deformation process. Dislocation glide deformation (low-temperature plasticity) promotes work-hardening, raising the local plastic yield stress but also inducing cracks. These can coalesce and concentrate stresses, initially above the increased plastic yield stress (allowing further dislocation glide) but eventually above the fracture stress, leading to microfracture. It is therefore probably wrong to consider all low-temperature plasticity microstructures as developing in isolation. Many are almost certainly part of a progressive deformation process which initiates as a dislocation mechanism but which is ultimately terminated by fracture.

The stresses induced across individual grains by point loading at grain contacts increases as deformation intensifies. But, due to the inherent heterogeneity of grain fracture strength on the grain-size scale, there is only a gradual and dispersed increase in the number of grains with intragranular microcracks. Consequently, fractured grains tend to remain in isolation during the earlier stages of deformation (faulting), particularly where sorting is poor and grain boundary cement acts in a strengthening and therefore isolating manner. However, through-going fractures with little or no displacement and no microbreccia or cataclastic infilling also occur and which provide evidence for the process of linkage of the intragranular microcracks.

Linkage of intragranular microfractures

A common feature of the low deformation zones in the Skiag Bridge fault zone is the presence of through-going fractures with little displacement (<20 μm) and no microbreccia-cataclasite infilling (Fig. 3). Such fractures are usually at least several grain diameters in length, and some continue for many tens of grain diameters. Our observations suggest that these *linked fractures* can still be considered as extension fractures which developed primarily by the same range of mechanisms as the isolated intragranular microfractures (i.e. cleavage 1–3 and low-temperature ductile fracture). Consequently, linked fractures must contain segments of initially separated intragranular microfractures which developed by different mechanisms (see Fig. 4). Because only short segments of the linked fractures exploit grain boundaries, we conclude that the grain boundaries were stronger than most grains and generally acted as barriers to fracturing. Furthermore, point-loading at grain contacts also tends to concentrate fracturing across rather

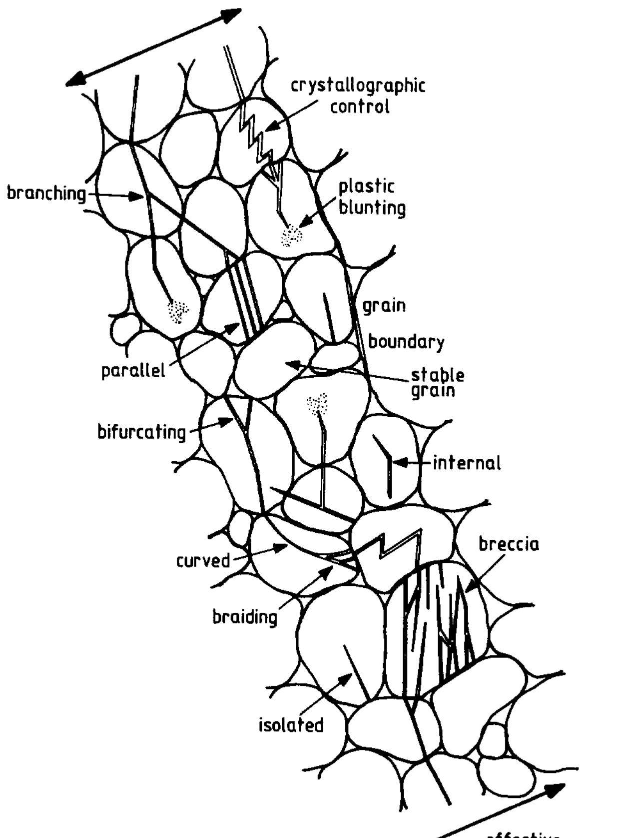


Fig. 4. Schematic diagram of typical through-going extension fracture emphasizing the different types of component intragranular microfractures and particularly the irregular fracture trace on the scale of the grain size which results in an exaggerated fracture width.

than between grains. Thus, BIF mechanisms were suppressed during the evolution of the Skiag Bridge fault zone.

Suppression of BIF mechanisms relative to intragranular mechanisms may also be related to cementation of grain boundaries by diffusive mass transfer processes occurring either before or during deformation (faulting). Where grain boundary fractures have developed we suggest that less cementation has occurred, or adjacent grains have higher fracture stresses than their boundaries, or the boundary had a favourable orientation relative to the applied stresses for fracture.

Linkage of isolated intragranular microfractures, together with propagation of the linked fractures, also involves the same mechanisms as those recognized previously (i.e. cleavage 1–3 and low-temperature ductile fracture). The variety of linkage processes available means that linked fractures can have several crack-tips. Propagation of these fractures can therefore be in several different directions, each involving a different mechanism. Any crack-tips which propagate by mechanisms involving significant low-temperature plasticity (e.g. cleavage 3, low-temperature ductile fracture) will be prone to localized blunting and temporary arrest, whilst others continue to propagate.

A consequence of the linkage process is that the detailed microstructural characteristics of the linked fractures change along their length, particularly on the scale of the grain size. This results in an irregular fracture trace with an effective width of at least one and usually several grain diameters (Fig. 4). In cases of extreme intragranular disintegration, often stimulated by an inherited intragranular microstructure (such as a high subgrain density) and/or low-temperature plasticity and low-temperature ductile fracture deformation, this can result in a localized (sub-grain size) 'microbreccia-cataclasite' microstructure (e.g. Figs. 1e–h) along that portion of the linked fracture.

The linked fractures represent new planes of weakness which can reduce the shear yield or fracture strength of the original rock. This facilitates the initiation and localization of shear deformation and displacement along the linked fractures, as well as further propagation of any existing (e.g. arrested) crack-tips, and leads to the development of microbreccia-cataclasite zones and microstructures.

Development of microbreccia-cataclasite zones

The isolated low displacement extensional microfractures described in the last section, appear to control the localization of subsequent deformation (faulting), particularly the development of microbreccia-cataclasite zones (e.g. Fig. 5). Because the effective fracture width of the microfractures can be several grain diameters and the fracture traces are commonly irregular within individual grains (e.g. Figs. 3 and 4), shear displacement along these isolated fractures is likely to induce local regions of extension and/or compression, interfacial friction and grain comminution by irregular fracturing. This accounts for the formation of narrow microbreccia-cataclasite filled through-going fracture zones in the Skiag Bridge fault zone (similar features have also been described by Tullis 1986, Pollard & Segall 1987, Power *et al.* 1988). With increasing displacement (i.e. $>100\,\mu$m), these develop into fine-grained microbreccia-cataclasite zones (matrix grain size $<5\ \mu$m) containing progressively smaller and fewer large clasts. TEM analysis of the microbreccia-cataclasite zones in the Skiag Bridge fault zone will be described in detail elsewhere (work in preparation). The important features for the present discussion are as follows. There is a significant build-up of dislocation densities and sub-structures (e.g. subgrains) within clasts and in parts of the matrix compared to the undeformed host rock (Figs. 6a & b). This again emphasizes the role of low-temperature plasticity in the faulting process. Associated with this microstructure is the development of voids (Fig. 6b) and evidence (Fig. 6c) for cement growth (e.g. quartz and phyllosilicates). The latter suggests that fluid-assisted diffusive mass transfer processes also continued to play a role throughout the evolution of this fault zone. Fracturing of these cements in the rock matrix provides evidence for the repeated (i.e cyclic) nature of the fracture-dominated but low-temperature plasticity and diffusive mass transfer assisted deformation events.

Although the overall decrease in the average grain size in the microbreccia-cataclasite zones suggests that progressive fracturing (comminution) generally accompanies displacement, there is not a simple relationship between decreasing grain size and increasing displacement. There are examples of low-displacement ($<100\,\mu$m) fine-grained cataclastic zones which contain only a small percentage ($<20\%$) of fragments whose diameter is greater than 50 times the matrix grain size. There are also zones with larger displacement (i.e. >1 mm) containing more than 50% of clasts of this size. In some instances, whole grains located within the effective width of the initial fracture zone have been assimilated bodily into the microbreccia-cataclasite zone. Such large 'fragments' probably represent examples where BIF mechanisms isolated the original grain. The reduced frequency of such grains in the more mature displacement zones (displacements $\gg 1$ mm) indicates that they are reduced in size during subsequent deformation and fracturing possibly by the concentration of stress within large, hard particles set in a weaker matrix. This process is similar to the 'stress transfer' mechanism of fracture proposed for boudinage development by Lloyd *et al.* (1982).

The fracture deformation mechanism (cleavage 1–3, low-temperature ductile fracture) recognized as being active during the initial stages of evolution of the Skiag Bridge fault zone, are also active within the microbreccia-cataclasite zones. However, as grain comminution develops, they are also probably accompanied by grain boundary sliding and grain rolling processes.

The geometry of the initial microfracture arrays and the low displacement microbreccia-cataclasite zones indicates that shearing on the initial through-going micro-

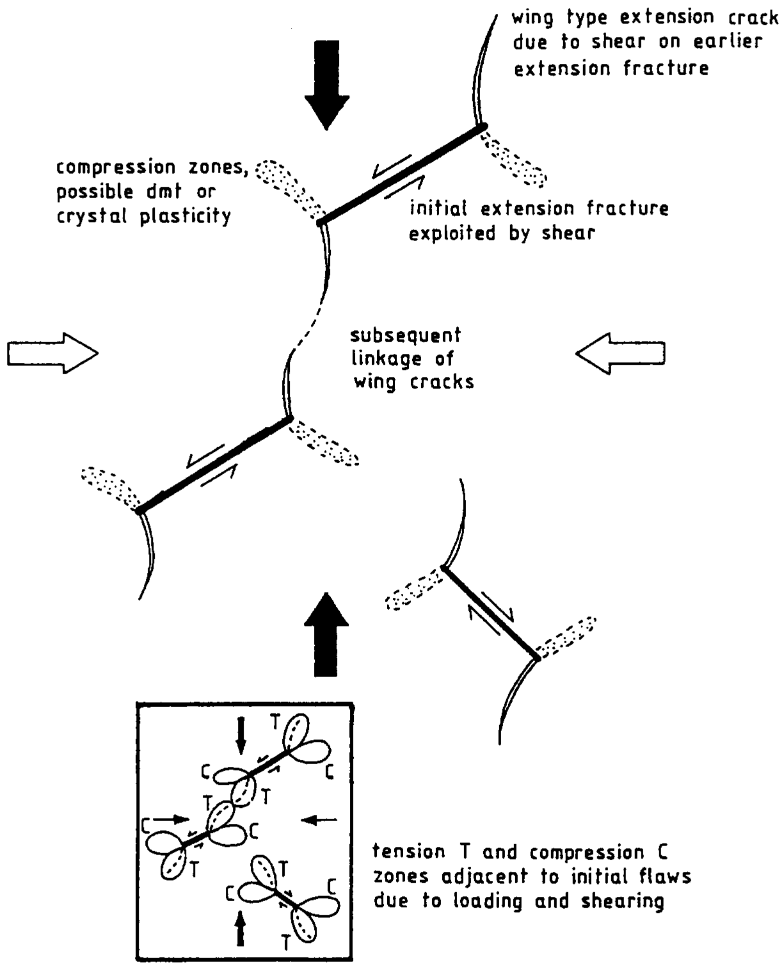


Fig. 7. Schematic formation of extensional 'wing cracks' and local zones of either diffusion mass transfer or crystal plastic deformation (low-temperature plasticity) mechanisms due to shearing on earlier formed fractures (composite diagram based on figures in Adams & Sines 1978, Horii & Nemat-Nasser 1986, Pollard & Segall 1987; inset after Ashby & Verrall 1977).

fractures promotes further extension fracturing at high angles to the shear direction (shown schematically in Fig. 7). These so-called 'wing cracks' (Adams & Sines 1978, Horii & Nematt-Nasser 1986, Pollard & Segall 1987) are themselves subsequently exploited by shear displacement, leading to microbreccia-cataclasite formation. The overall effect therefore is for the isolated through-going fractures to link-up and for the rock to become broken-up into discrete blocks bounded by microbreccia-cataclasite zones (Fig. 8). The formation of wing cracks also involves zones of compression associated with the master fractures (Fig. 7). Such regions may be identified initially by diffusive mass transfer and/or low-temperature plasticity deformation microstructures, but eventually the enhanced compression should result in intragranular extension fractures. The whole microstructural evolutionary process is then able to continue with the development of linked through-going extension fractures, shear localization and displacement resulting in microbreccia-cataclasite filled fractures, and the eventual formation of another set of wing cracks. This process is summarized schematically in Fig. 9, based on the microstructure shown in Fig. 8.

The width of the microbreccia-cataclasite zones tends to increase with displacement. In the wall rock adjacent to the main fault the zones are typically <100 μm wide, but along the main fault itself the zones are up to 3–4 cm thick. However, as we have already seen with the comminution of grain and fragment sizes, there is not a simple progressive increase in width with displacement. Initially, any increase in zone width is likely to be rapid due to the large effective width of the early microfractures (e.g. Fig. 4). The incorporation of wall rock fragments into the fracture zone involves wear of any asperities as well as 'spalling' of grains or parts of grains from semi-planar wall rock–fault-zone interfaces (Fig. 10). Spalling arises because shear displacements in the fracture zone induce tensional stresses in the wall rock grains adjacent to the fracture, leading to extensional microfractures sub-parallel to the main fracture (e.g. Fig. 5). These fractures remove support from the wall rock interface and induce assimilation of the wall rock fragment into the fracture zone. Further deformation in the fracture zone promotes a break-up of the fragments either by a 'stress transfer' process, where stress transferred from the matrix concentrates in the centre of the elongate fragments (see Lloyd *et al.* 1982), or by bending induced fragmentation. The process is likely to be cyclic and repeated until the grain is completely absorbed into the fracture zones. The fragments of such 'drawn-out'

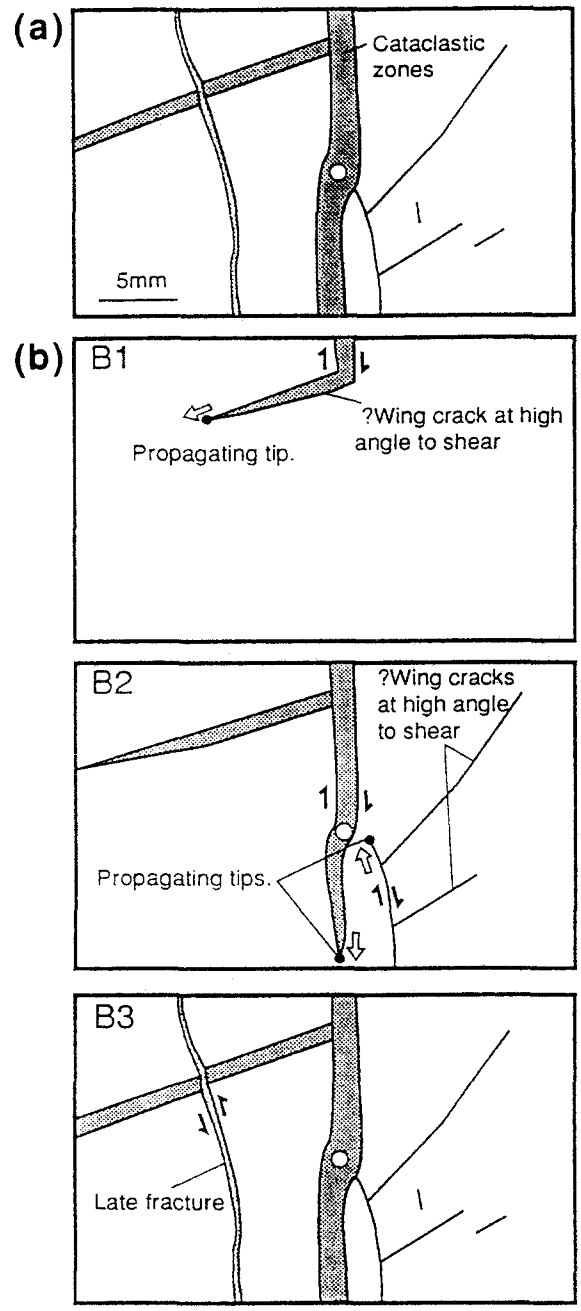


Fig. 9. Summary diagram of the evolution of the microstructure shown in Fig. 8. (a) Sketch identifying the main features of the blocky microstructure and fracture array. (b) Possible evolutionary sequence B1–B3 for the fracture array, which involves the propagation and linking of microbreccia-cataclasite zones. Note that many of the low-displacement fractures at a high angle to the main (widest) vertical microbreccia-cataclasite zone have the geometries expected for 'wing' cracks.

grains may remain in close proximity (see Fig. 5), particularly when diffusive mass transfer processes have been simultaneously active leading to re-cementation of the spalled fragments. The spalling process is also important in the cyclic development of wall rock–fracture-zone interfacial asperities, which helps maintain the increase in fracture zone width.

The incorporation of wall rock fragments into the fracture zones is enhanced by an initial low-temperature plasticity work-hardening ('cold-working') deformation in wall rock grains up to several grain diameters from the fracture. This is clearly shown (Fig. 11) by SEM electron channelling analysis (see Lloyd 1985, 1987, Lloyd *et al.* 1991, for details of the technique). A grain (Fig. 11a) two diameters away from the fracture yields an electron channelling pattern typical of an undistorted, non-work-hardened lattice (Fig. 11b). For a grain one diameter away, there is a broadening of the channelling bands and lower contrast (Fig. 11c), consistent with the effects of work-hardening due to low-temperature plasticity. The 'spalled grain' adjacent to the fracture provides a very poor quality electron channelling pattern (Fig. 11d), consistent with significant penetrative work-hardening. Obviously, such heavily work-hardened grains contain large internal stresses and are therefore susceptible to fracture mechanisms, particularly those involving low-temperature plasticity (e.g. cleavage 3, low-temperature ductile fracture).

SEM electron channelling pattern analysis of microbreccia-cataclasite fragments is probably capable of distinguishing block rotations and tilts, from which local fault zone deformation histories can be reconstructed. Complete fault zone deformation histories could then be derived via the sum of the local increments. Similar arguments can be made for the recognition and reconstruction of grains which were initially incorporated intact into the microbreccia-cataclasite zones.

CONCLUSIONS

The examples presented here illustrate how upper crustal fault zones can develop in quartzites. Initially, individual grains fracture in isolation, but eventually link to form isolated fractures. Continued fracturing within and adjacent to these initial fractures results in the formation of the linked fracture array which subsequently develops into the macroscopic fault zone. Figure 12 provides a schematic summary of this evolutionary process.

Initially (Fig. 12-1), deformation induces stress concentrations at grain contacts which promote (Fig. 12-2) intragranular extension fractures (e.g. Fig. 1) and also both low-temperature plasticity and low-temperature ductile fracture deformation (e.g Fig. 2). Continued deformation (Fig. 12-3) causes a linkage of the intragranular microfractures (e.g. Fig. 3). On the larger scale (Fig. 12-4), the linked microfracture has an irregular trace and therefore an effective fracture width of several grain diameters (e.g. Fig. 4). Such linked fractures represent a new weakness in the bulk rock on to which subsequent deformation and displacement are localized (Fig. 12-5). Because of the exaggerated initial fracture width, only slight displacement produces a relatively wide initial displacement fracture zone filled with microbreccia-cataclasite (Fig. 12-5; e.g. Fig. 4) and the juxtaposition of relatively undeformed and highly deformed border areas (e.g. Fig. 5). Continued deformation and displacement (i.e. faulting) causes widening of the fracture zone (Fig. 12-6) by wear of asperities and

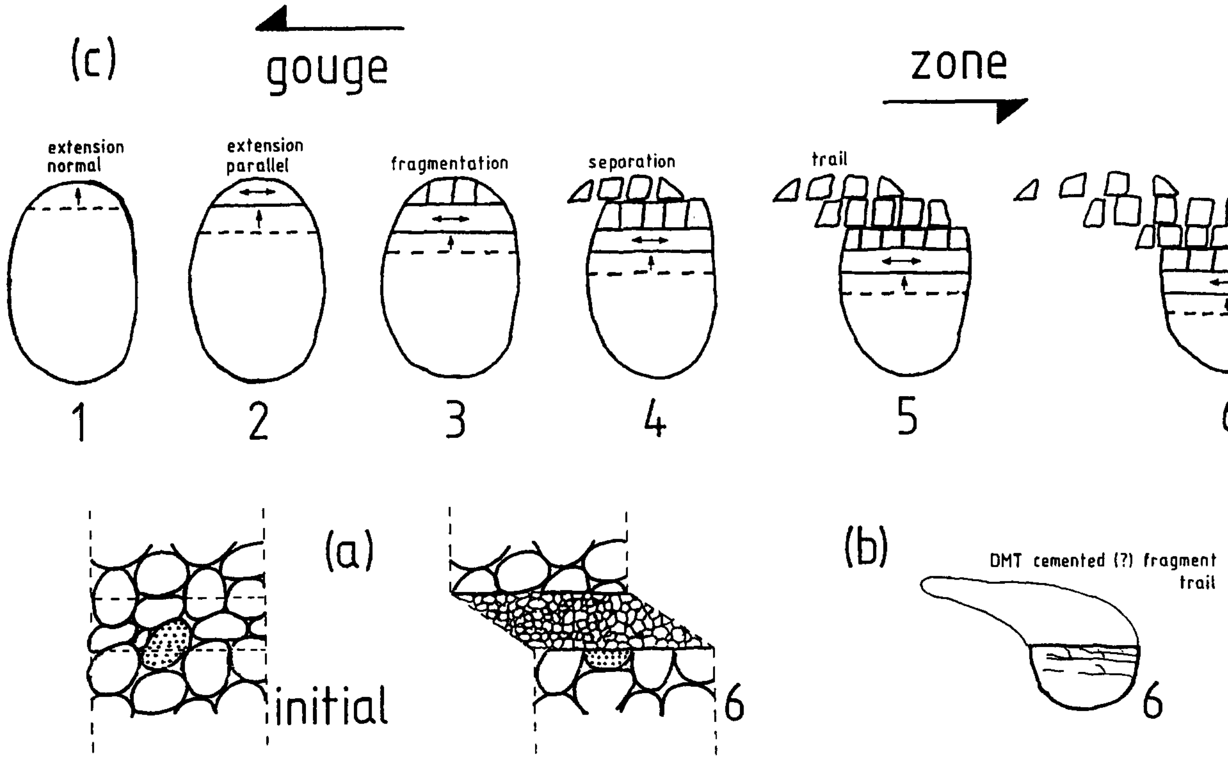


Fig. 10. Schematic diagram illustrating the gradual but continuous assimilation of an individual grain into microbreccia-cataclasite zones by progressive grain 'spalling'. (a) Generalized development of a sinistral displacement microbreccia-cataclasite zone; reference grain indicated by dot ornament. (b) Detail of reference grain showing 'shadow' consisting of 'spalled' fragments, which may be cemented by diffusion mass transfer processes. (c) Detail of grain spalling process: (1) initial transgranular extension fracture adjacent and parallel to the microbreccia-cataclasite zone; (2) partitioning of stress directions (arrows) between fragment and grain; break-up of fragment and further transgranular fracturing; (4)–(6) process repeated, resulting in destruction of original grain and progressive assimilation of fragments into the microbreccia-cataclasite zone as displacement continues.

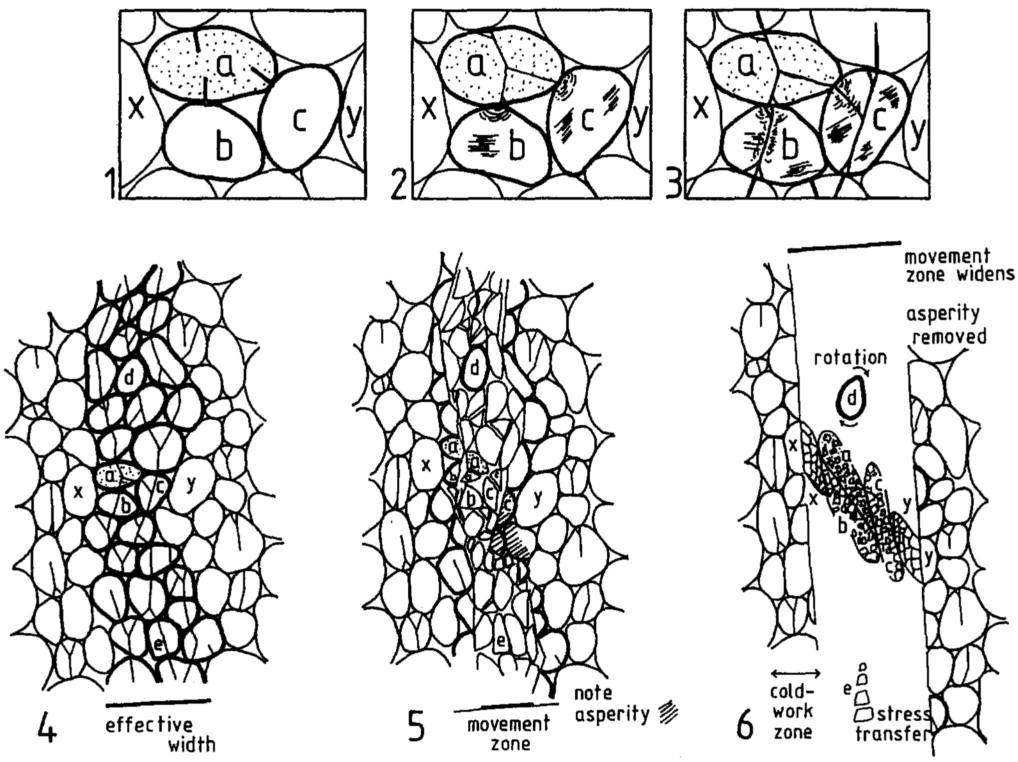


Fig. 12. Schematic summary showing the evolution of microbreccia-cataclasite fault zones in quartzite under upper crustal deformation conditions. Parts 1–3 show the deformation on the scale of the grain size (e.g. grains a–c, x and y). Parts 4–6 consider a somewhat larger scale but include the previously identified grains and also grain d, which is wholly incorporated into the fault zone and suffers rotation during subsequent deformation. See text for detailed description.

extensional spalling of wall rock grains (e.g. Figs. 5 and 10), leading to the formation of a work-hardened (cold-worked) zone in the wall rock adjacent to the fracture (e.g. Fig. 11). Deformation and displacement are also accommodated by further low-temperature plasticity, low-temperature ductile fracture and diffusive mass transfer processes. On the even larger scale (not shown in Fig. 12), break-up of the bulk rock may continue by the movement on established fracture zones and the initiation of an hierarchic or cyclic array of 'wing cracks' at high angles to each other (e.g. Figs. 7–9).

Inherited microstructures present in the parental grains (e.g. cement phases; grain size, sorting, packing and contact area; and grain crystal lattice orientation and internal dislocation and subgrain microstructure) can have a crucial role in influencing the exact fracture processes. Their distribution results in a heterogeneous distribution of fracture strengths which controls some of the linking of microfractures into more extensive fractures arrays and the structure of the microbreccia-cataclasite zones.

This study emphasizes how different processes are involved in the production of individual fractures, with both intragranular and through-going fractures contributing. We have also shown that the evolution of the Skiag Bridge fault zone has involved the three main categories of deformation mechanisms (i.e. fracture, low-temperature crystal plasticity and diffusion mass transfer). The interrelationship between these categories (e.g. low-temperature ductile fracture) and the transition between individual fracture mechanisms (e.g. from cleavage 1 through to cleavage 3 and low-temperature ductile fracture) are significant aspects of this evolution. Thus, the examples presented here demonstrate the complex interrelationships which exist between a group of deformation mechanisms and emphasize the potential importance of low-temperature plasticity and low-temperature ductile processes during faulting under upper crustal conditions.

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