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Deformation in Moffat Shale detachment zones in the western part of the Scottish Southern Uplands

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Abstract – A study of the décollement zones in the Moffat Shale Group in the Ordovician Northern Belt of the Southern Uplands of Scotland reveals a progressive sequence of deformation and increased channelization of fluid flow. The study concentrates on exposures of imbricated Moffat Shale on the western coast of the Rhins of Galloway. Initial deformation occurred in partially lithified sediments and involved stratal disruption and shearing of the shales. Deformation then became more localized in narrower fault zones characterized by polyphase hydrothermal fluid flow/veining events. Deformation continued after vein formation, resulting in the development of low-temperature crystal plastic microstructures and further veining. Late-stage deformation is recorded as a pressure solution event possibly reflecting the cessation of slip on these faults as the slice became accreted. Most deformation can be ascribed to SE-directed thrusting and incorporation of the individual sheets into the Southern Uplands thrust stack. Later sinistral shear deformation, not observed in overlying turbidites, is also localized in these fault zones. The study reveals the likely structures formed at levels of an accretionary prism deforming under diagenetic to low-grade metamorphic conditions.

Keywords: Southern Uplands, Scotland, faults, deformation, fluid flow.

1. Introduction

The overall structure of the Southern Uplands of Scotland is well established although the tectonic setting and evolution during Early Palaeozoic times remains a subject of active debate (e.g. Stone *et al.* 1987; see review by Strachan, 2000; Smith *et al.* 2001; Oliver, Stone & Bluck, 2003). The Lower Palaeozoic rocks of the Southern Uplands consist of a stack of stratigraphically, and often petrographically distinct, ‘tracts’ or thrust sheets developed during SE-directed thrusting, although also subjected to sinistral transpression and NW-vergent backthrusting (Needham & Knipe, 1986). The thrust sheets are older to the NW despite internally displaying dominant NW-younging directions. This paradox of Southern Uplands structure was resolved with the recognition of reverse faults (Craig & Walton, 1959) which have subsequently been shown to form the tract or thrust sheet bounding faults. The origin of the thrust sheets has been ascribed to the formation of an accretionary prism that developed along the northwestern margin of the Early Palaeozoic Iapetus ocean from Early Ordovician until Late Silurian times (Leggett, McKerrow & Eales, 1979; Leggett, McKerrow & Casey, 1982). An alternative view is that the thrust system formed during the closure of a back-arc basin and its subsequent development as a foreland basin (Stone *et al.* 1987). The source of andesitic detritus crucial to this model has, however, recently been shown to be Neoproterozoic rather than Ordovician (Phillips *et al.* 2003). Both models recognize the Moffat Shale Group at the base of the succession as the major detachment (or décollement) horizon along which the sedimentary section was stripped from its basement. The basement is thought to be oceanic crust, generated either at a mid-ocean ridge or by back-arc spreading dependent on the favoured model. The basin floored by oceanic crust was thought to have closed during the Wenlock and the thrust system continued to develop on continental basement. Both models have similarities in that they envisage progressive deformation of sediments occurring during the subduction of ocean crust and contractional deformation of the sedimentary section above a detachment. The deformation of the Moffat Shale Group is not in itself diagnostic of the tectonic setting but is here placed in the context of the forearc model, as favoured by Needham (1993, 1994), and can be usefully compared with observations from décollement zones at present day active margins. It is likely that the basal detachments to thrust wedges that are undergoing internal deformation, dewatering and diagenesis will be similar whether in a forearc or back-arc setting.

The Moffat Shale Group has long been recognized as an important décollement zone (e.g. Fyfe & Weir, 1976; Webb, 1983), but the internal deformation has not been subject to detailed study, partly due to the paucity of good exposure in inland areas of the Southern Uplands. The Moffat Shale Group occurs at the base of sequences

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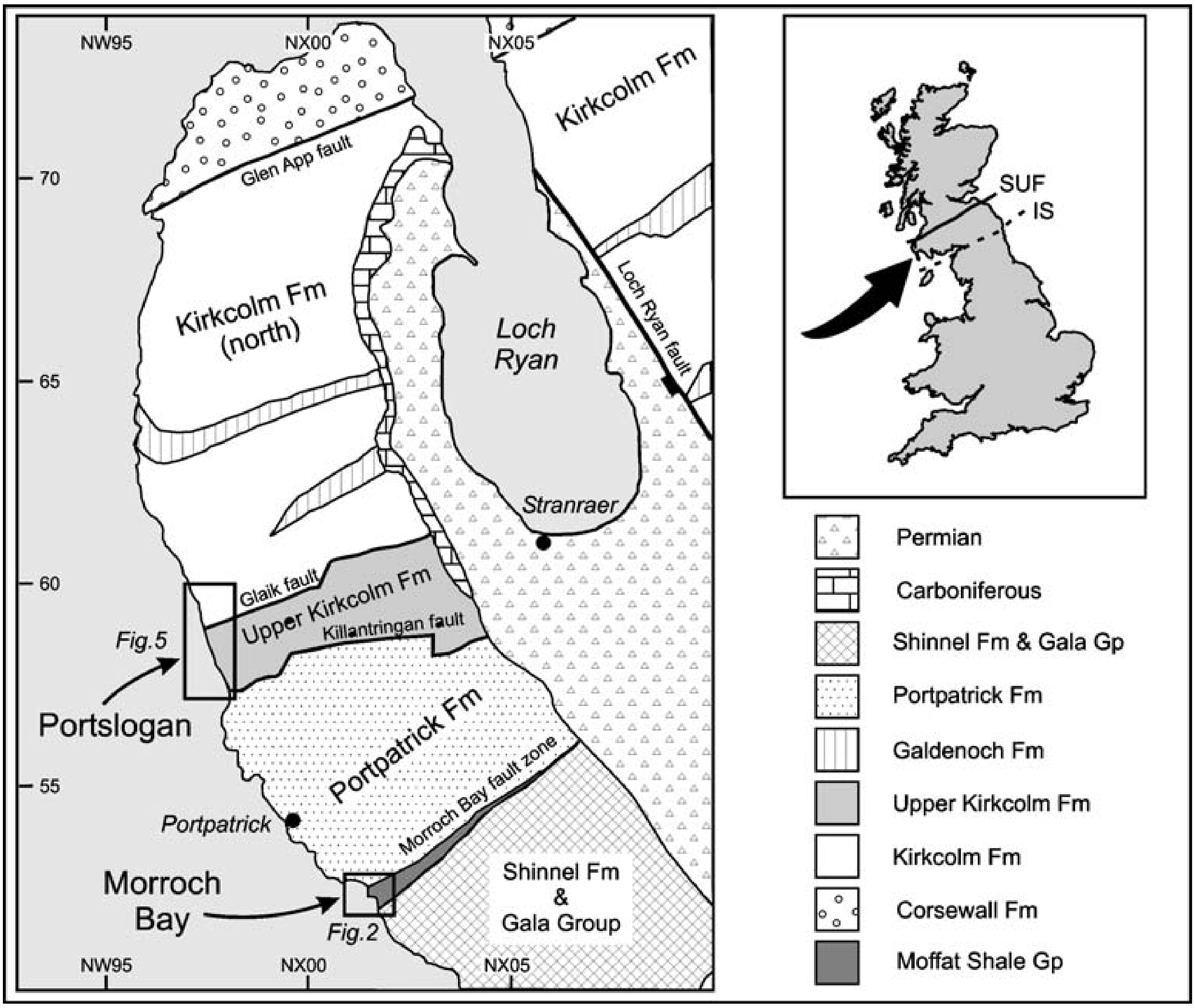

Figure 1. Map of the Ordovician Northern Belt on the Rhins of Galloway, western Southern Uplands and its location in Great Britain (inset). Areas described from the Morroch Bay and Portslogan sections are shown. UK National Grid squares are marked on the edge of the map. IS – Iapetus Suture, SUF – Southern Uplands Fault.

in the Ordovician Northern Belt and at the base of the Gala Group turbidites in the pre-Wenlock Central Belt. Good coastal exposures of the Moffat Shale Group occur along the tract-defining faults on the west coast of the Rhins of Galloway (Fig. 1).

2. The Rhins of Galloway

The faults described here define the southern boundaries of three stratigraphically distinct tracts which lie between the trace of the Glen App Fault and the Morroch Bay fault zone. The faults bounding the tracts are named the Glaik, Killantringan and Morroch Bay faults (Stone, 1995) (Fig. 1). The tracts are defined by the distinctive greywackes that they contain and are dominated by the Kirkcolm, Upper Kirkcolm and Portpatrick formations, respectively, although other, volumetrically less significant formations are represented. The stratigraphy of these formations is summarized by Floyd (2001) and they range in age from late Llanvirn (Llandeilian) to late Caradocian. Each tract comprises a thin sequence of pelagic and hemipelagic sediments, the Moffat Shale Group, that includes cherts, black shales, blue-grey mudstones with interbedded volcaniclastics including tuffs, agglomerates and metabentonites (Stone, 1995). These are interpreted as the ocean floor sediments and are overlain by thick turbidite sequences, interpreted as the trench fill (Leggett, McKerrow & Eales, 1979). The turbidites in the tracts have different ages and stratigraphies (Kelling, 1961; Stone, 1995). The Kirkcolm tract contains turbidites of the Kirkcolm and Galdenoch formations whilst the Portpatrick Formation occupies the tract of the same name. The sequence in the Kirkcolm tract contains *N. gracilis* to ‘*peltifer*’ faunas. The Upper Kirkcolm Formation overlies *clingani* biozone Moffat Shale. The Portpatrick Formation overlies *clingani* biozone Moffat Shale and contains *linearis* faunas (Rushton, Stone & Hughes, 1996).

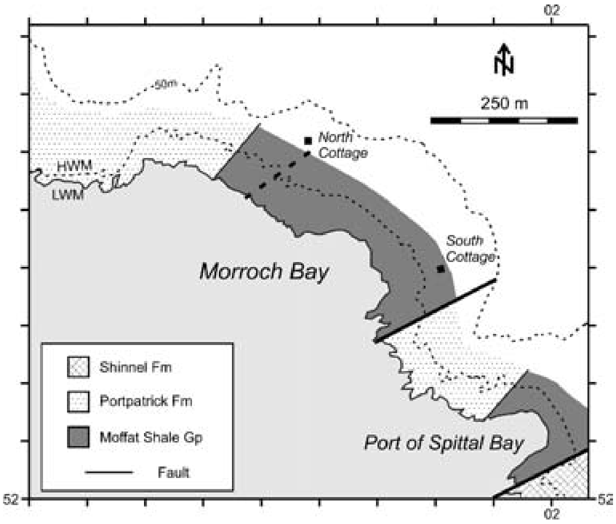

Figure 2. Map of the Moffat Shale outcrop, Morroch Bay, based on Stone (1995). Location shown in Figure 1. The dashed line near the North Cottage shows the position of the fault across which repetition can be detected biostratigraphically. Low- and high-water marks shown.

Based on the available Ordovician timescales, the Kirkcolm tract was accreted to the thrust stack some 3–10 Ma before the Portpatrick tract, judging by the minimum ages of the turbidites in each tract (Stone, 1995). The exposure, in coastal sections on the Rhins, of the tract boundaries allows the examination of décollement zones developed at different stages in the evolution of the prism. The level of exposure provides an excellent basis for the study of processes operative along the accretionary décollement at deeper levels.

The southern exposures of both Kirkcolm and Portpatrick formations have younger ages for the onset of turbidite sedimentation above the Moffat Shale Group. In Morroch Bay interbedded Moffat Shale and Portpatrick formations have a *clingani* biozone fauna, whereas in Port of Spittal Bay the Moffat Shale ranges up into the *P. linearis* biozone (Rushton, Stone & Hughes, 1996). The fault zones described here were examined in two coastal sections, at Morroch Bay (NX016525) and Portslogan between Broadsea Bay and Knock Bay (NW977585).

2.a. Morroch Bay

The Morroch Bay section described here consists of a 400 m, dominantly NW-younging sequence of black shales, cherts and cherty mudstones (Fig. 2). Logging of the section has revealed a series of distinct, strike-parallel fault zones, although many minor veins also occur (Fig. 3). The faults dip steeply to the south

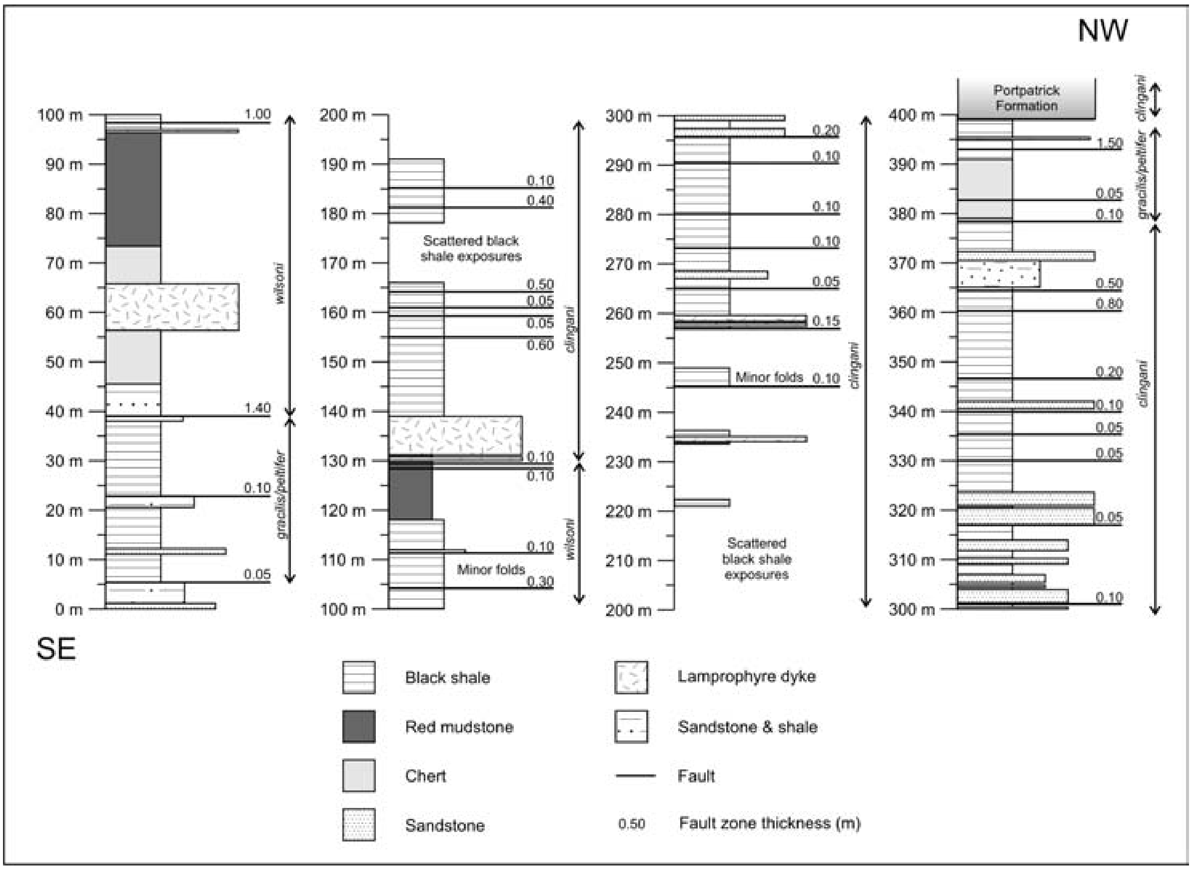

Figure 3. SE–NW structural log through Morroch Bay from the base of the Moffat Shale sequence to the base of the Portpatrick Formation turbidites.

and strike NE–SW, lying parallel to bedding which is slightly overturned. Many of the faults lie within the black shales. Others separate distinct lithologies and one stratigraphical repetition can be demonstrated biostratigraphically by the graptolite fauna (Stone, 1995). Large-scale folding is absent but many of the inter-fault black shale slices contain minor folds, both steeply and gently plunging. Gently NE-plunging folds verge to the SE whilst the steeply plunging folds show sinistral vergence. Other slices are homoclinal. The deformation style is generally coherent although there is some stratal disruption, usually of cherts interbedded with the black shales.

The faults are marked by zones of intense quartz veining (Fig. 4). This is restricted to within 1 m of the fault surface. The faults may be individual, thick veins or interleaved zones of variably deformed quartz veins and slices of black shale. The shale often contains many polished, scaly slip-surfaces and the fabric may be folded. Folds of the fabric show steep plunges suggesting strike-slip reactivation. The fault zones are characteristically narrow, usually less than 20 cm wide. Faults between different lithologies tend to be entirely vein material, up to 10 cm wide. Some of the veins have been subsequently deformed. Discrete fractures cut the zones, and late-stage post-veining brecciation is also observed but not ubiquitously developed. This is usually localized within 20 cm of the fault surface. Chert bands adjacent to the thrust surfaces usually show little internal deformation except for some minor fracturing, the thrust cutting the chert being a discrete fault surface. Deformation away from the fault zones is variable in intensity although mostly it is localized in the fault zones. There is a well-developed slaty cleavage sub-parallel to bedding in the shales, but veining is absent and small-scale sedimentary features are often preserved. The faults show evidence of both thrust and strike-slip displacement. Thrusting, in the current reference frame, is N-side up, that is, SE-directed thrusting prior to rotation into the present steeply-dipping to overturned orientation. Gently plunging, SE-verging folds are associated with this deformation.

There is abundant evidence for sinistral reactivation of the Morroch Bay fault zone. Sinistrally verging, steeply plunging folds deform many of the thrust-related faults. There are also rhomb-shaped asymmetric extensional blocks of sandstone and chert, enclosed in a shale matrix, that indicate sinistral shear. A N–S-striking, extensional crenulation cleavage, localized at the southern end of the bay adjacent to the fault contact with turbidites that form the headland, is also indicative of sinistral shear.

The occurrence of structures related to sinistral shear in the Moffat Shales of Morroch Bay contrasts with structures in the Portpatrick Formation turbidites to the north. Here, folds are upright, gently plunging, SE-verging structures with an axial planar cleavage (Needham, 1993) and appear to be related to SE-thrusting. Only the Morroch Bay fault zone shows evidence of sinistral reactivation.

2.b. Portslogan

The section runs through the southern margin of Kirkcolm and Upper Kirkcolm tracts and consists of an imbricated sequence involving the Moffat Shale Group and overlying greywackes (Fig. 5). The section is steeply dipping to overturned and dominantly youngs to the north although asymmetric SE-verging folds with wavelengths on the 10–100 m scale are developed (Fig. 6).

Internally, the different lithologies show a variety of small-scale deformation features and there is more stratal disruption than the Morroch Bay tract boundary, particularly in the turbidites to the south of the black shale exposures. The black shales appear pervasively deformed. Lithological banding is irregular and discontinuous. At Bere Holm [NW 979 581], the black shales contain lenticular sandstone blocks adjacent to the contact with the stratigraphically overlying greywackes (see Knipe & Needham, 1986; Figs 6, 7). The base of the greywackes appears unmodified by sedimentary loading, which suggests that the blocks may have a tectonic origin. Some of the blocks define a discontinuous layering, and it appears that an initially intact sandstone bed was dismembered during progressive deformation localized within the shale. The blocks are oblate and lie in the plane of the cleavage. The blocks are unfractured internally and appear to have deformed by mesoscopically ductile processes.

Closer to the thrust surface the shale becomes highly quartz veined. This increases in intensity towards the fault and affects both the sandstone blocks and the shaly matrix. The intensity of this veining adjacent to the fault is such that the veins comprise more than 50 % of the rock volume. The veining is probably indicative of hydrofracturing due to elevated pore fluid pressures. The veins exhibit little preferred orientation and show complex cross-cutting relationships, suggestive of multiple fracture-veining events. The polyphase nature of this veining is confirmed by the fact that many of the veins are folded and then cross-cut by later, undeformed, veins. Some of the veins are also cut by thin (<1 mm wide) irregular dark seams which lie, generally, sub-parallel to the major fault surface. The black shale wall-rock around the veins is often deformed into a series of irregular crenulations and minor folds in addition to being cut by polished and striated scaly slip surfaces. The décollement surfaces themselves are poorly exposed but, where visible, are discrete fractures, often with a few centimetres of quartz veining. Similar faults placing black shales over greywacke near Cave Ochtree Point [NW 976 590] are sharply defined planar fractures with little veining.

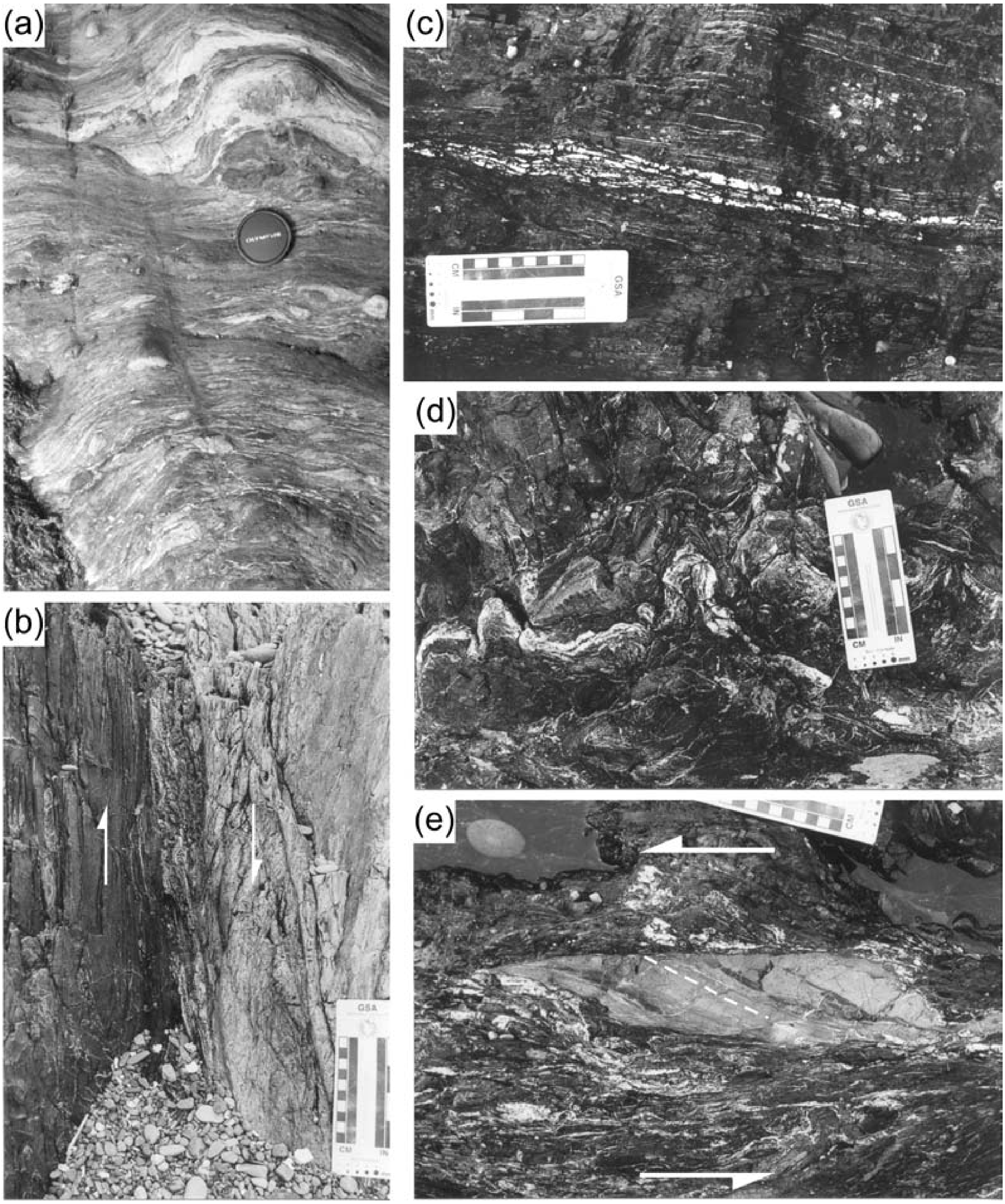

Figure 4. Field photographs of Moffat Shale fault zones. (a) Deformed black shale, Portslogan section including dismembered sandstone layers. The lens cap is 5 cm in diameter. (b) Fault zone between black shale and chert, Morroch Bay, consisting of interleaved shale and quartz vein material. (c) Interleaved black shale and quartz veins in narrow fault zone, Morroch Bay. (d) Veined fault zone folded by steeply plunging folds, Morroch Bay. (e) Rhombic block of sandstone formed by pull-apart of bedding during sinistral shear, Morroch Bay. The long sides are faults and bedding is dashed.

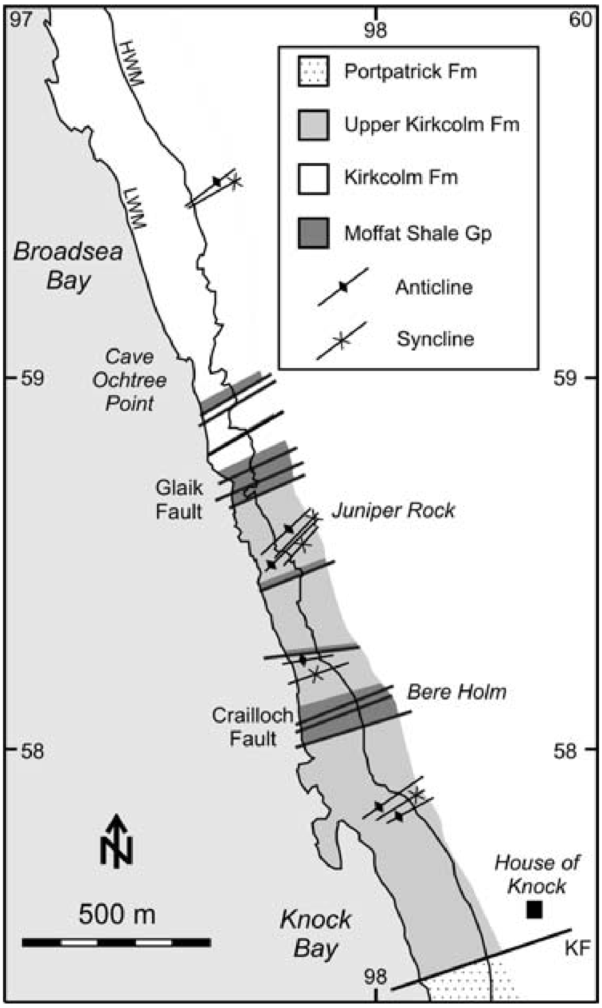

Figure 5. Map of the Portslogan section showing map-scale folds and faults. KF – Killantringan Fault. Low- and high-water marks shown. Location of figure shown in Figure 1.

Shales interbedded with greywackes adjacent to the fault in the footwall have an intensely developed slaty cleavage.

Footwall turbidites are generally unaffected except for localized cataclasis and veining within a few centimetres of the actual fault. At Gipsy Cave [NW 980 579], however, a 1 m wide zone in the footwall to the thrust consists of a greywacke microbreccia which is cut by a series of anastomosing closely spaced dark seams. There is also a broader zone of stratal disruption extending *c*. 200 m into the turbidites of the footwall.

3. Microstructures

Microstructures were investigated using a combination of optical and electron microscopy, both scanning (SEM) and transmission (TEM) modes. Figures 7 and 9 show the microstructure of samples from faults in Morroch Bay and Figure 8 from samples taken from the Portslogan section. The results of the microstructural analysis are placed in context in the following section.

3.a. Slaty cleavage microstructure

Many of the black shales exhibit few features optically due to their fine grain size. The shales have a strong domainal slaty cleavage which often appears continuous at low magnifications. This is defined by a dimensional and crystallographic preferred orientation of phyllosilicates and a dimensional preferred orientation of inequant detrital quartz grains. Radiolarian-bearing black shales display a strong flattening of the tests parallel to the cleavage. Locally, small kinks of detrital phyllosilicates are visible optically.

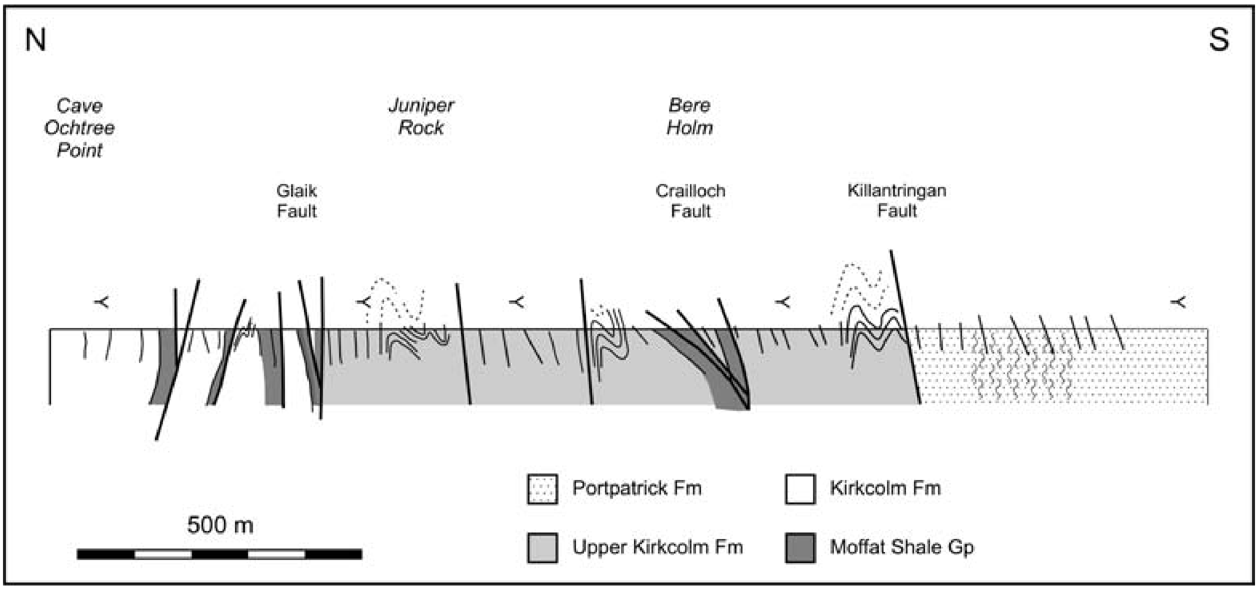

Figure 6. Cross-section through the Portslogan section.

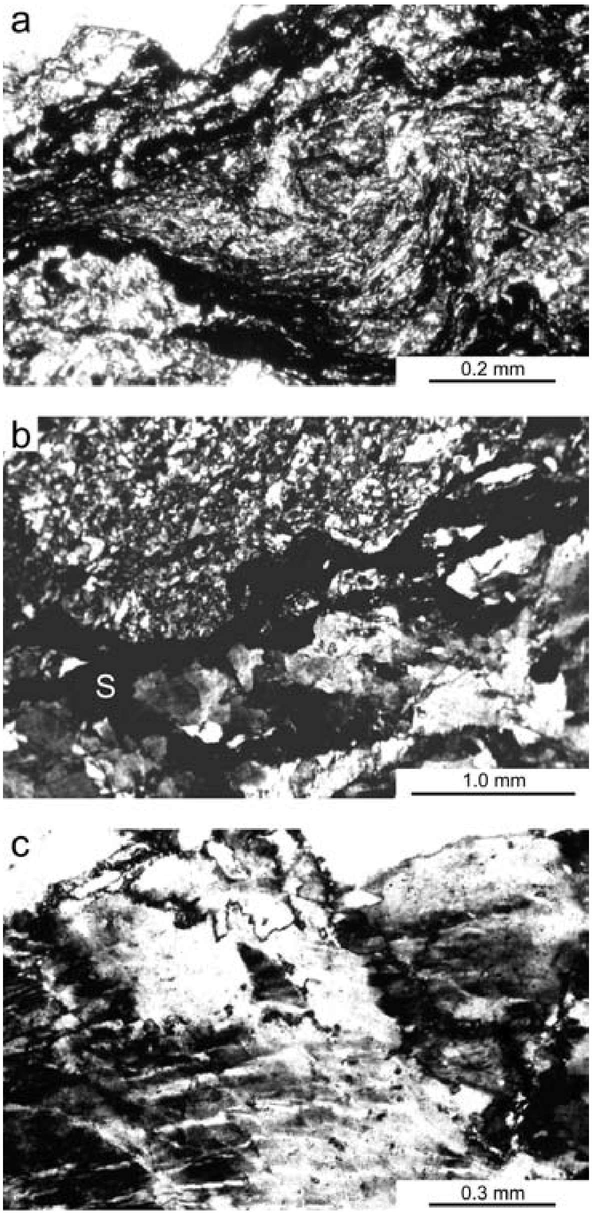

Figure 7. Photomicrographs showing typical deformation features in the Morroch Bay fault zones. (a) Folded black shale fabric including dark irresolvable solution seams. Quartz vein material occupies the upper left-hand side of the view. (b) Irregular stylolitic seam, S, juxtaposing areas of different grain size and deformation state. (c) Deformation features vein quartz-deformation bands, undulose extinction, serrated and bulged grain boundaries.

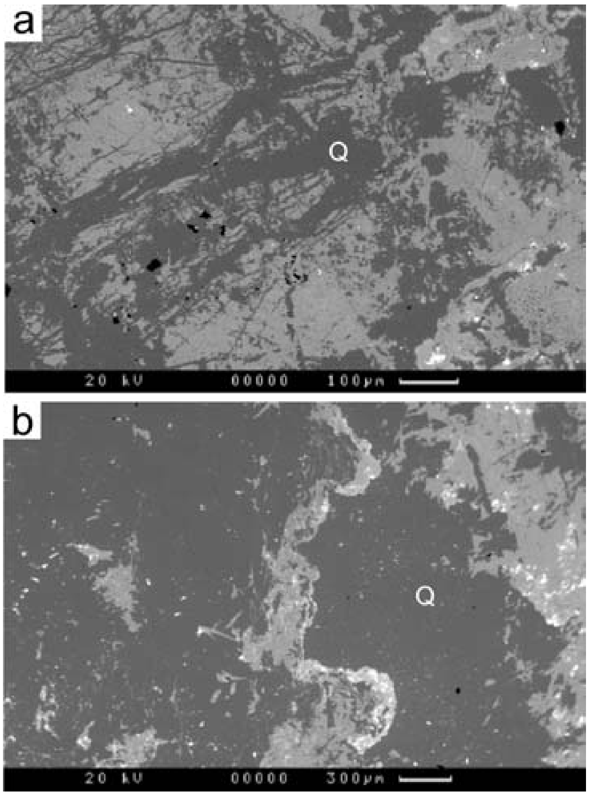

Figure 8. SEM backscattered electron micrographs of quartz veins in black shale from the Portslogan area. (a) Array of thin, quartz-filled microfractures (darker phase labelled Q) cutting fine-grained shale matrix (lighter). (b) Buckled phyllosilicate fabric enclosed in darker quartz vein fill. Note lighter (phyllosilicate) inclusions in quartz veins.

Electron microscopy shows the cleavage to be a modified crenulation fabric. The cleavage is divided into oriented phyllosilicate rich domains which define the cleavage and quartz rich domains. Clusters of framboidal pyrite a few micrometres across are also common. The shale is also traversed by shear zones consisting of aligned phyllosilicates and concentrations of dark, irresolvable material. These may cross-cut the slaty fabric at a low angle or lie parallel to it. They appear to be an intensification of the same and a localization of diffusive mass transfer (DMT) deformation. Differently oriented packages of cleavage may be separated by the shear zones. Similar fabrics have been described by Agar, Prior & Behrmann (1989). The cleavage is locally folded by subsequent deformation (Fig. 7a).

3.b. Vein microstructure

Microscopic examination reveals much more information on the veined rocks. Some veins cut sharply across the cleavage and are usually quartz filled although heavily twinned calcite is also present in some specimens. Two forms are exhibited by the quartz, a microcrystalline type with a grain size less than 0.05 mm and coarser crystalline quartz with a grain size of up to 1 mm (Figs 7b, 9a). Subsequent deformation tends to obscure the relationship between the two types of quartz but in some cases the coarser quartz can be seen to occupy vug-like infills similar to those described by Stel (1981) and Stel & Lankreyer (1994). The irregular morphology of the microcrystalline quartz distinguishes it from that produced by dynamic recrystallization. Some of the quartz appears to have grown in that form, whilst other areas exhibit a

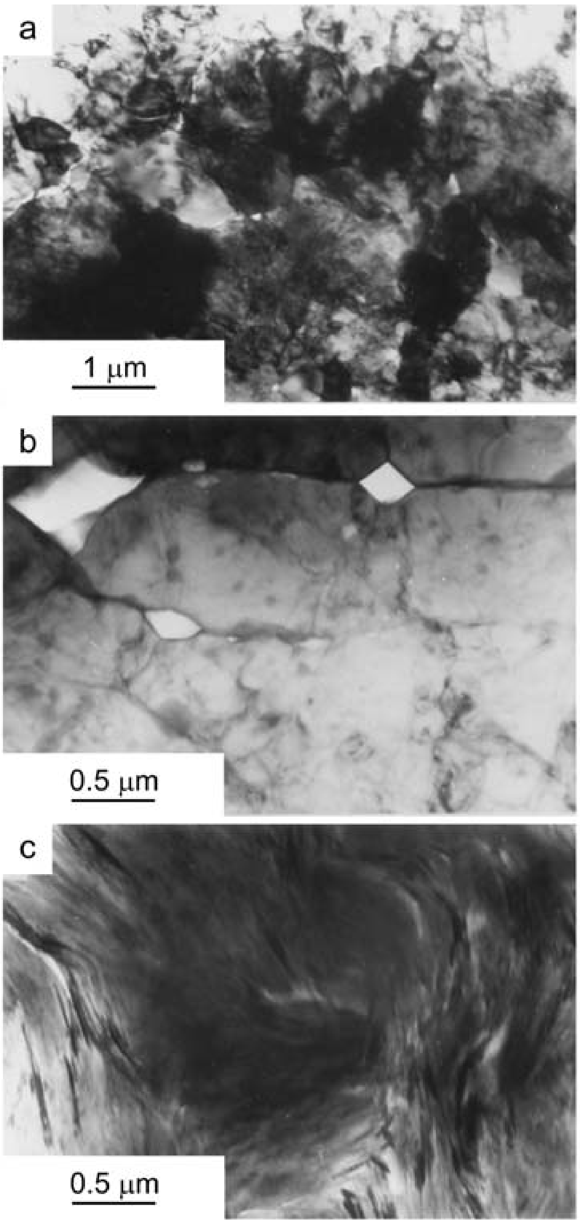

Figure 9. TEM micrographs of Moffat Shale deformation features in sample from Morroch Bay. (a) Microstruture of cryptocrystalline quartz. Note high inclusion content and irregular morphology. (b) Blocky quartz grains and grain boundary voids, the margins of which are crystallographically controlled. (c) Microstructure of stylolitic seams showing a fine-grained aggregate of illitic phyllosilicates. Note small grains along the axes of kinked phyllosilicates. Sample from Morroch Bay.

cataclastic texture. The vein calcite is highly twinned and has a relatively uniform grain size of about 0.3 mm. Multiple fracture-veining events are also indicated by cross-cutting quartz veins in different orientations (Fig. 8a).

There is also microstructural evidence of post-veining deformation. The coarse quartz displays abundant evidence of low-temperature plasticity, with features indicating low strain and possibly work hardening (Fig. 7c). These include undulose extinction, sub-grain formation, deformation bands, bulged grain boundaries, serrated grain boundaries and small zones of secondary recrystallization. Undulose extinction and bulged grain boundaries are the most pervasive features. Deformed veins are cross-cut by undeformed veins.

The quartz veins have high inclusion contents (Fig. 9b), including linear bubble trails that may represent healed microfractures formed during repeated fracture-veining events. Later fractures are represented by bands of undeformed quartz that cut across the veins with undulose extinction and represent infill of dilational fractures. Some of the microcrystalline quartz appears to be re-cemented cataclastic material.

3.c. Later deformation

Later deformation which obscures the coarse/microcrystalline quartz relationship is represented by a series of dark stylolitic surfaces which juxtapose areas of different grain size and deformation state (Fig. 7b). The surfaces which appear as dark seams in hand specimen are stylolitic in morphology and vary in width from 0.01 to 0.2 mm. They generally lie subparallel to the fault surface and appear to be solution seams. Thicker seams contain screens of black shale matrix but mostly consist of dark, optically irresolvable material. The cleavage in the shale is also deformed. It is folded and cut by shear zones at a low angle to the slaty fabric (Figs 7a, 8b). Later cataclasis also occurs in some of the fault zones producing millimetre-sized fragments with intragranular cracks. A post-cataclasis solution overprint tends to produce more rounded grains and seams similar to those described above.

The stylolitic seams consist of an aggregate of fine-grained illitic phyllosilicates (Fig. 9c) which are, in general, oriented parallel to the seam boundary, but also display domains where the long axes of the phyllosilicates are at high angles to the seam boundaries and the preferred orientation is poor. The grains are less than 1 μm in length and have aspect ratios of around 10:1. The areas in which the grain long axes are at high angles to the seam boundaries appear to be recrystallized kinks with more equant grains growing along the axes of the kinks. Seam margins are sharp, the phyllosilicates lying parallel to the boundary. Fe–Ti oxides and rounded, relict quartz grains were also identified within the seams.

4. Conditions of deformation

The combination of field and microstructural data indicates a progressive sequence of conditions and mechanisms of deformation operating during the evolution of these fault zones (Fig. 10). The sequence is summarized in the next sections.

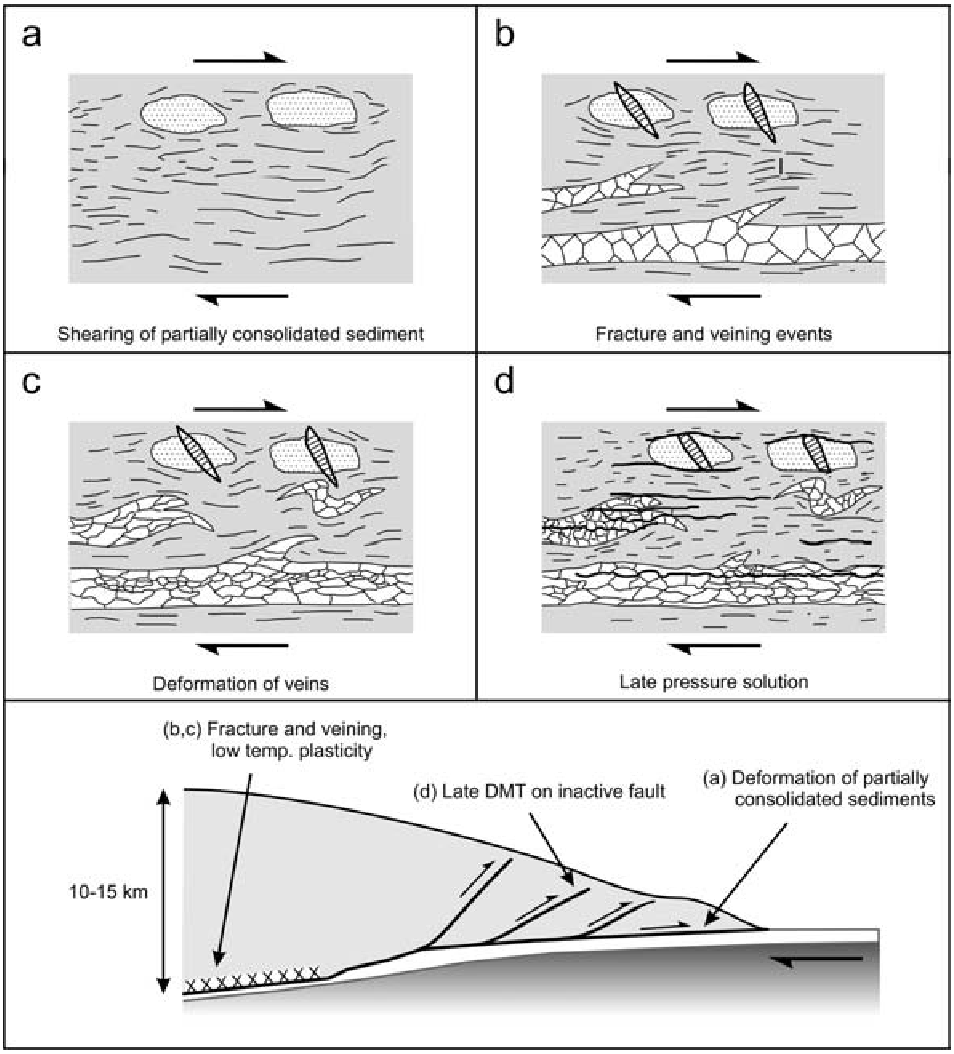

Figure 10. Synthesis of the deformation history. (a) Initial bed-parallel shear of partially consolidated sediment results in the development of an aligned phyllosilicate microstructure and disaggregation of sandstone layers. (b) Continued burial, dewatering and consolidation requires that further slip is accommodated by failure along the microfabric. The resulting drop in fluid pressure leads to the precipitation and sealing of the fault zones. (c) Continued slip results in repeated fracture-veining events, low-temperature crystal plastic deformation of the existing veins and deformation of the black shale fabric. (d) Reduced slip rates, as the fault becomes inactive, due to the activity of lower newly formed faults, results in the formation of pressure solution seams parallel to the fabric. (bottom) Diagrammatic summary showing the likely positions of the various deformation events illustrated in (a) to (d).

4.a. Disruption of sand layers

Disrupted sandy layers show little or no internal structure, suggesting that frictionally controlled grain boundary sliding predominated in the early pre-cleavage stages of the deformation history. The nature of the relict sedimentary layering in the shale strongly suggests that the initial deformation took place under conditions of partial lithification. By analogy with structures from present-day prisms, the initiation of scaly slip surfaces could take place at shallow depths ahead or at the toe of the thrust wedge (Maltman, 1998). Initial burial by the turbidites of the Portpatrick and Kirkcolm formations will have helped to develop overpressures in the shale. With subsequent layer-parallel shear, as the décollement formed, there would be episodic changes in permeability of the fault zone with time. Shearing of the shale either collapses the pore spaces, promoting dewatering or failure on localized slip surfaces with associated dilation. The permeability of the sediments would become directional with preferential flow parallel to the fabric favoured (Bolton & Maltman, 1998). Both décollement zones exhibit a progressive localization of deformation but variability in deformation style. In the Morroch Bay case, deformation is localized within 1 m of the fault surfaces. In the Portslogan section deformation takes place throughout the shale sequence, gradually becoming more localized as fracturing occurs.

4.b. Fracture and diffusional mass transfer

Increasing tectonic burial favours the onset of fracture and diffusive mass transfer processes. The likely burial depths for deformation of the Moffat Shales and the overlying turbidites correspond with the transition from aseismic to seismic behaviour of the basal décollement in accretionary prisms (Moore & Saffer, 2001). The development of discrete fractures and cleavage is therefore to be expected under the prevailing late diagenetic to low-grade metamorphic conditions. Fault-parallel veined fractures indicate that at least transient high pore-fluid pressures were attained and hydrofracturing occurred. The veins also indicate that the host-rock was sufficiently cohesive to fail by fabric-parallel fracture rather than disaggregation. High fluid pressures are common in active accretionary complexes (Moore *et al*. 1991, 1995). A model for fault-parallel flow during high fluid pressure hydrofracturing has been proposed by Brown *et al*. (1994). The recognition that the Moffat Shale décollement zones show evidence of repeated fracture/veining events indicates repeated slip on the fault zones. The texture of the veins indicates rapid precipitation of quartz, possibly resulting from a drop in fluid pressure as slip occurs, a phenomenon reported from other fault zones (Sibson, Robert & Poulsen, 1988; Boullier *et al*. 2004). Earlier fabrics, cross-cut by the veins, are more ductile in nature and may reflect the aseismic stage of the fault history. The increased vein concentration would also serve to change the mechanical properties of the shale, making it harder to deform by bed-parallel slip and promoting further fracturing. Some of the vein fill may have been generated locally by DMT processes during cleavage formation, but the association of the quartz veins with the fault zones and the volume of vein material suggests that longer distance transport has occurred. Fluids bearing silica in solution, generated by metamorphic reactions at greater depths, may move as pulses up the décollement (Shipley *et al*. 1994). The formation and recrystallization of phyllosilicates may release silica into solution as would quartz dissolution. Calcium may be generated by the metamorphism of plagioclase to albite, a process indicated by the albitic composition of all detrital feldspars in the footwall turbiditic sandstones. This is unlikely to have been their original composition given their original volcanic-arc source (Stone, 1995). The presence and interrelationship of the crystalline and microcrystalline quartz suggest a fine to coarse crystallization sequence. Such a sequence was found in crystallization from colloidal silica gel (Oehler, 1976) and in natural cataclasites (Stel, 1981; Stel & Lankreyer, 1994).

4.c. Veining

Initial vein formation was followed by continued deformation as expressed by buckled veins and cross-cutting stylolites. Deformation produced progressive work hardening of the quartz veins. Little recovery appears to have taken place, due to the low temperatures at which deformation was proceeding. Prehnite–pumpellyite facies conditions are estimated at 300 °C and 2.5 kbar (Oliver & Leggett, 1980). This is supported by illite crystallinity data suggesting upper anchizone to epizonal conditions in the Morroch Bay area (Merriman *et al*. 1995), corresponding to a burial depth of 8–10 km with a geothermal gradient of $< 25\,^{\circ}\mathrm{C\ km^{-1}}$. Needham (1993) demonstrated that the metamorphism was syntectonic. Bedding-parallel veins developed during flexural slip folding are cross-cut by the axial planar cleavage developed during the later stages of fold tightening and flattening. The presence of bulged grains indicates deformation at temperatures lower than those needed for subgrain nucleation. Smith & Evans (1984) estimated that the healing of cracks into inclusion trails will occur in geologically short times at temperatures greater that 200 °C in the presence of a pore fluid.

4.d. Pressure solution

The next deformation recorded by the veins is a pressure solution overprint in the form of stylolitic seams, indicating shortening at a high angle to the fault zone. Their nucleation appears to have been controlled by the presence of black shale inclusions as quartz–phyllosilicate contacts are zones of enhanced solution due to surface adsorption effects in the phyllosilicates. Microcrystalline quartz would also be more susceptible to dissolution due to its finer grain size and correspondingly higher surface area. TEM studies show that many grain boundaries are phyllosilicate-free but have abundant voids along their length (Fig. 9b). White & White (1981) calculate that such voids enhance grain boundary diffusion. If these voids are extant during stylolite growth, which is likely as the quartz appears unaffected by secondary recrystallization, they may have allowed easier fluid penetration, resulting in the growth of new phyllosilicates, enhanced pressure solution and new seam formation. The irregular nature of the stylolites may therefore reflect the initial distribution of interconnected easy diffusion paths. The contribution of transient microcracks to fluid movement, especially along quartz–phyllosilicate interfaces, may be important as there is evidence for polyphase veining and healed fractures. Pressure solution processes occur at lower strain rates than dislocation creep processes and so the switch from crystal plastic to DMT may indicate a drop in strain and displacement rate (Knipe, 1989, 1990). This culminates in the cessation of movement. The evidence for maximum stress at a high angle to the fault surface also supports this. Similar late-stage stylolites are reported in cataclasites by House & Gray (1982). Some of the dark seams that lie parallel to and intensify the slaty cleavage may have formed earlier in the deformation history as they are folded along with the cleavage. Low strain rate events may, therefore, not be confined solely to the late stages of the fault history and may have occurred intermittently during the evolution of the fault.

4.e. Localized late-stage cataclasis

Localized late-stage cataclasis is possibly due to reactivation of the faults, although that described in the greywacke may be earlier as the extent of the late-stage brecciation is usually restricted to within a few centimetres of the fault surface. The steep orientation of the fault zones after back-rotation in the thrust stack places them in a favourable orientation for strike-slip reactivation. Sinistral strike-slip reactivation during late Silurian times may account for the cataclasis. However, reactivation of faults from the Late Palaeozoic to the present is also likely, with deformation occurring under the shallower burial conditions likely to favour cataclasis (Anderson, Parnell & Ruffell, 1995; Needham & Morgan, 1997).

5. Summary and conclusions

The Moffat Shale décollement zone was studied at two different locations. These reflect deformation at different times in the evolution of the prism and show that behaviour of the deformation zones varied. Fluid flow as recorded by the veins is highly channelized, occurring either along faults in the shale sequence or in the zone immediately adjacent to the décollement. There is a progressive sequence of deformation mechanisms beginning with grain-boundary sliding in partially lithified sediments, through DMT processes and including low-temperature plasticity of quartz. The style of veining indicates the existence of elevated fluid pressures, particularly along the décollement. It is possible that some of this fluid is locally derived, resulting from the formation of the cleavage in the shales, but most is derived from longer distance transport along the faults. The development of veins is likely to have a pronounced effect on the mechanical behaviour of the fault zones. This is probably manifested as a work hardening effect. The presence of quartz veins is likely to make the fault zone harder to deform and will favour the failure of the shale host-rock rather than failure along existing veins, so promoting polyphase veining and increased vein density. The polyphase nature of the veins also reflects fluid pressure cycling in that slip-events, promoted by high fluid pressures, will in turn cause a reduction in fluid pressure and quartz precipitation. Low-temperature plastic deformation of the veins, without significant recovery, will also result in work hardening leading ultimately to fracture. Evidence for channellized fluid flow in the shallower levels of present-day accretionary prisms (Shipley *et al.* 1994) suggests that an interconnected fracture network exists. This must extend to the fluid source depth although the evidence from the Southern Uplands suggests that self-sealing of the fault zone permeability occurs by vein filling and DMT. Presumably, as deformation continues, new fracture pathways develop, replacing those which become sealed by cementation and pressure solution. It is possible to enhance the concept of dynamic permeability (Stephenson, Maltman & Knipe, 1994) to include variations in permeability due, not only to microstructural changes in the host sediment, but also to failure along slip planes in that sediment. Such discontinuities, as generated experimentally by Brown *et al.* (1994), contribute an increase in the total permeability of the décollement zone and are now represented in their sealed form as veins.

The contrasting deformation styles observed in the Morroch Bay and Portslogan sections suggest that deformation was initiated at different levels. There is more evidence for wet sediment deformation (stratal disruption) in the Portslogan section, suggesting initiation at shallow levels although continuing to depths where rock fracture and abundant quartz veining could occur. The Morroch Bay section shows much more localized deformation with relatively coherent packages of sediment between the faults. As deformation of the overlying turbidites of the Portpatrick Formation occurred during prehnite–pumpellyite facies metamorphism it is likely that deeper burial occurred before the onset of faulting in the Morroch Bay section. In this respect, the Kircolm Formation thrust sheet is important in providing extra burial for the Portpatrick Formation and underlying Moffat Shale Group. The tectonically thickened Kirkcolm and Corsewall formations would provide sufficient burial depth for the observed syn-deformational metamorphism to occur. It appears therefore that the Morroch Bay fault zone was initiated at greater depths below the thrust wedge.

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References

AGAR, S. M., PRIOR, D. J. & BEHRMANN, J. H. 1989. Back-scattered electron imagery of the tectonic fabrics of some fine grained sediments: implications for the fabric nomenclature and deformation processes. *Geology* **17**, 901–4.

ANDERSON, T. B., PARNELL, J. & RUFFELL, A. H. 1995. Influence of basement on the geometry of Permo-Triassic basins in the northwest British Isles. In *Permian and Triassic Rifting in Northwest Europe* (ed. S. A. R. Boldy), pp. 103–22. Geological Society of London, Special Publication no. 91.

BOLTON, A. & MALTMAN, A. 1998. Fluid-flow pathways in actively deforming sediments: the role of pre fluid pressures and volume change. *Marine and Petroleum Geology* **15**, 281–97.

Boullier, A.-M., Fujimoto, K., Ohtani, T., Roman-Ross, G., Lewin, E., Ito, H., Pezard, P. & Ildefonse, B. 2004. Textural evidence for recent co-seismic circulation of fluids in the Nojima fault zone, Awaji island, Japan. *Tectonophysics* **378**, 165–81.

Brown, K. M., Bekins, B., Clennell, B., Dewhurst, D. & Westbrook, G. 1994. Heterogeneous hydrofracture development and accretionary fault dynamics. *Geology* **22**, 259–62.

Craig, G. Y. & Walton, E. K. 1959. Sequence and structure in the Silurian rocks of Kirkcudbrightshire. *Geological Magazine* **96**, 209–20.

Floyd, J. D. 2001. The Southern Uplands terrane: a stratigraphical review. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **91**, 349–62.

Fyfe, T. B. & Weir, J. A. 1976. The Ettrick Valley thrust and the upper limit of the Moffat Shales in Craigmichan Scaurs (Dumfries and Galloway Region: Annandale and Eskdale District). *Scottish Journal of Geology* **12**, 93–102.

House, W. M. & Gray, D. R. 1982. Cataclasites along the Saltville thrust, U. S. A. and their implications for thrust sheet emplacement. *Journal of Structural Geology* **4**, 257–69.

Kelling, G. 1961. The stratigraphy and structure of the Ordovician rocks of the Rhinns of Galloway. *Quarterly Journal of the Geological Society of London* **117**, 37–75.

Knipe, R. J. 1989. Deformation mechanisms – recognition from natural tectonites. *Journal of Structural Geology* **11**, 127–48.

Knipe, R. J. 1990. Microstructural analysis and tectonic evolution in thrust systems: examples from the Assynt region of the Moine Thrust Zone, Scotland. In *Deformation Mechanisms in Ceramics, Minerals and Rocks* (eds D. J. Barber and P. G. Meredith), pp. 228–61. London: Unwin Hyman.

Knipe, R. J. & Needham, D. T. 1986. Deformation processes in accretionary wedges – examples from the SW margin of the Southern Uplands, Scotland. In *Collision Tectonics* (eds M. P. Coward and A. C. Ries), pp. 51–65. Geological Society of London, Special Publication no. 19.

Leggett, J. K., McKerrow, W. S. & Casey, D. M. 1982. The anatomy of a Lower Palaeozoic accretionary forearc: the Southern Uplands of Scotland. In *Trench–Forearc Geology* (ed. J. K. Leggett), pp. 495–520. Geological Society of London, Special Publication no. 10.

Leggett, J. K., McKerrow, W. S. & Eales, M. H. 1979. The Southern Uplands of Scotland a Lower Palaeozoic accretionary prism. *Journal of the Geological Society, London* **136**, 755–70.

Maltman, A. J. 1998. Deformation structures from the toe of active accretionary prisms. *Journal of the Geological Society, London* **155**, 639–50.

Merriman, R. J., Roberts, B., Peacor, D. & Hirons, S. R. 1995. Strain-related differences in the crystal growth of white mica and chlorite: a TEM and XRD study of the development of metapelitic microfabrics in the Southern Uplands thrust terrane, Scotland. *Journal of Metamorphic Geology* **13**, 559–76.

Moore, J. C., Brown, K. M., Horath, F., Cochrane, G. R., Mackay, M. & Moore, G. 1991. Plumbing accretionary prisms: Effects of permeability variations. *Philosophical Transactions of the Royal Society of London* **A335**, 275–88.

Moore, J. C. & Saffer, D. 2001. Updip limit of the seismogenic zone beneath the accretionary prism of southwest Japan: an effect of diagenetic to low grade metamorphic processes and increasing effective stress. *Geology* **29**, 183–6.

Moore, J. C., Shipley, T. H. & others. 1995. Abnormal fluid pressures and fault zone dilation in the Barbados accretionary prism: evidence from logging. *Geology* **23**, 605–8.

Needham, D. T. 1993. The structure of the western part of the Southern Uplands of Scotland. *Journal of the Geological Society, London* **150**, 341–54.

Needham, D. T. 1994. The structure of the western part of the Southern Uplands of Scotland: Reply. *Journal of the Geological Society, London* **151**, 732–4.

Needham, D. T. & Knipe, R. J. 1986. Accretion and collision related deformation in the Scottish Southern Uplands. *Geology* **14**, 303–6.

Needham, T. & Morgan, R. 1997. The East Irish Sea and adjacent basins – new faults or old? *Journal of the Geological Society, London* **154**, 145–50.

Oehler, J. W. 1976. Hydrothermal crystallization of silica gel. *Bulletin of the Geological Society of America* **87**, 1143–52.

Oliver, G. J. H. & Leggett, J. K. 1980. Metamorphism in an accretionary prism. Prehnite–pumpellyite facies metamorphism of the Southern Uplands of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **71**, 235–46.

Oliver, G. J. H., Stone, P. & Bluck, B. J. 2003. Ballantrae complex and Southern Uplands terrane. In *Geology of Scotland, 4th edition* (ed. N. Trewin), pp. 166–200. Geological Society Publishing House.

Phillips, E. R., Evans, J. A., Stone, P., Horstwood, M., Floyd, J. D., Smith, R. A., Akhurst, M. C. & Barron, H. F. 2003. Detrital Avalonian zircons in the Laurentian Southern Uplands terrane, Scotland. *Geology* **31**, 625–8.

Rushton, A. W. A., Stone, P. & Hughes, R. A. 1996. Biostratigraphical control for thrust models for the Southern Uplands of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **86**, 137–52.

Shipley, T. H., Moore, G. F., Bangs, N. L., Moore, J. C. & Stoffa, P. L. 1994. Seismically inferred dilatancy distribution, northern Barbados Ridge decollement: implications for fluid migration and fault strength. *Geology* **22**, 411–14.

Sibson, R. H., Robert, F. & Poulsen, K. H. 1988. High-angle reverse faults, fluid pressure cycling and mesothermal gold-quartz deposits. *Geology* **16**, 551–5.

Smith, D. L. & Evans, B. 1984. Diffusional crack healing in quartz. *Journal of Geophysical Research* **89**, 4125–35.

Smith, R. A., Phillips, E. R., Floyd, J. D., Barron, H. F. & Pickett, E. A. 2001. The Northern Belt 100 years on: a revised model of the Ordovician tracts near Leadhills, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **91**, 421–34.

Stel, H. 1981. Crystal growth in cataclasites: diagnostic microstructures and implications. *Tectonophysics* **78**, 585–600.

Stel, H. & Lankreyer, A. C. 1994. Flow and deformation of viscous, silica-oversaturated dispersions in low-grade faults. *Journal of Structural Geology* **16**, 303–13.

Stephenson, E. L., Maltman, A. J. & Knipe, R. J. 1994. Fluid flow in actively deforming sediments, dynamic permeability in accretionary wedges. In *Geofluids* (ed. J. Parnell), pp. 113–26. Geological Society of London, Special Publication no. 78.

STONE, P. 1995. *Geology of the Rhins of Galloway district*. Memoir for the 1:50000 geology sheets 1 and 3 (Scotland). Keyworth: British Geological Survey.

STONE, P., FLOYD, J. D., BARNES, R. P. & LINTERN, B. C. 1987. A sequential back-arc and foreland basin thrust duplex model for the Southern Uplands Scotland. *Journal of the Geological Society, London* **144**, 753–64.

STRACHAN, R. A. 2000. Mid-Ordovician to Silurian sedimentation on the northern active margin of Iapetus. In *Geological History of Britain and Ireland* (eds N. H. Woodcock and R. A. Strachan), pp. 107–23. Oxford: Blackwell Science Ltd.

WEBB, B. C. 1983. Imbricate structure in the Ettrick area, Southern Uplands. *Scottish Journal of Geology* **19**, 387–400.

WHITE, J. C. & WHITE, S. H. 1981. On the structure of grain boundaries in tectonites. *Tectonophysics* **78**, 613–28.