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Deformation processes and weakening mechanisms within the frictional–viscous transition zone of major crustal-scale faults: insights from the Great Glen Fault Zone, Scotland

M. Stewart[a, 1], R.E. Holdsworth[a,*], R.A. Strachan[b]

[a]*Reactivation Research Group, Department of Geological Sciences, University of Durham, Durham DH1 3LE, UK*
[b]*Department of Geology, Oxford Brookes University, Gypsy Lane, Headington, Oxford OX3 0BP, UK*

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Abstract

The Great Glen Fault Zone (GGFZ), Scotland, is a typical example of a crustal-scale, reactivated strike-slip fault within the continental crust. Analysis of intensely strained fault rocks from the core of the GGFZ near Fort William provides a unique insight into the nature of deformation associated with the main phase of (sinistral) movements along the fault zone. In this region, an exhumed sequence of complex mid-crustal deformation textures that developed in the region of the frictional–viscous transition (ca. 8–15 km depth) is preserved. Fault rock fabrics vary from mylonitic in quartzites to cataclastic in micaceous shear zones and feldspathic psammites. Protolith mineralogy exerted a strong control on the initial textural development and distribution of the fault rocks. At lower strains, crystal-plastic deformation occurred in quartz-dominated lithologies to produce mylonites simultaneously with widespread fracturing and cataclasis in feldspar- and mica-dominated rocks. At higher strains, shearing appears to increasingly localise into interconnected networks of cataclastic shear zones, many of which are strongly foliated. Textures indicative of fluid-assisted diffusive mass transfer mechanisms are widespread in such regions and suggest that a hydrous fluid-assisted, grainsize-controlled switch in deformation behaviour followed the brittle comminution of grains. The fault zone textural evolution implies that a strain-induced, fluid-assisted shallowing and narrowing of the frictional–viscous transition occurred with increasing strain. It is proposed that this led to an overall weakening of the fault zone and that equivalent processes may occur along many other long-lived, crustal-scale dislocations.

1. Introduction

The increased application of microstructural criteria in recent years has substantially aided our understanding of the various deformation mechanisms and rheological behaviours that occur within crustal faults and shear zones (for recent reviews see Schmid and Handy, 1991; Snoke et al., 1998). In general, deformation in the upper crust is considered to be characterised by a regime of frictional flow in which the deformation mechanisms involve brittle fracture and dilatancy that are known experimentally to depend mainly on effective pressure. At greater depths, the rheological behaviour changes to a regime of viscous flow in which a range of non-frictional, thermally activated mechanisms are involved in both crystal-plasticity and diffusional creep processes. In the continental crust, the region separating these two very different flow regimes—*the frictional–viscous transition*—is generally believed to be located in the mid-crust (ca. 10–15 km depth) and to exist over a depth range of several kilometres. Such regions are generally not accessible along many widely studied, currently active major faults such

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* Corresponding author.
E-mail address: R.E.Holdsworth@durham.ac.uk (R.E. Holdsworth).
[1] Present address: School of Ocean and Earth Sciences, University of Southampton, Southampton Oceanography Centre, Empress Dock, European Way, Southampton SO14 3ZH, UK.

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as the San Andreas Fault Zone, but can be examined directly along ancient, exhumed examples of crustal-scale fault zones where deeper crustal sections, including those in the vicinity of the frictional–viscous transition are exposed at the surface.

Early models of deformation along crustal-scale fault zones (e.g. Sibson, 1977; Scholtz, 1988) consider the frictional–viscous transition in terms of a change from cataclasis to crystal-plasticity. Were this appropriate, laboratory experimental studies suggest that the textural and rheological evolution of fault rocks within the transition zone should be controlled primarily by changes in pressure, temperature, fluid pressure and strain-rate (e.g. Tullis and Yund, 1977, 1992; Hirth and Tullis, 1994). However, a wealth of theoretical, experimental and microstructural studies suggest that the situation is likely to be fundamentally influenced by several additional factors in real fault zones. These factors include: the polymineralic nature of most fault rocks and their protoliths (e.g. Jordan, 1987; Handy, 1990); the presence of pre-existing mechanical anisotropies (White et al., 1986; Holdsworth et al., 1997); the likely importance of grainsize-sensitive deformation mechanisms (e.g. Schmid et al., 1977; White et al., 1980; Schmid and Handy, 1991); the mechanical and chemical effects of active fluid phases (e.g. Fyfe et al., 1978; Atkinson and Meridith, 1987; Tullis and Yund, 1980); and the rheological effects of syn-tectonic metamorphic reactions (Brodie and Rutter, 1985). As a result, it is widely postulated that the frictional–viscous transition zone of crustal-scale faults is likely to be a complex region of gradational behaviour that evolves with increasing strain (Schmid and Handy, 1991). In order to assess the relative importance and interplay of the various possible controlling factors in the region of the frictional–viscous transition, there is a clear need for descriptive field and microscopic studies of fault rocks along ancient exhumed fault zones. The present study describes in detail the petrology, structure and microfabrics of mid-crustal fault-rocks from the core of the Great Glen Fault Zone in Scotland. These rocks illustrate that contrasting deformation mechanisms are spatially partitioned in natural fault zones and that this distribution changes as the fault zone evolves. They also provide evidence for deep-seated mechanisms that may account for the apparent weakness and

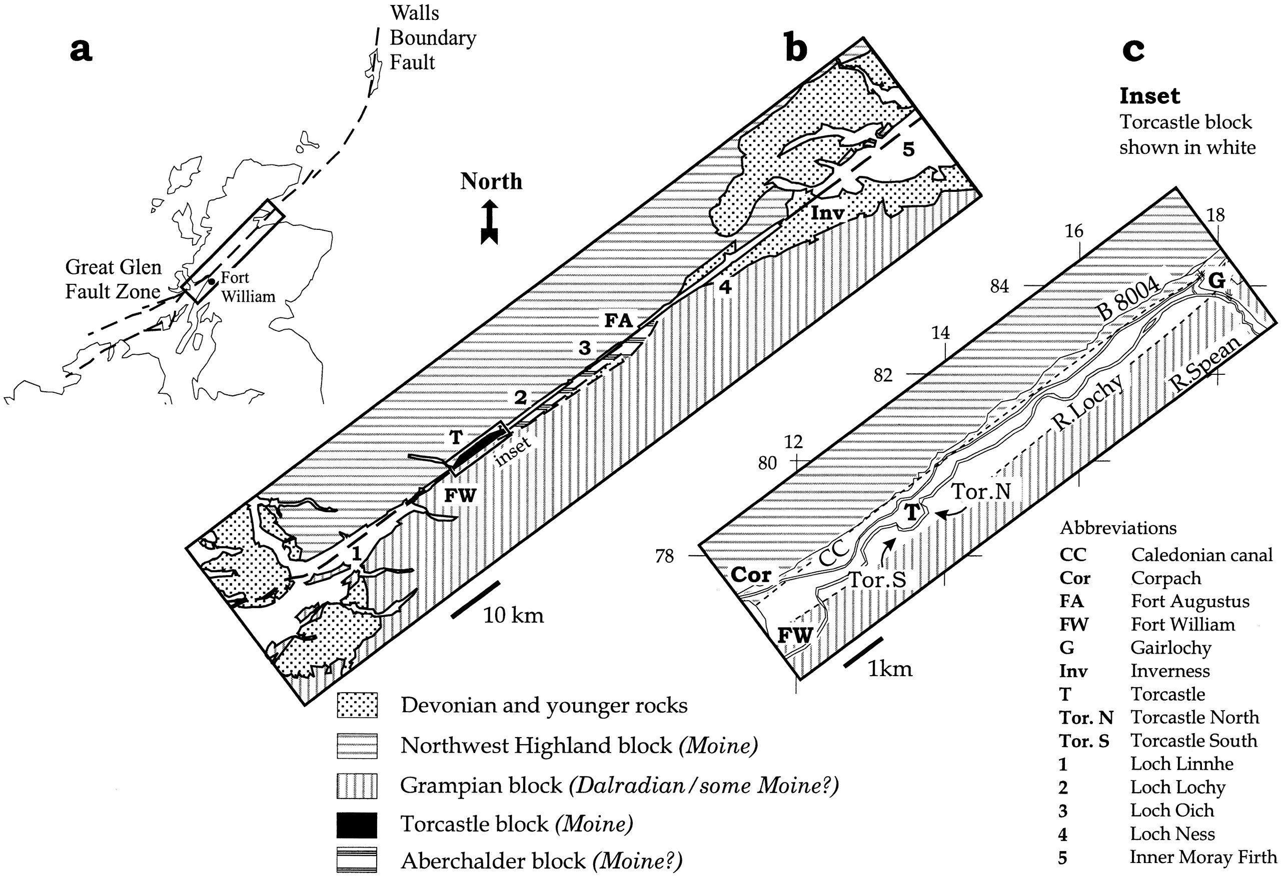


Fig. 1. (a) Regional map of the trace of the GGFZ in Northern Britain. (b) Simplified geological map of the GGFZ in mainland Scotland (for location see (a)); based on Stewart (1997). (c) Map of the Torcastle Block (for location see (b)) showing position of Torcastle North and South exposures (Figs. 2 and 3, respectively). Marginal numbering corresponds to UK national grid system.

long-term movement histories of many crustal-scale faults.

2. Regional geology of the GGFZ

The Great Glen Fault Zone (GGFZ) is a major, subvertical, reactivated fault that cuts across the Ordovician–Silurian Caledonian orogenic belt of Scotland (Fig. 1a; Kennedy, 1946). It is a ca. 3-km-wide zone of fracturing and intense cataclasis that trends 037° through the Scottish mainland, swinging into a more north-northeast trend where it is thought to link into the Walls Boundary Fault system on Shetland (Fig. 1a; Flinn, 1961; McBride, 1994). On the mainland, different structural levels are preserved adjacent to the GGFZ as a result of differential displacement and exhumation across the structure (Stewart, 1997; Stewart et al., 1997, 1999). A central zone ca. 300 m wide is thought to contain the principal displacement surfaces and separates the two regional crustal blocks that define the wall-rocks to the GGFZ, termed here the Northwest Highland and Grampian crustal blocks (Fig. 1b). In addition, two narrow, highly deformed fault-bounded slivers, the Torcastle and Aberchalder blocks are entrained within the fault zone (Figs. 1b and c).

Regional structural studies of the GGFZ suggest that the earliest, main phase of sinistral movements along the GGFZ occurred between ca. 428 Ma and 390 Ma (Stewart, 1997; Stewart et al., 1997, 1999). Post-Caledonian dextral movements of a few tens of kilometres have been demonstrated previously from the displacement of geological markers (Rogers et al., 1989). Detailed mapping of the Great Glen area southwest of Fort Augustus (Fig. 1b) has allowed characterisation of fault-fabrics and the nature of deformation processes associated with the GGFZ (Stewart, 1997). Brittle fault rocks and fractures dominate most of the fault zone. Exposure is limited as it is mostly submerged by water or covered by glacial till. Existing exposures of fault-rocks are mainly confined to the margins of the fault-zone valley, and rocks from the central, highly deformed core of the fault are very rarely observed.

To the northwest of the GGFZ, the Northwest Highland block is dominated by Neoproterozoic metasediments of the Moine Supergroup (Holdsworth et al., 1994 and references therein) deformed and metamorphosed during two periods of tectonothermal activity: the ca. 870–780 Ma Knoydartian event and the ca. 470–430 Ma Caledonian orogeny (Vance et al., 1998). These rocks are intruded by various felsic and mafic igneous suites of pre-Caledonian to late Caledonian age, and later, by post-tectonic Permo-Carboniferous lamprophyric and Tertiary basaltic dyke swarms.

To the southeast of the GGFZ, Neoproterozoic to early Cambrian metasedimentary rocks of the Dalradian Supergroup dominate the Grampian block (Harris et al., 1994 and references therein). These rocks were deformed during Grampian orogenesis at ca. 470–460 Ma and were subsequently intruded during the late stages of the Caledonian orogeny (ca. 425 Ma) by granitic plutons and associated minor intrusions. Later, post-tectonic igneous suites include early Devonian intrusives and extrusives, Permo-Carboniferous lamprophyres and Tertiary basaltic dykes. In the northeastern part of the Grampian Block, rocks thought to form the lower parts of the Dalradian Supergroup are underlain by migmatites dated at ca. 840 Ma (Noble et al., 1997) which may, at least in part, correlate with the Moine Supergroup. Sheared rocks within the Aberchalder block have been interpreted as derived from these migmatitic protoliths (Stewart et al., 1999).

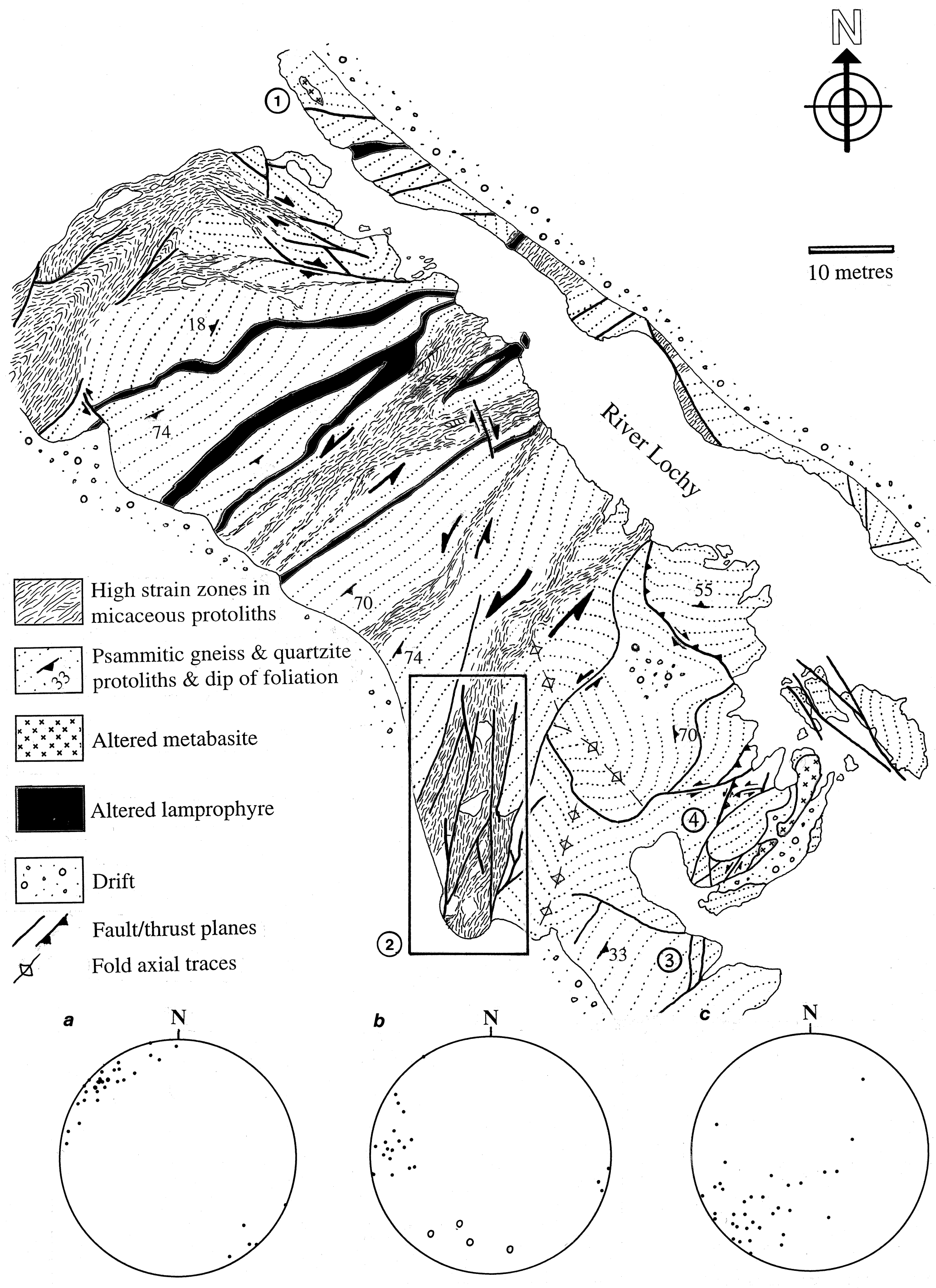
The narrow, fault-bounded Torcastle block lies in the centre of the GGFZ between Fort William and Loch Lochy (Fig. 1b). The rocks appear to be derived from a metasedimentary Moinian protolith and are especially important as they preserve a diverse assemblage of fault rocks formed by both viscous and frictional flow processes, some of which appear to have operated simultaneously. Thus, the Torcastle block preserves exhumed fault rocks formed at greater depths than those currently seen elsewhere along the GGFZ in the Scottish mainland. They also allow direct study of the nature and interaction of deformation processes in the frictional–viscous transition zone.

3. Pre-GGFZ geology of the Torcastle block

The best exposures of the Torcastle block occur at two locations along the River Lochy, 4 km northeast of Fort William (Fig. 1c). These localities are here termed Torcastle North (NN 135 791; Fig. 2) and Torcastle South (NN 133 785; Fig. 3).

3.1. Protolith lithology and distribution

In order to characterise fully the structures and fault-fabrics that are associated with the GGFZ, it is important to identify features related to the pre-existing history of the regional protoliths. This is not always straightforward because the deformation fabrics produced by the fault are often intense and widespread. There are, however, numerous low strain zones in all of the different protolith lithologies that preserve regional characteristics and structures.



Poles to main shear-zone fabric (n = 32)

- Poles to sinistral synthetic shears (n = 21)

o Poles to dextral antithetic shears (n = 4)

Lineation, defined by chlorite mimetic after trails of disaggregated biotite (n = 35)

Fig. 2. Detailed geological map of the main fault rock exposures at Torcastle North (for location, see Fig. 1c). Stereoplots show: (a) poles to main shear-zone foliation; (b) poles to sinistral and dextral shears; (c) stretching lineations within shear-zone from boxed area 2 (which also shows location of Fig. 5). Numbers circled refer to localities described in the text.

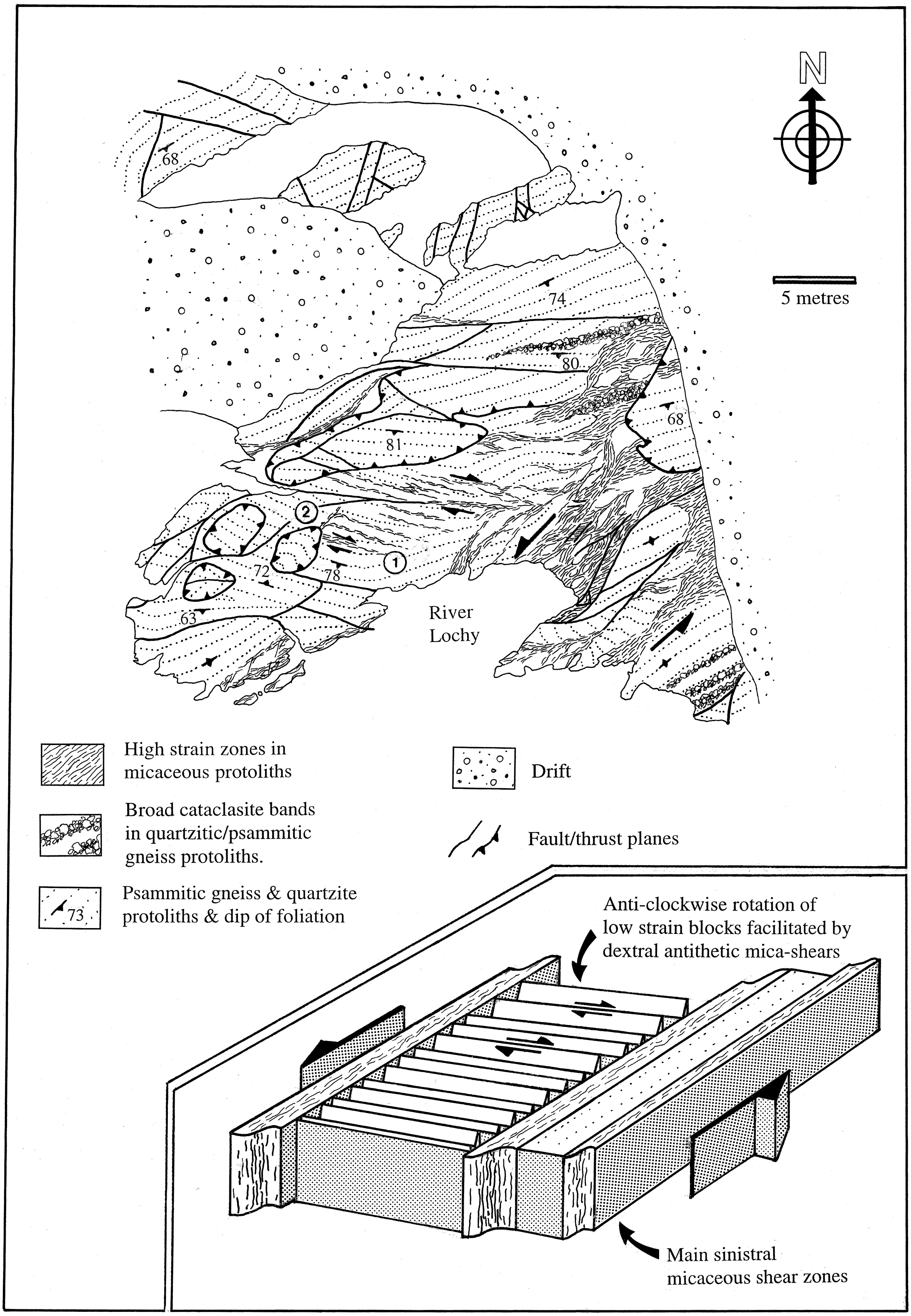


Fig. 3. Detailed geological map of the main fault rock exposures at Torcastle South (for location, see Fig. 1c). Numbers circled refer to localities described in the text. Inset: Schematic block diagram illustrating the relationship between fine ESE-trending dextral antithetic shears and the main NE-trending sinistral shear zones.

Psammitic lithologies dominate at both sets of exposures with subordinate proportions (ca. 15–20%) of semipelitic and pelitic gneiss (Figs. 2, 3 and 4a)—especially at Torcastle South—and less common quartzite horizons (< 10%). The metasediments are interdigitated with numerous, small (< 1 m wide) metabasic horizons that occur as both laterally continuous units, sub-parallel to the regional fabric and large (1–10-m-wide) discontinuous pods. Distinctive garnetiferous amphibolite pods at Torcastle South are comparable to similar units found widely within the Glenfinnan Group of the Moine Supergroup (Holdsworth et al., 1994). The gneissic banding and occasional migmatitic segregations in the pelitic lithologies are also consistent with a Moine protolith. Mineralogically, the metasediments comprise quartz, feldspar (mostly plagioclase), muscovite and secondary chlorite (after biotite and garnet). The presence of garnet in addition to the migmatitic segregation fabric implies amphibolite facies metamorphic conditions prior to faulting.

The northern exposures comprise upstanding areas of low strain feldspar-rich psammites and quartzites separated by low-lying belts of pelitic protolith that define a series of metre-scale shear zones (Fig. 2). The protolith fabric is defined by gneissic banding and also by alignment of muscovite and chlorite (after biotite) crystals in the psammites and trends northeast across most of the outcrop. However, at the southeastern end, it is folded by a gentle upright fold that is in turn disrupted by later faults (Fig. 2). Three undeformed northeast-trending, altered lamprophyre dykes of probable Permo-Carboniferous age dissect the outcrop, the largest of which is ca. 3 m thick.

At Torcastle South (Fig. 3), pelitic and semi-pelitic gneisses form a low-lying area at the eastern end of this outcrop which represents part of a ca. 10-m-wide, northeast-trending, high strain zone. To the west, the regional fabric runs generally east–west in units of semipelitic and psammitic gneisses. An eroded subhorizontal fault surface occurs at the base of three small upstanding blocks at the western end of the promontory. Folding is rare, the only fold (ca. 5-m wavelength) observed occurs at the extreme western end of the outcrop.

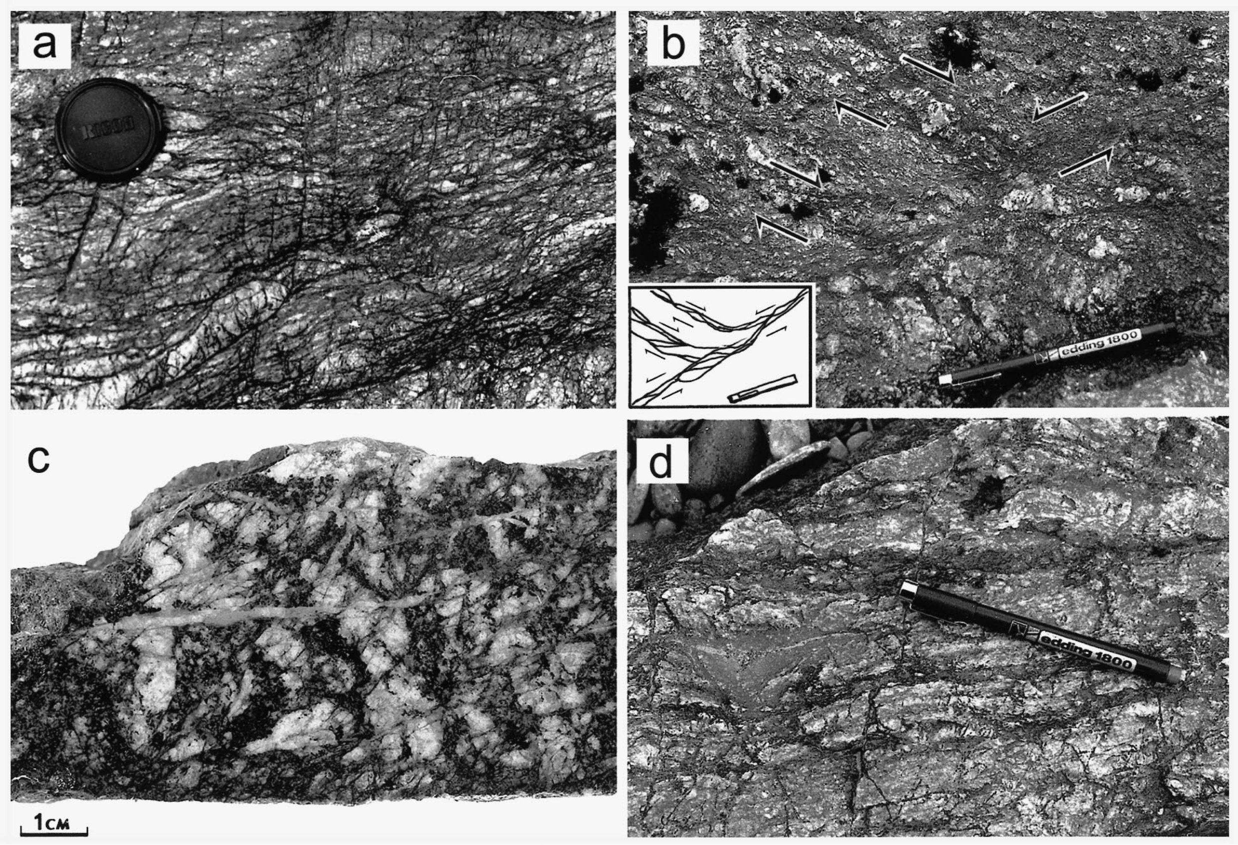


Fig. 4. Field and hand-specimen photographs of representative Moine protoliths and GGFZ fault rocks from the Torcastle block—all plan views. (a) Typical fractured semi-pelitic gneiss (locality 4, Fig. 2); (b) Heterogeneously sheared micaceous unit derived from cataclastic deformation of pelitic gneiss (locality 2, Fig. 3)—note interlinked systems of sinistral and dextral brittle shears (see inset). (c) Cataclasite derived from feldspathic psammitic gneiss (locality 3, Fig. 2); (d) Mylonite derived from quartzite (locality 1, Fig. 2).

3.2. Regional fabrics

Without exception, all protolith assemblages are coarse grained, with average grainsizes typically 0.5–2.0 mm. Grains smaller than 0.2 mm are uncommon and many grains (especially quartz and muscovite) are over 4 mm across. Textures are typically inequigranular and seriate to interlobate in form. Many of the abnormally large quartz grains enclose smaller quartz grains, or appear to partially consume adjacent grains. It is suggested that these textures indicate a period of static recrystallisation, where the high temperature overprint of a pre-existing metamorphic fabric initiates grain boundary area reduction (GBAR) processes in order to achieve greater microstructural stability (e.g. Passchier and Trouw, 1996). This is most likely to be related to regional Caledonian events reworking rocks deformed and metamorphosed initially during the Neoproterozoic Knoydartian event.

These regional fabrics locally exhibit asymmetrical geometries, suggesting that a component of non-coaxial shear accompanied regional metamorphism. There are several lines of evidence that indicate that this deformation was regional in origin rather than being related to the GGFZ. First, the orientation of the mineral lineations associated with these asymmetric fabrics is extremely variable, suggesting that significant reorientation by later deformation events has occurred. Second, exactly comparable fabrics are present in all semipelitic and pelitic lithologies observed in the adjacent Moine Supergroup, well away from the effects of GGFZ-related deformation (Stewart, 1997). Third, shear senses indicted by the asymmetric fabrics are variable and show no systematic patterns. It is therefore interpreted that these are regional (Caledonian or Knoydartian age) fabrics that are not related to movements along the GGFZ.

4. GGFZ-related deformation

4.1. Geometry and distribution of main deformation phase

Regionally, the strain distribution and type of fault-rocks associated with the GGFZ are highly heterogeneous. This occurs for two main reasons: 1) the rocks are polymineralic aggregates composed of varying proportions of different minerals that respond to the same deformation event in contrasting ways; and 2) earlier fabrics are variably overprinted by those formed during later stages of fault movement under different physical conditions. However, in the existing exposures of the Torcastle block, the effects of later deformations are relatively minor compared to adjacent areas and fabrics formed during the main phase of sinistral shear along the GGFZ are well preserved.

In the Torcastle exposures, the most intense GGFZ-related strains appear to occur in the semipelitic and pelitic gneisses through the development of major networks of fine micaceous shear zones (Figs. 2, 3 and 4b). These enclose lower strain augen and blocks of cataclastically deformed psammite (Fig. 4c) and plastically deformed quartzite (Fig. 4d). Studies in the adjacent Northern Highland and Grampian blocks suggest that the lithology-controlled partitioning of strain in this way occurred once the lithological banding and regional fabrics had been drawn into parallelism with the GGFZ (Stewart, 1997; Stewart et al., 1999).

Four large micaceous shear zones cut across the Torcastle North outcrop ranging in width from 1 m to over 20 m, and one large (ca. 15 m wide) shear zone dissects the main Torcastle South exposure (see Figs. 2 and 3, respectively). At Torcastle North, a large section of a major northeast-trending high-strain zone was mapped in detail to assess the sense and distribution of displacement (Locality 2 on Fig. 2, stereoplots a–c; Fig. 5). The subvertical deformation fabric is superficially simple and planar (Fig. 2, stereoplot a). Sparse lineations defined by elongate chlorite fibres are only preserved in freshly exposed foliation surfaces and consistently plunge at shallow to moderate angles towards the southwest (Fig. 2, stereoplot c). The vertical fabric and shallow-plunging lineation are together consistent with strike-slip or transpressional displacements (e.g. Tikoff and Greene, 1997; Dewey et al., 1998). Sinistral shear sense is indicated by shear-bands, Riedel faults (Fig. 2, stereoplot b; Fig. 5, localities 1 and 2) and steeply plunging, southwest-verging folds (locality 3 on Fig. 5). Metre-scale sinistral offsets of low-strain blocks entrained within the high strain fabric are also observed in three blocks of anorthositic composition (localities 4, 5 and 6 on Fig. 5). In addition to these clear sinistral kinematic indicators, a small number of asymmetric folds observed in a narrow zone bounded by north-northeast trending Riedel faults (area 7 on Fig. 5) imply a dextral sense of offset. It is not possible to tell whether the dextral folds formed synchronous with the sinistral deformation in a zone of localised retrocharriage, or whether they relate to a separate, presumably later deformation event.

Overall, the predominance of asymmetric, sinistral shear sense indicators suggests that the higher strain, micaceous shear zones at both localities are dominated by non-coaxial deformation. In detail, these wide shear zones are composed of many narrow bands (0.5–1.0 mm wide on average, although locally up to 1 cm across) of fine-grained muscovite and biotite, the latter being almost entirely replaced by brown–green chlorite. These bands are typically very closely spaced, separated on a millimetre to centimetre scale, anastomosing and coalescing to create a through-going interconnected network on all scales (Figs. 4b and 6a). Asymmetric, sheared muscovite porphyroclasts and quarter mats (cf. Hanmer and Passchier, 1991) of mica flanking feldspar grains within and marginal to these shear zones indicate predominantly sinistral non-coaxial shear. However, intervening low strain lenses composed of quartz, feldspar, coarse-grained muscovite and garnet (pseudomorphed by chlorite) exhibit symmetrically flattened shapes that are commonly dismembered by symmetric conjugate shears. This suggests an additional component of coaxial flattening normal to the foliation in the fault zone.

It seems likely that the micaceous rocks have acted as preferential sites for strain accommodation due to the dominance of weak phyllosilicate minerals and the strong pre-existing planar anisotropy represented by the aligned mica foliae (Shea and Kronenberg, 1993; Wintsch et al., 1995).

In the predominantly quartzo-feldspathic lower strain regions between the micaceous shear zones, the pre-existing protolith foliation is variably overprinted by diffuse cataclastic deformation, faulting and irregular folding (e.g. Figs. 2, 3, 4c and 6b). In places, the cataclastic texture intensifies in psammitic rocks to

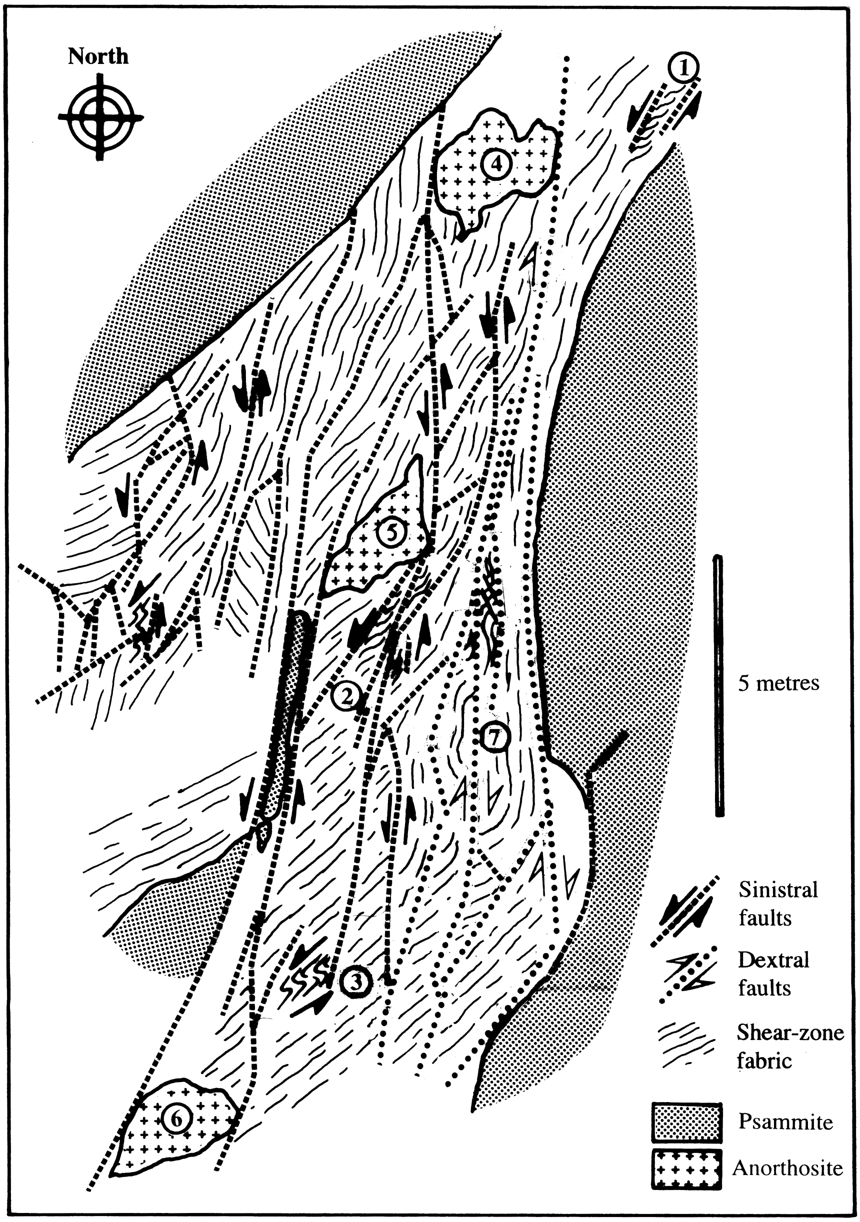


Fig. 5. Detailed map of faults and shear-fabrics observed in a northeast-trending micaceous shear-zone at Torcastle North (locality 2, Fig. 2). Note the units of anorthosite (4–6) that are dismembered by sinistral shears suggesting that individual shear surfaces display metre-scale displacements. Numbers circled refer to features described in the text.

form northeast-trending belts, tens of centimetres across, of pale-coloured cataclasite with gradational margins. On a metre- to tens-of-metre-scale, the lower strain regions display complex domainal deformation patterns. Good examples occur at Torcastle South (e.g. at localities 1 and 2 on Fig. 3; see also Fig. 4b), where a series of narrow (tens of centimetres wide) mica-shears strike east-southeast, dip consistently subvertically and display dextral kinematic indicators. They appear to swing anticlockwise into the larger northeast-trending shear zone to the east. At locality 2 (Fig. 4b) dextral shears are seen to link into a fine northeast-trending shear band exhibiting clear sinistral shear fabrics. The east-southeast-trending dextral micaceous shear bands are interpreted to represent antithetic shears accommodating anticlockwise rotations of low strain blocks between large northeast-trending sinistral shear zones (Fig. 3 inset); a similar pattern is seen at the northern end of the Torcastle North exposures (Fig. 2). The dextral shears appear to be prominent in these areas because the regional gneissic fabric was favourably orientated for slip leading to a domainal style of deformation involving block rotation (cf. Nur et al., 1989). Undulatory low-angle fault zones with highly variable slickenline orientations and senses of shear also occur at both localities (Figs. 2 and 3). Faults of this kind may act as detachments for adjacent domains of block rotation or as more general, three-dimensional strain accommodation surfaces within the fault zone (cf. Woodcock, 1987).

In summary, field observations suggest that strain in the central part of the GGFZ localised preferentially into micaceous protoliths and zones of feldspathic cataclasite to form an interconnected network of northeast-trending, steeply dipping, anastomosing shear zones that enclose lensoid augen and blocks of lower strain quartzo-feldspathic material (Figs. 2 and 3). Kinematic partitioning of strain has also occurred, so that high strain regions are generally characterised by sinistral non-coaxial deformations, whilst lower strain

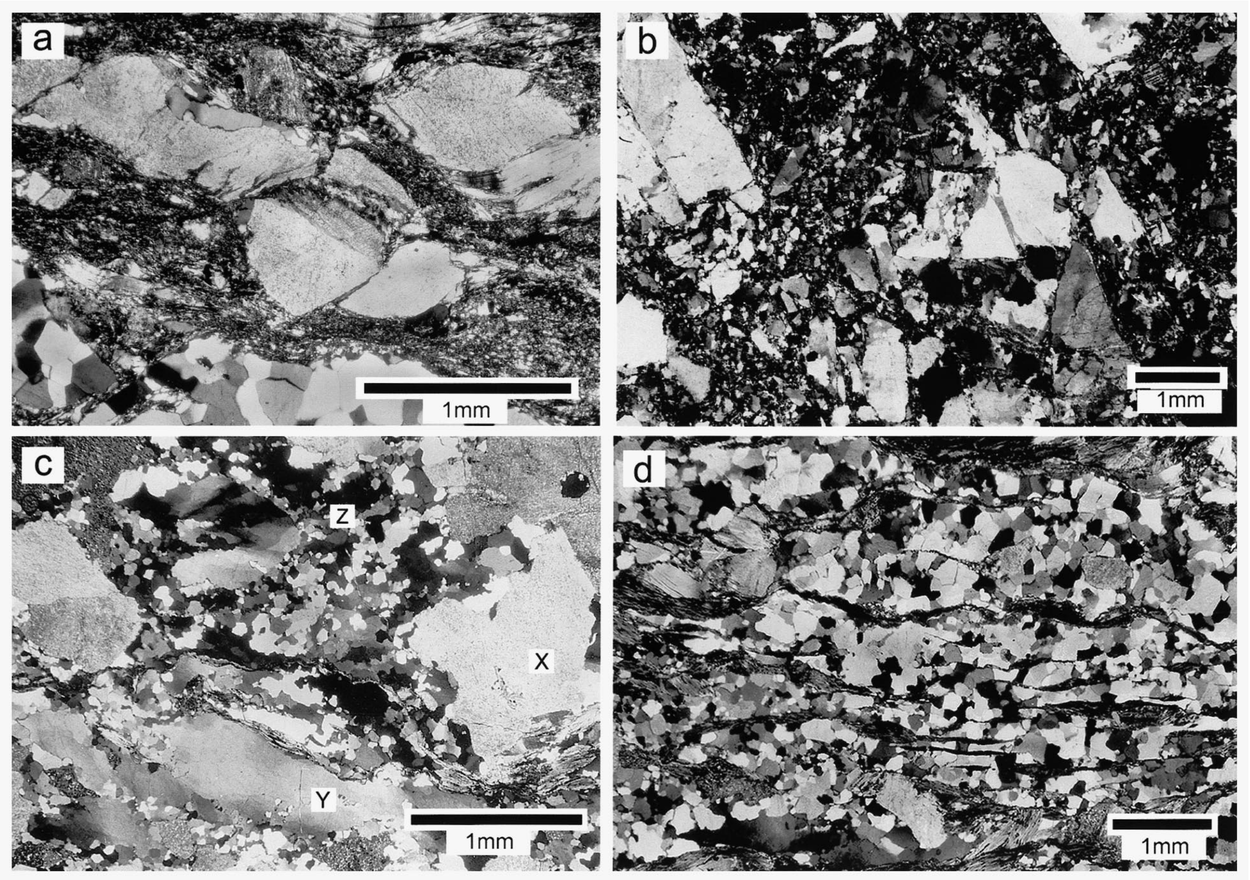


Fig. 6. Photomicrographs showing typical Torcastle block fault rock fabrics. (a) Micaceous shear zones: narrow bands comprising fine, mechanically fragmented muscovite anastomose around low-strain quartzo-feldspathic augen (locality 2, Fig. 2). (b) Cataclastically deformed psammite (locality 3, Fig. 2). (c) Lower strain quartz-rich protomylonite: original grains of feldspar (X) and quartz (Y) are surrounded by a matrix of annealed, dynamically recrystallised quartz neoblasts (Z) (locality 1, Fig. 2). (d) Higher strain quartzite mylonite: strongly aligned foliae of chlorite and muscovite within a matrix of original undeformed feldspar porphyroclasts and fine-grained, dynamically recrystallised quartz neoblasts (locality 1, Fig. 2). All views under crossed polars. See text for further details.

zones display coaxial flattening or more complex domainal patterns of block rotation and faulting.

4.2. Later deformation fabrics

Structures that post-date the early fabrics described above are represented by two distinguishable sets of discontinuous cataclasite seams and numerous discrete faults that dissect the outcrops. The first set of centimetre- to tens-of-centimetre-wide cataclasites is typically foliated and mainly comprises mechanically disaggregated feldspar and muscovite, with foliae defined by chlorite (after disaggregated biotite). A later set of unfoliated centimetre-scale cataclasites occurs, within which all constituent minerals are mechanically fragmented. In outcrop, these are typically very dark in colour. Both of these sets of later cataclasites are relatively uncommon compared to those associated with the main phase of sinistral movement, and typically cross-cut earlier fault-rocks and regional fabrics in random orientations. The sense of shear along these later structures is unknown. Brittle faults related to later displacement events along the GGFZ (see Stewart, 1997, Stewart et al., 1999 for details) appear to reactivate the margins of micaceous shear zones, and to locally displace the post-Caledonian lamprophyres (e.g. Fig. 2).

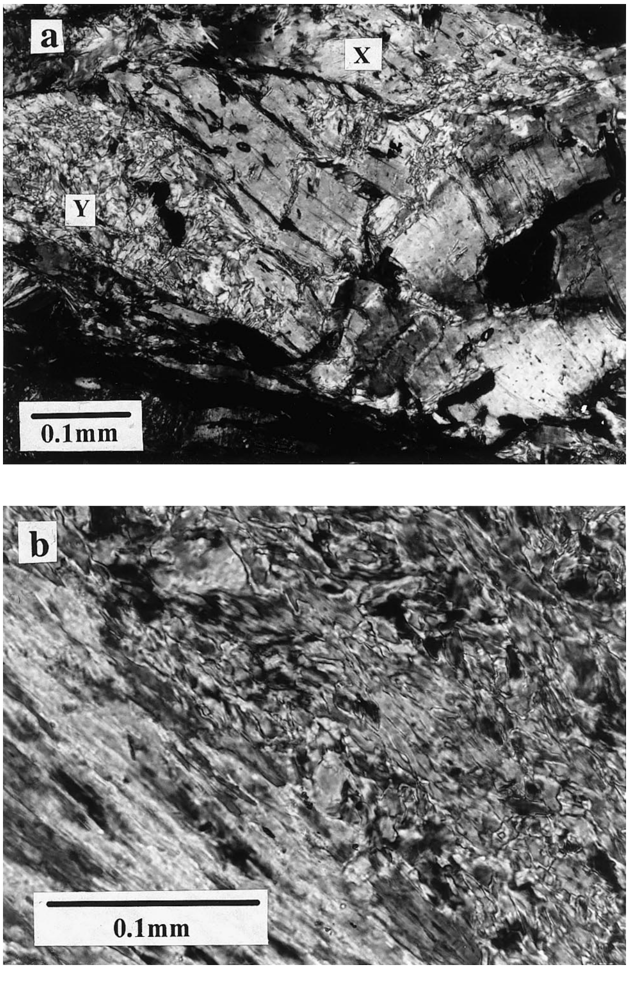


Fig. 7. Photomicrographs showing detailed deformation textures in micaceous shear zones from the Torcastle block. (a) Kinked and cataclastically fragmented porphyroclasts of muscovite (X). Matrix (Y) is composed of closely packed, intensely kinked muscovite with fine sub-grains and neoblasts developed. (b) Muscovite and chlorite creating a fibrous texture in foliated domains of fine-grained matrix. Both views under crossed polars.

4.3. Fault rock textures and microfabrics

The Torcastle block is unique in the GGFZ as it preserves both crystal-plastic and cataclastic textures thought to have formed more-or-less contemporaneously during the main phase of sinistral shearing. The type of fault rock developed appears to be significantly influenced by the protolith composition so that the original relative proportions of quartz, feldspar and mica exerted a critical control on the style of deformation. However, it is often difficult to interpret the observed fault rock textures because: i) our understanding of the deformation behaviour of natural polymineralic aggregates is incomplete (e.g. see Handy, 1990, 1994); and ii) there is a paucity of published experimental data regarding the operative deformation textures and mechanisms that occur in some rock types, notably polycrystalline phyllosilicate aggregates (e.g. see Wintsch et al., 1995).

Micaceous protoliths: Optical microscopic study of samples from the Torcastle block indicates that deformation of protolith muscovite occurs predominantly by brittle cataclasis. Mica shears (Fig. 6a) mainly comprise cataclastically deformed porphyroclasts of muscovite across a broad range of grainsizes, from complete original grains (> 0.5 mm) to fine (0.1–0.01 mm) clasts observed under high magnification. Larger porphyroclasts exhibit kinking, fracturing, and in many cases evidence for separation or slip along (001) surfaces (Fig. 7a). Smaller porphyroclasts occur as coherent grains of angular shape, occasionally show undulatory extinction and tend to occur as randomly oriented sub-equant clasts or elongate shards (Fig. 7a), possibly derived from fragmentation along (001) surfaces. Cataclastic deformation therefore appears to have been the grainsize-reducing mechanism at least down to grainsizes of ca. 0.05 mm.

The porphyroclasts are surrounded by a very fine-grained (< 0.05 mm) crystalline matrix of muscovite that appears to comprise inequigranular grains and subgrains when viewed under high magnification. It is difficult to determine the mechanism of deformation purely from optical observation, but there appear to be three types of fabric within the matrix that may have formed by differing mechanisms. First, many

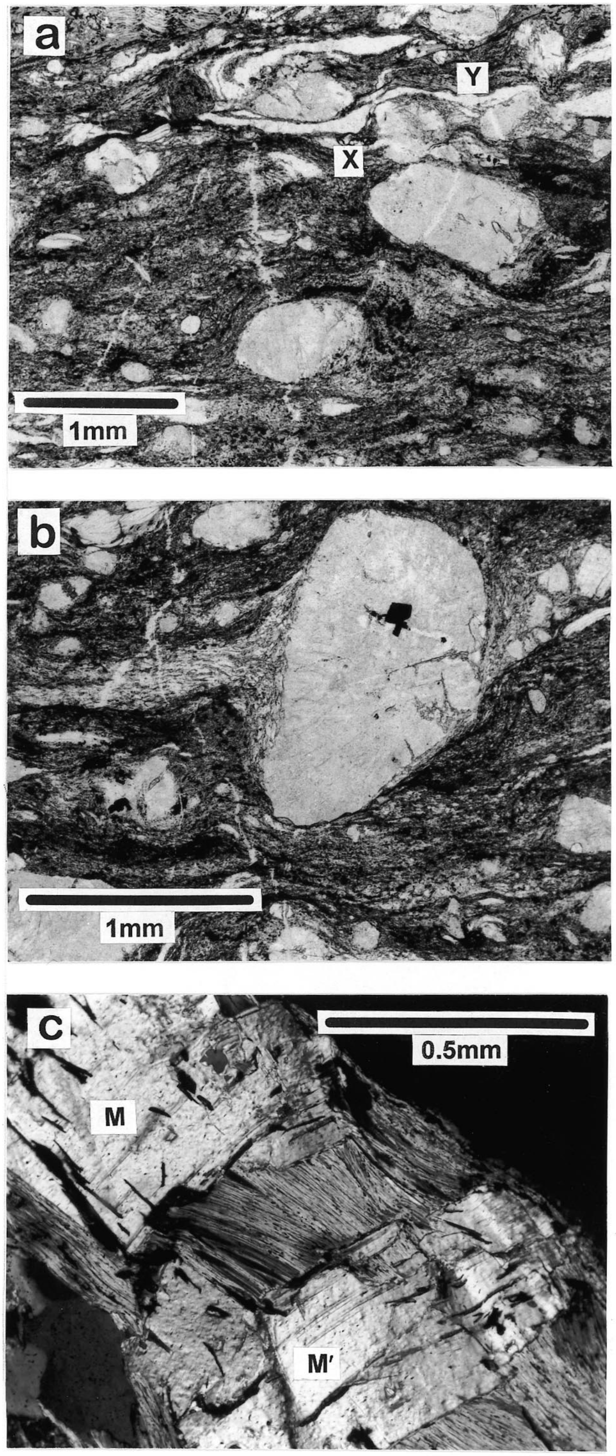


Fig. 8. Photomicrographs showing high-strain fault rocks (locality 2, Fig. 2) preserving textures indicative of fluid-assisted diffusional creep. (a) Low-power view of foliated cataclasite. Foliation is defined by aligned opaques, domains of different grain-size, aligned bands of cataclastically deformed feldspar, flattened quartz aggregates and dark-coloured, diffuse pressure solution seams. Note fibrous overgrowths surrounding brittle deformed feldspar clasts (X), and pulled apart feldspar clasts with intergranular fibrous infills (Y). (b) Detalied view of feldspar clasts with well-defined fibrous overgrowths and wrapping by foliation and pressure solution seams. (c) View of brittle deformed muscovite clasts (M, M′) pulled apart with fibrous chlorite (after biotite?) overgrowths in high strain micaceous shear zone. (a) and (b) viewed in PPL, whilst (c) viewed under crossed polars.

domains appear as a chaotic mass of muscovite that may represent intense micro-kinking, subgrain and neoblast development within and around grains whose original boundaries are difficult to distinguish (Fig. 7a and b). Second, there occur uncommon fine angular and elongate muscovite grains with sharp grain boundaries that are interpreted as representing cataclastically fragmented porphyroclasts. Third, some areas are composed of aggregates of muscovite and chlorite which occur either individually or together as ribbons defining crude discontinuous fibrous foliations at varying low to moderate angles to the shear band margins (Fig. 7b). These fabrics may be evidence for localised crystal-plasticity representing zones of micrometre-scale microkink bands (cf. Shea and Kronenberg, 1993). It is also possible that many of the crystalline textures within the matrix formed in response to a degree of static annealing, perhaps facilitated by fluid.

The process of grain refinement at such finer grain-sizes is complicated by textural evidence to suggest that fluid-assisted diffusional creep mechanisms were also significant in the deformation of these highly strained micaceous rocks. Fibrous chlorite is widely developed along brittle shears in small dilational jogs (Fig. 6a) and in adjacent low strain regions where large kinked muscovites are stretched by arrays of intragranular tensile fractures filled with fibrous brownish-green chlorite, possibly after biotite (Fig. 8c). The fibrous chlorites appear to define the fine, south-west-plunging mineral lineation observed in the field in the micaceous rocks (Fig. 2, stereoplot c). The operation of diffusional mechanisms could also account for the development of the localised foliations and apparently statically annealed textures in the intensely deformed regions of fine-grained muscovite matrix.

Interpreting microstructures developed within micaceous rocks is difficult given the lack of published data in this field. However, it is clear that the main grain-size-reducing mechanism down to scales of ca. 0.05 mm is cataclastic. Below this scale, grain refinement may result from a combination or overprinting of cataclastic, crystal-plastic and diffusive creep deformation mechanisms. In either case, it would appear that these mica-shears represent a transition between frictional and viscous modes of creep.

It is difficult to determine how biotite deformed as it is completely replaced by mostly undeformed, post-tectonic chlorite, although a few grains are kinked and fractured in regions adjacent to late brittle fractures.

Psammitic protoliths: In most psammites, feldspar is the most abundant mineral (ca. > 60% by volume). In regions little affected by cataclasis, individual feldspar grains typically retain their original grain shape and exhibit no sign of internal crystal-plastic straining. In contrast, adjacent quartz grains display well-developed undulatory extinction, deformation bands, grain flattening and sub-grains. In such regions, the dominant feldspars therefore appear to form a rigid load-bearing framework that probably largely determined the rheology of the psammites at low to moderate strains (Domain 1 of Handy, 1990). As a result, it is suggested that these feldspathic psammites could have been initially resistant to deformation, leading to early partitioning of strain into adjacent micaceous or quartzitic protoliths.

In areas of high strain, the resistant feldspars were susceptible to cataclasis and brittle faulting (Figs. 4c and 6b). Fracturing is common, and under high-power magnification, progressive disaggregation of feldspar grains is seen to occur along cleavage planes adjacent to grain margins or kink planes (cf. Tullis and Yund, 1987). With increasing deformation, intragranular to transgranular brittle fractures or fine cataclasite seams develop. These enlarge and become interconnected leading to the progressive development of a disjunctive foliation defined by linked, characteristically pale-coloured cataclastically deformed feldspar seams. The overall rock microstructure therefore becomes increasingly dominated by a fine-grained cataclastic matrix breaking down the feldspar load-bearing framework, forming an apparently interconnected shear zone network.

The highest strained regions of psammite are characterised by highly evolved ultracataclastic rocks that often display a crude foliation defined by dark-coloured seams comprising high concentrations of fine-grained opaques, chlorite and often muscovite (Fig. 8a). Intervening lighter coloured regions are composed of very fine-grained clasts and neoblasts of quartz and feldspar. Dark-coloured seams commonly wrap around and intensify adjacent to resistant relic porphyroclasts of feldspar and quartz that also display ubiquitous fibrous overgrowths of quartz and/or phyllosilicates in low stress pressure shadows (Figs. 8a and b). These textures imply that pressure solution creep was an important syntectonic process. Under high magnification, the fine (> 0.01 mm), comminuted ultracataclastic matrix of quartz, feldspar and mica grains possesses a straight-edged polygonal crystalline texture. This may imply that fluid present in these fine-grained rocks promoted a degree of static annealing following grain-scale cataclasis. All these textures suggest that in the highest strain rocks, fluid-assisted diffusive mass transfer (DMT) mechanisms were operating synchronously with shear. These could have included grain boundary sliding mechanisms in addition to pressure solution creep.

Quartzitic protoliths: At low strains, original quartz grains in quartzite units commonly exhibit intense undulatory extinction, deformation banding, subgrain polygonisation and grain flattening (e.g. grain Y in Fig. 6c). Grain boundaries are typically highly irregular and interlobate, indicating that grain boundary migration was operative. Dynamically recrystallised, strain-free neoblasts occur along many grain boundaries and within grains along deformation bands. These features imply that dislocation creep and glide were important crystal-plastic deformation mechanisms. Although grain boundaries are generally interlobate, they appear to have been subject to some subsequent degree of straightening, possibly implying minor static recrystallisation effects. Original feldspar and muscovite grains within these quartzitic protomylonites are typically fractured or undeformed and are wrapped by the foliation in surrounding quartz-rich domains (Figs. 6c and d).

A significant occurrence of a rock thought to be a high strain quartz mylonite has been identified at Torcastle North (Locality 1, Figs. 2 and 4d). These rocks are composed of rare, large (ca. 1.0 mm) original quartz grains that are highly flattened, displaying undulose extinction and subgrain development consistent with intracrystalline deformation. These porphyroclasts are enclosed by a matrix of much smaller grains (ca. 0.1–0.2 mm) with an equigranular and granoblastic texture (Fig. 6d). The smaller polygonal grains, which lack undulose extinction and sub-grains, are thought to represent dynamically recrystallised neoblasts that have subsequently undergone a period of static recrystallisation at low- to moderate-temperatures. The granoblastic nature of the quartz neoblasts is conceivably consistent with high temperature dynamic recrystallisation (e.g. Hirth and Tullis, 1992). This is considered to be unlikely, however, as there is no evidence of crystal-plastic behaviour in adjacent, coexisting feldspar grains which are either undeformed or cut by healed microfractures and fine-grained, annealed cataclasite bands. The high strain origin of the annealed mylonitic fabric is indicated by the strongly aligned mica grains (Fig. 6d), some of which are entirely enclosed within single, polygonal grains of apparently unstrained quartz. In addition, when samples are examined optically at low magnifications (e.g. Fig. 9), grains of chlorite (mimetic after biotite) form continuous interconnected foliae that closely resemble recrystallised *S–C* mylonite textures described by Lister and Snoke (1984); asymmetric mica-fish and shear bands consistently indicate sinistral senses of shear.

5. Discussion

5.1. Reactivated fault zones

The reactivation of pre-existing continental fault-zones such as the GGFZ during later displacement events is a characteristic feature of deformation in continental lithosphere (Holdsworth et al., 1997). The earliest deformation products and textures developed along such dislocations are particularly valuable as they preserve information about the primary lithological and environmental variables that may have largely determined the subsequent textural and rheological evolution of the fault zone. Careful mapping of such fault zones is required because later deformations either overprint or fault-out earlier structures, and the intense brecciation or phyllonitisation means that the fault zones are highly susceptible to erosion leading to poor exposure. In many cases, the earliest fault fabrics are typically those formed under higher temperature conditions, whilst later reactivation displacements follow exhumation and therefore tend to be associated with lower temperature fabrics, often with different shear-sense indicators (e.g. Grocott, 1977).

5.2. Relative timing of fault rock development and depth of formation

The Torcastle block preserves the most complete assemblage of fault rocks formed during the main phase of sinistral movement along the GGFZ. The quartz mylonites formed predominantly by crystal-plastic viscous mechanisms and have been subjected to post-tectonic static recrystallisation. The preservation of these equigranular granoblastic textures in which the neoblasts are unaffected by low-temperature, intracrystalline plastic or brittle deformation suggests that most of the cataclasis in adjacent psammitic units occurred synchronously with mylonitisation in the quartzites, i.e. bulk semi-brittle deformation (Carter and Kirby, 1978; Scholtz, 1988; Schmid and Handy, 1991). The fine-grained, polygonal texture developed in the ultracataclasites may indicate that these rocks have experienced a secondary static annealing event similar to that seen in the quartzite mylonites. In the micaceous shear zones, the millimetre-scale low strain augen separating micaceous sinistral shear planes commonly contain statically recrystallised aggregates of quartz. This suggests that the development of the micaceous shear zones was broadly contemporaneous with mylonitisation and cataclasis in the adjacent units of quartzite and psammite. The post-tectonic grain growth of comminuted muscovite appears comparatively limited compared to the quartzites which may signify that shearing was active for slightly longer during progressive down-temperature deformation. This would imply that as the shear zone evolved, later sinistral strains were partitioned into these horizons.

The restricted mineralogy of the lithologies at Torcastle and lack of rock compositions suitable for the growth of widespread syn-tectonic metamorphic index minerals makes it difficult to assess precisely the physical conditions under which deformation occurred. A broad indicator of temperature is provided by the contrasting response of quartz and feldspar. It has been

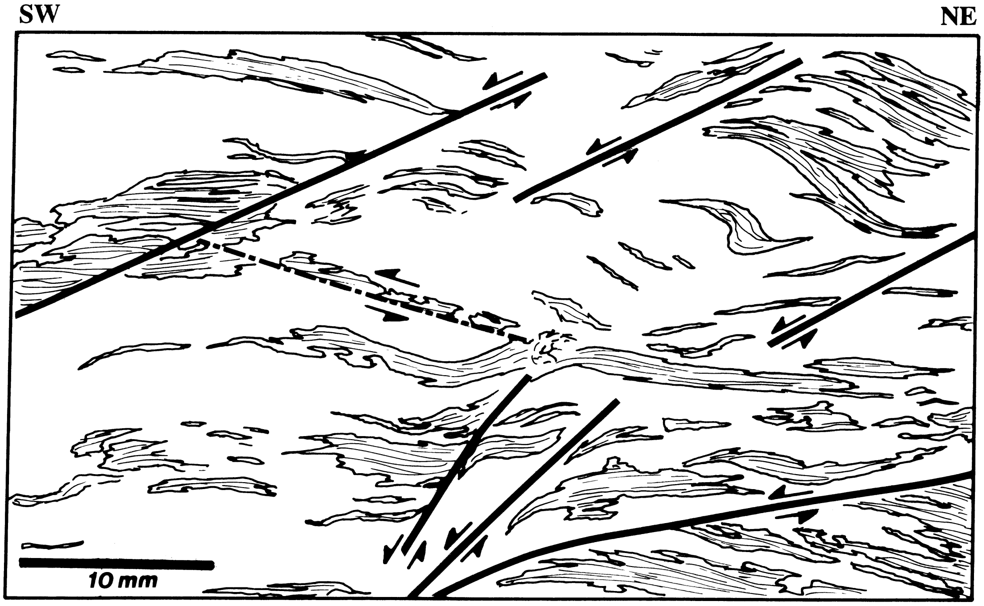


Fig. 9. Sketch of sinistral synthetic shear bands observed in an oriented thin-section of mica-rich quartz blastomylonite from Torcastle North (locality 1, Fig. 2). Section viewed down dip parallel to muscovite mineral lineations, with the right side oriented toward the northeast. Aggregates of muscovite and chlorite define the main mylonitic foliation (quartz and feldspar grains—the blank areas—are not shown for clarity) which is cross-cut by asymmetric sinistral shear bands. Solid lines represent C' shears, whilst the dashed line is a low angle synthetic shear.

argued that the deformation of quartz was pervasively crystal-plastic in nature, the exact process being undetermined due to overprinting by the effects of a later static recrystallisation. This implies that temperatures were greater than ca. 250–300°C, the temperature above which quartz experiences widespread crystal-plastic creep (White, 1976; Schmid and Haas, 1989). In contrast, at low to moderate strains, feldspar responded in a completely brittle manner, implying that temperatures were less than 450–500°C (Simpson, 1985). This behaviour suggests that deformation occurred in the frictional–viscous transition zone. Assuming normal geothermal gradients (30°/km), a temperature range of 250–450°C implies depths of the order of 8–15 km. These conditions are consistent with the observed low-temperature mineral assemblage of white mica, chlorite and quartz. In fine-grained, high strain regions, the latter minerals are commonly developed in syn-tectonic overgrowths reflecting the operation of fluid-assisted diffusional mechanisms. The fairly advanced degree of recovery in quartz could suggest that temperatures and depths were at least initially at the upper end of the temperature range. The local development of possible biotite in some fibrous infills (e.g. Fig. 8c) seems to support this suggestion.

Our observation that cataclasis is the dominant deformation mechanism responsible for the observed grainsize reduction in the micaceous lithologies (e.g. Figs. 6a, 7a and b) seems to be at odds with the prediction of experimental investigations of the behaviour of single crystals and polycrystalline aggregates of mica (e.g. Mares and Kronenberg, 1993; Shea and Kronenberg, 1993). These studies suggest that plastic flow in micas involving dislocation glide and kinking should occur at low differential stresses (< 200 MPa) across a very broad range of temperatures and strain rates. We are unable to account for the apparent absence of widespread crystal-plasticity in muscovite for grainsizes > 0.05 mm in the Torcastle block, although we note that predictions made by Mares and Kronenberg (1993) concerning the relative strengths of biotite and muscovite also appear to be at odds with microstructural observations made in naturally deformed rocks (e.g. Wilson and Bell, 1979).

There is no regional geological evidence indicating that the geothermal gradient was elevated in the region of the GGFZ. In the Torcastle block, the viscous nature of quartz deformation suggests low strain-rates, which indicate that shear heating was unlikely to have been a significant process. There is also no evidence for syn-tectonic igneous intrusion within the Torcastle block. The occurrence of fine-grained, apparently static recrystallised textures suggests that deformation ceased whilst the rocks were still at depths and temperatures sufficient to allow secondary recrystallisation to occur, particularly in the quartz mylonites. The fact that the resultant fabrics were not subsequently deformed at lower temperatures suggest that the rocks forming the Torcastle block were exhumed as a single, coherent unit with little further internal strain. Later deformation at upper crustal levels is represented by relatively minor, dark-coloured cataclasites, faults and fractures that cross-cut all other fabrics. Regionally significant displacements at this time appear to have been confined to slip along block-bounding fault surfaces.

5.3. *Evidence of fluid influx*

Regionally, there is widespread evidence to suggest that voluminous hydrous fluids infiltrated along the GGFZ, including the alteration of feldspar to fine-grained aggregates of sericite, and the total conversion of biotite and garnet to chlorite (Stewart et al., 1999). In the Torcastle block, some of the effects of fluid infiltration appear to be post-tectonic, e.g. randomly orientated chlorite aggregates pseudomorphing garnets that retain sub-spherical shapes. Calcite crystals that infill transgranular microfractures cutting across the foliation in micaceous units are also commonly unstrained, although these veins may be locally disrupted and offset across late-stage brittle shears and fractures. There is also evidence to suggest that fluids were influential in the deformation of fault rocks, especially at high strains. The cataclastic rocks are often foliated and preserve textures consistent with the operation of fluid-assisted diffusive mass transfer (DMT) mechanisms synchronous with the main phase of sinistral shearing along the GGFZ (e.g. Figs. 8a–c).

6. Conclusions and rheological implications

6.1. *Semi-brittle deformation*

The Torcastle fault-rock outcrops provide an important insight into the nature of mid-crustal deformation processes that were associated with the initial phase of sinistral strike-slip movement along a crustal-scale structure, the GGFZ. The main phase of deformation fabrics appear to have developed at low metamorphic grades (equivalent to sub-greenschist to greenschist facies) within the frictional–viscous transition zone and yield new insights into the rheology and fault-fabric evolution in this region.

The present study confirms that frictional and viscous modes of deformation act synchronously in the transition zone. Thus in the GGFZ, cataclastic deformation occurs in micaceous and psammitic units simultaneously with crystal-plastic dynamic recrystallisation in adjacent quartzitic rocks. Such regimes of 'semi-brittle' deformation have been proposed based on the results of numerous theoretical, experimental and field studies of the frictional–viscous transition zone (Carter and Kirby, 1978; Schmid and Handy, 1991). Our study demonstrates that the intensity and style of deformation is very strongly influenced by the differing compositions and rheologies of the protolith rock types leading to a complex distribution of fault rocks. We suggest that the compositionally heterogeneous Moine rocks of the Torcastle block are not atypical of mid-crustal rocks in continental regions. Hence, the widely studied deformation behaviour of homogeneous granitoids (e.g. Carter et al., 1981; Simpson, 1985; Fitz Gerald and Stünitz, 1993) cannot be applied as a universal rheological model for continental basement rocks. More importantly, however, our study also suggests that the regime of synchronous cataclasis and crystal-plasticity that supposedly typifies semi-brittle deformation is only significant at low to moderate strains in natural fault zones (see below).

6.2. Switch in deformation mechanisms

In the GGFZ, there is evidence for a grainsize-controlled switch from frictional cataclastic flow to *diffusional viscous creep* in the high strain parts of the fault zone where most of the major displacements were accommodated. Thus with increasing deformation in the Torcastle block, displacements appear to have increasingly localised into the anastomosing network of micaceous and feldspathic cataclasites that link-up to form a through-going network. In the highest strain regions, characterised by ultrafine-grained psammitic and micaceous fault rocks, textures indicative of fluid-assisted DMT synchronous with the main phase of shearing are widespread, e.g. fibrous overgrowths, solution seams. These features are absent in less deformed parts of the fault zone. The appearance of these textures implies a progressive change from a regime dominated by frictional cataclasis to one of viscous, fluid-assisted diffusional creep. Given the occurrence of these textures in the finest grained regions of cataclastic fault rock, it is reasonable to conclude that the change in deformation regime is controlled by the strain-induced, brittle reduction in grainsize (cf. the upper crustal fault zones of Mitra, 1984; Wojtal and Mitra, 1986).

6.3. The rheological importance of fluids

The present study demonstrates that under the *P*–*T* conditions typically associated with the frictional–viscous transition in most continental settings, the influx of hydrous fluids is likely to be absolutely fundamental in bringing about the grainsize-controlled switch to diffusional creep in the high strain parts of the fault zone. According to numerous theoretical and experimental studies (e.g. Schmid et al., 1977; Schmid, 1982; Handy, 1989), the onset of diffusion-dominated creep will lead to a marked, long-term weakening of the fault zone. This could explain why the GGFZ has subsequently been reactivated so many times since the main phase of deformation investigated here. This model may well account for long-term weakening mechanisms along many other large-scale continental fault zones thereby emphasising the potentially important roles played by fluids in determining crustal and lithospheric rheology.

6.4. General rheological model

Based on our observations in the Torcastle block and other parts of the GGFZ (Stewart et al., 1999), we propose a model that has general application to all crustal-scale fault zones (Fig. 10). Our textural observations suggest that, during the main phase of sinistral shearing, cataclastic deformation in the deeper part of the frictional regime and in the frictional–viscous transition zone led to the onset of fluid-assisted DMT. Following the arguments of Schmid and Handy (1991), this would have caused a progressive shallowing of the domain of viscous flow in the finest-grained, highest strain parts of the fault zone (arbitrarily shown in the centre of the vertical fault zone modelled in Fig. 10). The weakening effect associated with the onset of grainsize-sensitive creep would also lead to increased localisation of shearing into the high strain fault strands. Thus, the change in deformation mechanism along the interconnected fault network is thought to have brought about a marked shallowing and narrowing of the frictional–viscous transition zone in the vicinity of the fault zone (Fig. 10). This corresponds to the main load-bearing region of the crust and these processes should therefore lead to the establishment of a long-term zone of weakness.

Our study has emphasised the role of cataclasis, but, in the region of the frictional–viscous transition, there are several other deformational and metamorphic processes that may lead to marked grainsize reduction and hence promote the onset of diffusional creep and weakening (Fig. 10). These include dynamic recrystallisation of quartz (e.g. White et al., 1980), fluid-assisted neocrystallisation of feldspar (Fitz Gerald and Stünitz, 1993; Stünitz and Fitz Gerald, 1993); and growth of fine-grained, retrograde phases such as phyllosilicate (White and Knipe, 1978; Mitra, 1984; Brodie and Rutter, 1985). In the latter case, the introduction of a new, mechanically weak phase may also lead to reaction softening (White and Knipe, 1978; Wintsch et al., 1995). Variables such as temperature, protolith composition, the presence and composition of a hydrous fluid phase and the degree of fracture and shear zone interconnectivity on several scales are likely to determine

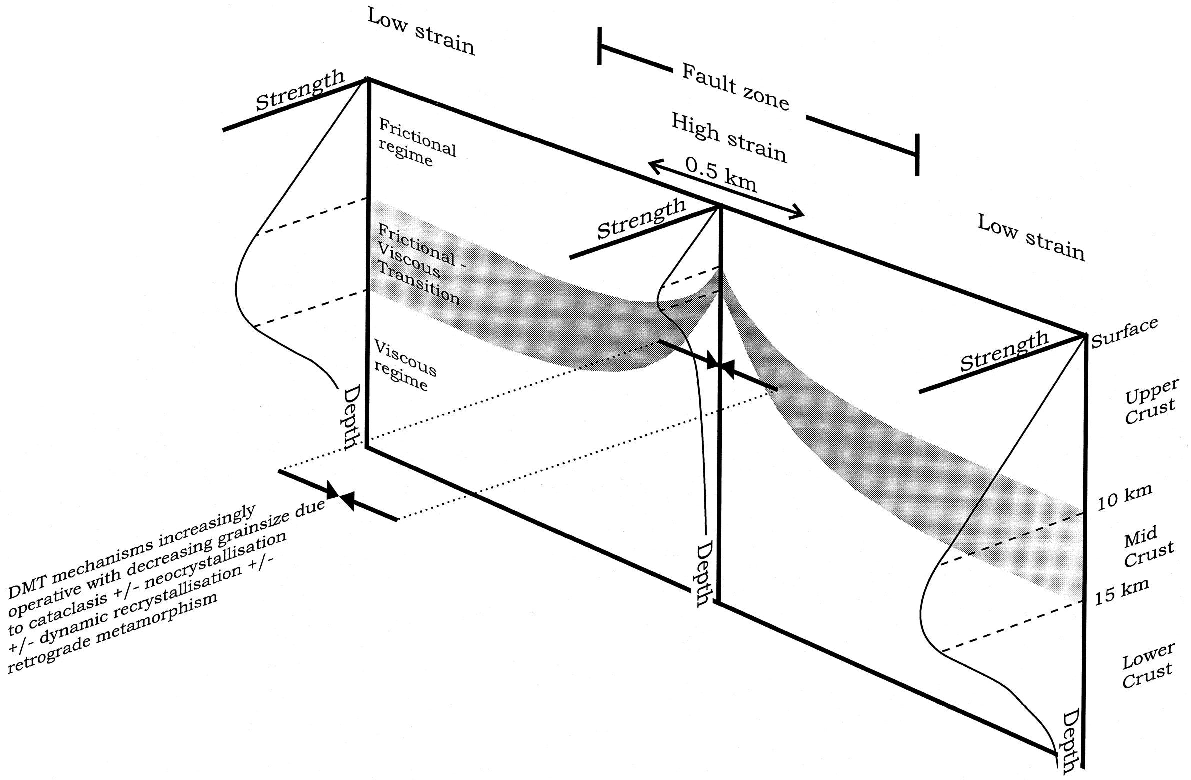


Fig. 10. Schematic three-dimensional strength vs. depth profiles through a vertical, crustal-scale fault zone and adjacent wall rocks based in part upon text of Schmid and Handy (1991). In high-strain fault strands, the grainsize-controlled switch from frictional cataclasis to diffusional viscous creep leads to a shallowing of the transition zone and to weakening. The frictional–viscous transition narrows as the strain localises into the interconnected network of high-strain fault strands and the weakening rapidly spreads to affect the entire fault zone (compare protolith/low strain and high strain strength curves). In this hypothetical example, the weakest region is shown in the centre of the fault zone—in real examples, there may be several of these regions corresponding to major fault strands, including those at the fault zone margin(s). It is proposed that most of the weakening mechanisms are long term leaving the fault zone prone to reactivation during later deformations.

which of these processes are dominant in a given fault zone. In many natural fault zones, more than one grainsize-reduction mechanism may operate simultaneously (e.g. Imber et al., 1997).

In conclusion, the present investigation illustrates the importance of field-based studies of the distribution, nature and possible interaction of contemporaneous and different deformation mechanisms in natural fault zones on all scales. Such qualitative observations are complimentary to more quantitative theoretical and experimental approaches and collectively, these methods will lead to a more complete understanding of fault and shear zone rheology.

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