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Mechanisms of mélange formation: examples from SW Japan and southern Scotland

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Abstract—The formation of synthetic Riedel shears either as discrete faults or ductile shear-zones is important in the fragmentation of layers to form mélanges. The magnitude of longitudinal and shear strain necessary for this fragmentation has been assessed using a simple rigid-domino model for layer-parallel shear. The strain required for layer fragmentation is a function of block aspect ratio and initial fracture dip relative to layering. Layer stretching can occur during simple shear if folds are developed but a component of extension parallel to the shear zones reduces the strain required for fragmentation. Simple models of this type break down when there is a component of dilation across the mélange block bounding fractures allowing shale matrix infill or mineral vein growth. Some mélanges show evidence, in the form of symmetrical structures, of a more coaxial deformation history and this may in part reflect deformation partitioning between sandstone and shale layers. Other mechanisms of mélange formation include the development of out-of-sequence thrusts cutting through already dipping beds. The causes of strike-parallel extension are tentatively related to large-scale evidence of arc-parallel forearc stretching.

INTRODUCTION

Mélanges are a common constituent of many accretionary complexes and also occur in other tectonic settings such as foreland basins and strike-slip fault zones. At their simplest they consist of blocks of relatively low ductility rocks such as sandstone, chert or basalt enclosed in a more ductile shaly matrix. The matrix is commonly foliated, exhibiting a characteristic scaly fabric. Many mélanges result from the disruption of an initially intact succession and various environments have been suggested for this disruption including accretionary thrust zones, sedimentary slump sheets and mud diapirs (Cowan 1985). Despite their apparently chaotic nature, mélanges often exhibit a high degree of internal organization and display a consistent suite of structures which are indicative of the processes that formed the mélange. In the accretionary thrust and slump settings mélanges have experienced pronounced non-coaxial deformation and recognition of this has led to the application of concepts developed during the study of deeper level ductile shear-zones. Mélange blocks are often lenticular showing both symmetrical and asymmetrical forms. Many workers have described lozenge shaped asymmetrical blocks from mélanges (Uemura 1965, Hsu 1974, Korsch 1982). Such blocks can be defined by extensional shear fractures although similar geometries produced by more ductile deformation are also recognized. Needham (1987) recognized Riedel 1 or shear band type structures in mélanges and suggested that stratal disruption resulted from the development of these structures. The examples cited by Needham (1987) were from the mainly Cretaceous–Palaeogene Shimanto Belt accretionary complex of SW Japan and the Ordovician–Silurian Scottish Southern Uplands. Asymmetric mélange fabrics have now been described from other parts of the Shimanto Belt such as the eastern part of Shikoku (Kimura & Mukai 1991). These ideas were spectacularly applied to determine the shear sense in mélanges from central Japan by Kano *et al.* (1991) who suggested that such shear directions may directly reflect plate convergence vectors. Kiyokawa (1992) recognized asymmetric blocks where separation had included a component of dilation across the defining fractures, allowing influx of the shaly matrix.

Asymmetric mélange structures were recognized on a microstructural scale by Hammond (1987) and Fisher & Byrne (1987) from work in other accretionary complexes. Cowan (1990) analysed the rotation of sandstone blocks using the concepts developed for rigid inclusions in shear-zones. This allowed not only the determination of the magnitude of shear strain but the type of deformation for the mélange. This was found to be non-coaxial but not simple-shear. He did not address the mechanism by which the blocks initially formed. Due to the lithologies involved and the lack of markers there have been few analyses of strain in mélanges. In addition to Cowan's (1990) analysis, Kimura & Mukai (1991) measured strain from Shimanto Belt mélanges using block shapes and deformed radiolaria. They found the radiolaria to be more reliable strain markers. No assessment has been made of the strain required to fragment layers by Riedel shears and this is addressed here. Stratal disruption and scaly fabrics have also been recognized in cores recovered from active accretionary prisms and analysed using shear-zone criteria (Behrmann *et al.* 1988). The similarity with structures developed in shear-zones and fault zones in non-accretionary settings was emphasized by Agar (1990) and King & Sammis (1992).

Other mechanisms have also been invoked for the formation of shear-zone mélanges. More coaxial deformation styles with a greater symmetry of structures have also been described. These mélanges contain symmetrical boudins or blocks defined by conjugate fractures. Cowan (1982) suggested a spreading slump sheet environment for this type of deformation in some Franciscan mélanges. Similar broadly coaxial extension forming at least part of the deformation history, has been recognized in mélanges from Japan (Agar 1988) and Antarctica (Nell 1990). Nell (1990) also suggests that 'out-of-sequence' thrusts cutting through an already imbricated sequence can act to form mélanges. The thrusts in this case are broad shear-zones in which an initially intact sequence is disrupted. Criteria for distinguishing such shear-zone mélanges from diapiric mélanges were discussed by Orange (1990).

This summary shows that there are a wide variety of mechanisms for the formation of stratal disruption and mélange. This paper investigates these mechanisms to see if there are links indicating a common setting or the operation of a common set of processes. Of particular concern are the processes by which an initially intact sequence becomes disrupted and the nature and magnitude of the strains involved in this disruption. Many mélanges form in fault or shear-zones, accretionary or otherwise. Mélanges are amenable to analysis using the techniques and concepts developed during the study of faults and shear-zones in other tectonic settings. Analysis should be possible regardless of whether the mélange formed along an accretionary thrust fault or at the base of a slump sheet.

Mélanges take many different forms. This paper will concentrate on these which could also be described as 'broken-formations', the type I and IV mélanges of Cowan (1985). These mélanges consist of an initially intact sedimentary sequence which has been disrupted. They contain no exotic blocks although it is likely that some of the mechanisms described here could be successfully applied to the lithologically more diverse Type II mélanges. The examples described here are drawn from two accretionary complexes, the Shimanto belt of SW Japan and the Scottish Southern Uplands. All of the mélanges and broken formations described are believed to be tectonic in origin and are certainly not diapiric. They tend to occur as linear strike-parallel belts usually related to fault zones across which there is considerable displacement. No cross-cutting, intrusive relationships, suggestive of a diapiric origin were observed. Some of the examples used here come from areas in which the transition from a coherent to disrupted sequence can be observed. Others display discrete faulted contacts between disrupted units and coherent areas.

THE SHIMANTO BELT

The Shimanto Belt (Taira *et al.* 1982) is of Cretaceous to Lower Miocene age and forms the youngest accreted material exposed on-land inboard of the active Nankai Trough trench. The Shimanto Belt consists of two sub-belts, a northern one of Cretaceous age and a southern one dominantly Palaeogene in age. The Shimanto Belt runs from the Akaishi and Kanto mountains in central Japan to Kyushu and the Ryukyu islands in the southwest (Fig. 1). The examples described are from Eocene rocks in the Southern sub-belt on the Muroto peninsula of the island of Shikoku and from the Northern sub-belt of Kyushu.

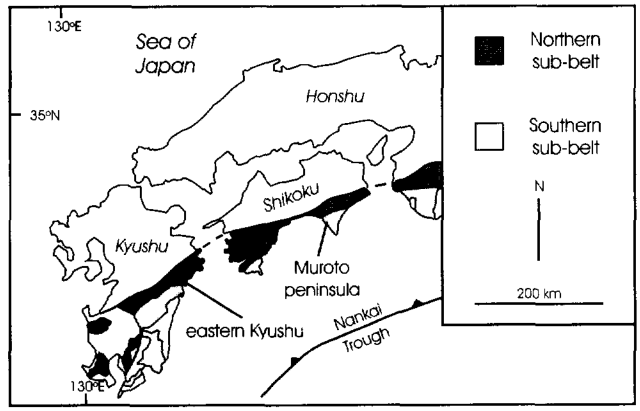


Fig. 1. Map of SW Japan showing the location of the Shimanto Belt and the areas studied.

Stratal disruption in the Southern Sub-belt, Muroto peninsula, Shikoku

The disrupted sequence studied lies on the western coast of the Muroto Peninsula at Kono near to the town of Aki. It consists of a deformed series of thin to medium bedded sandstones with interbedded shales of Eocene age. Much of the sequence is coherent but disrupted units are also present. There is a gradual northwest–southeast increase in disruption. Minor folds are well developed with upright ENE–WSW striking axial surfaces. The folds have 0.5 m half-wavelengths, are markedly periclinal and show considerable variations in profile along strike. Plunges range from horizontal to 90°, including locally downward facing folds. The periclinal form of folds and the lack of a single sense of vergence in the steeply plunging folds plunging folds points to the development of steep plunges in a single progressive deformation event. An associated weak cleavage in the shales sometimes displays a pencil morphology in fold hinge regions due to the intersection with bedding parallel fissility in the shales. In other fold hinge regions this bedding fissility is crenulated without the development of a discrete cleavage. The cleavage lies parallel to bedding on fold limbs and is a weak scaly fabric which fabric intensifies in areas of stratal disruption. The deformation recognized here is very similar to that described by Hibbard & Karig (1987) from further south in the Oligo-Miocene rocks of the Muroto peninsula.

Folds also occur in isolated hinges in areas of stratal disruption. The limbs of these folds are stretched and are now represented by trails of sandstone boudins (Figs. 2 and 3a). The stratally disrupted areas are characterized by oblate sandstone blocks showing either symmetrical or asymmetrical forms in vertical section perpendicular to strike. The sandstone blocks show elongate tails in

Fig. 2. Asymmetric fold hinge in disrupted unit at Kono. The sense of shear is left-hand side up. Note the train of sandstone boudins, produced by stretching of the fold limb during progressive shear, on the northwest (left-hand) side of the hinge.

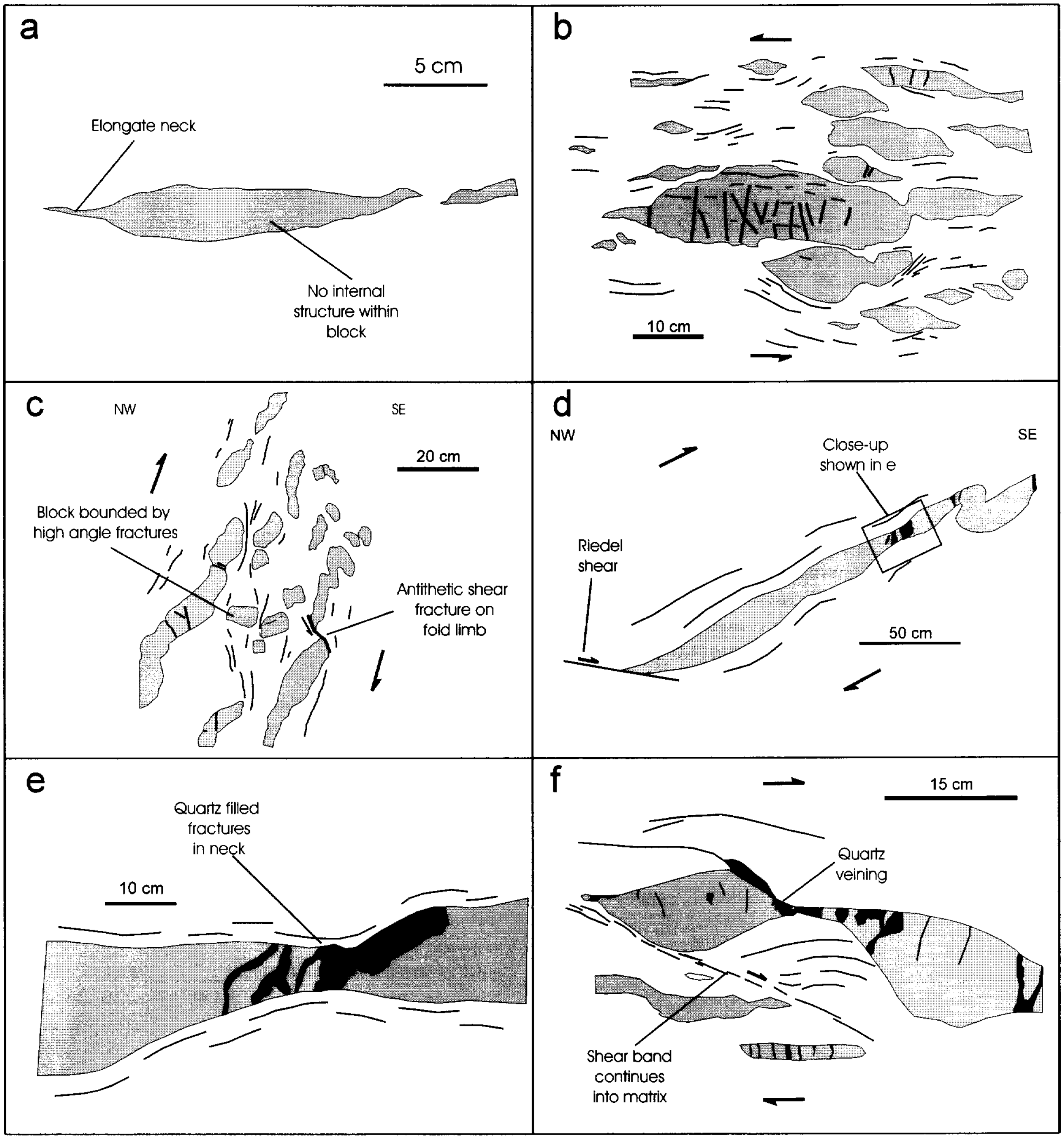


Fig. 3. Examples of mélange block/matrix relationships from SW Japan. (a) Sandstone block from Kono showing elongated tails. The block is almost symmetrical and shows no internal structure suggesting deformation when partially lithified. It lies on the northwest limb of the fold shown in Fig. 2. (b) Asymmetric sandstone blocks in shaly matrix, Kono. Sense of shear is top to the left. Note high angle fractures and preserved internal laminations in block, suggesting internal deformation of a lithified bed. Blocks all show the same sense of asymmetry. Shear bands are also developed in the shale matrix. (c) Sandstone blocks in mélange, Kono, bounded by fractures at a high angle to the layering and antithetic shear fractures on an asymmetric fold limb. The shear sense is left-hand side up. (d) Asymmetric fold in sandstone bed, eastern Kyushu, showing stretching of layer by pinch and swell and segmentation by a Riedel shear. The shear sense indicated is top to the right. (e) Close-up of neck region of boudin on fold limb in (d) showing final separation of bed accomplished by localization of quartz veining. (f) Asymmetric sandstone blocks, eastern Kyushu, with internal high angle fractures and quartz veining in neck region. Note continuation of shear bands into shale matrix. Shear sense is top to the right.

which considerable thinning of the original bed has occurred. The extreme necking of these boudins suggests that the sand deformed in a ductile manner prior to separation into isolated blocks. Some blocks show a bulbous form with no internal structure. These blocks exceed the average thickness of their source layer suggesting 'swelling' of the layer by intergranular particulate flow. This results in the obliteration of internal laminations within the blocks. The necking of layers shows two distinct forms. Firstly, there is a smooth decrease in thickness, leading ultimately to the separation of the layer into blocks. The other common form shows an abrupt decrease in layer thickness resulting in a 'Luders band' form similar to that produced by plastic deformation of metals and other materials. Some of the thinned segments are asymmetric, indicating a shear-band type origin. Asymmetric block formation by this mechanism is also indicated by the presence of well developed shear zones in the shaly matrix. These consist of domains in which the shaly fabric is strongly aligned. The shear zones lie at an angle of less than 30° to the main shaly fabric which parallels bedding, where visible, within the blocks. The ductile deformation appears to have initiated in partially lithified sediments.

There is little internal fracturing in many of the sandstones and, where faults occur, they are granular shear zones into which sand and mud has been entrained and/or injected. Some blocks do contain discrete fractures however. These blocks are derived from layers that were more lithified at the time of deformation and usually have the best preserved bedding laminae. The internal fractures generally lie at a high angle to bedding, either parallel to the block short axes or forming conjugate sets symmetrically arranged about the short axis (Fig. 3b). Fractures also define the block margins, dilation across them having allowed separation of the layers into blocks (Fig. 3c). Some of the layers are also cut by extensional shear fractures which have displacements antithetic to the shear direction indicated by folds within the disrupted units.

There are a number of small displacement (~ 1 m) thrust faults which are developed as discrete fracture surfaces. These cut through rocks that were already folded and cleaved. These thrusts dip gently to the northwest and have a top to the southeast sense of movement.

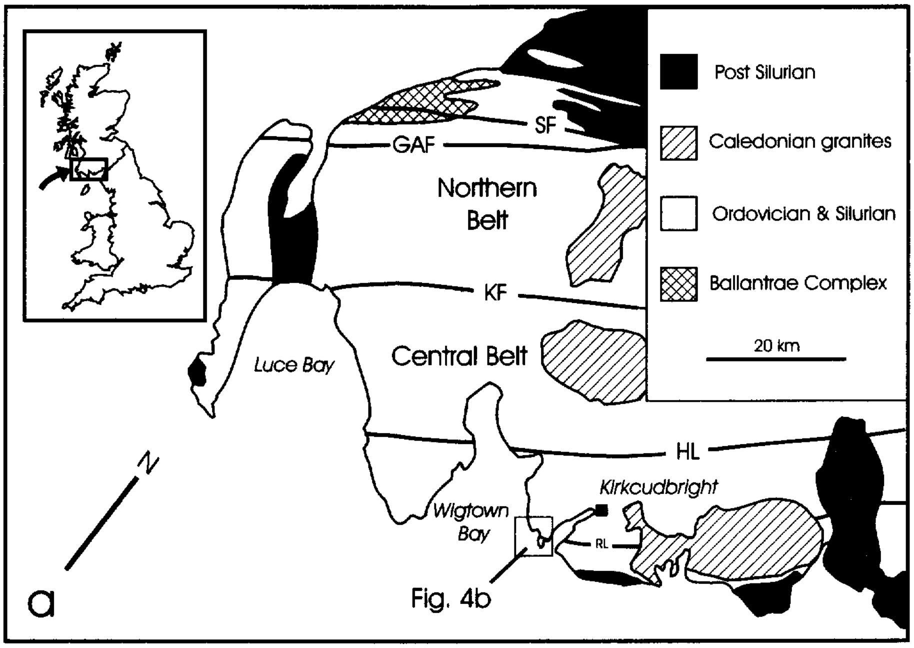
Stratal disruption in the Northern Sub-belt, eastern Kyushu

The Shimanto Belt of eastern Kyushu has experienced deformation under deeper level conditions with syntectonic greenschist facies mineral assemblages developed in deformed pillow lavas. This led Mackenzie *et al.* (1987) and Needham & Mackenzie (1988) to suggest that it represented an underplated sequence. An intense bedding parallel foliation is developed which also contains the long axes of the mélange blocks. Asymmetric mélange fabrics are well developed both by shear fractures and by more ductile shear band type extension. Figures 3(d)–(f) shows some typical mélange geometries from eastern Kyushu. Mélange blocks show a variety of forms. There are rhomb shaped blocks with their long-axes antithetically rotated away from the shear plane and also more symmetrical lenticular blocks. Some of the rhombic blocks are defined by shear fractures which continue into the matrix whilst in other cases the mélange fabric wraps around the blocks and is not cut. Quartz filled fractures perpendicular to the block long axes are common. Some of the fractures defining the rhombic blocks are also veined suggesting that they have a hybrid shear-dilation origin. Some sandstone layers show symmetrical pinch and swell or boudinage. Other, symmetrical, structures are conjugate quartz cemented fracture sets which cut either both blocks and matrix or just the blocks. These fractures lie at angles greater that 45° to bedding. In these cases the boudin neck is not always infilled by shale. Instead, ductile necking has been accompanied or followed by fracturing localized in the neck region. Quartz filled fractures concentrated in the neck region of the boudin actually account for the final separation of the layer into blocks. In some more extreme cases the majority of the block consists of vein quartz. Deformation appears to have continued under greenschist facies metamorphic conditions. The fracturing and associated vein filling has been followed by crystal-plastic deformation. Layer parallel quartz veins occur and these veins are themselves disrupted into rhomb shaped clasts, a feature more often observed at the microstructural scale. The vein quartz shows grain size reduction by dynamic recrystallization. There is also evidence that some larger blocks are progressively reduced in size by the development of new shear fractures/zones or further displacement on existing ones within the blocks. This has the effect of spalling fragments from the original block. Layering is also extended by Riedel shear fractures. This extension lies in the limbs of minor asymmetric folds (Fig. 3d). Development of the mélange structure in this area has been accomplished by a combination of symmetrical ductile extension represented by the pinch and swell/boudin structures. Ultimately, the ductile deformation may be succeeded by fracture in the boudin neck region and/or Riedel shear development. The localization of deformation could represent strain hardening as the sand undergoes progressive burial and lithification.

The northern Shimanto Belt of eastern Kyushu is affected by a number of post-mélange structures. The mélange fabric is refolded by asymmetric folds whose vergence indicates the same top to the southeast shear-sense as the asymmetric mélange clasts and early folds. There are also extensional faults with downthrows to the southeast. These tend to be discrete sharply defined fractures, sometimes with quartz veining. The dips of these faults are variable. Some cross-cut layering at a high angle (~ 60°) but others decrease their dips and detach on to bedding/foliation surfaces.

THE SOUTHERN UPLANDS

The Southern Uplands of Scotland are though to have originated as an Ordovician–Silurian accretionary prism (Leggett *et al.* 1979). The Southern Uplands can be subdivided into Northern, Central and Southern Belts (Fig. 4). The Northern belt is Ordovician in age, the Central Belt Ordovician and Silurian and the Southern Belt contains only Silurian (Wenlock) sediments. The examples described are from disrupted units within the Late Llandovery Hawick Rocks of the Central Belt. The main examples are from the east cost of Wigtown Bay between Ringdoo Point and Dove Cave and from Meggerland Point to Meikle Pinnacle (Fig. 4b) in the Hawick Rocks. The original distribution of the disrupted zones is



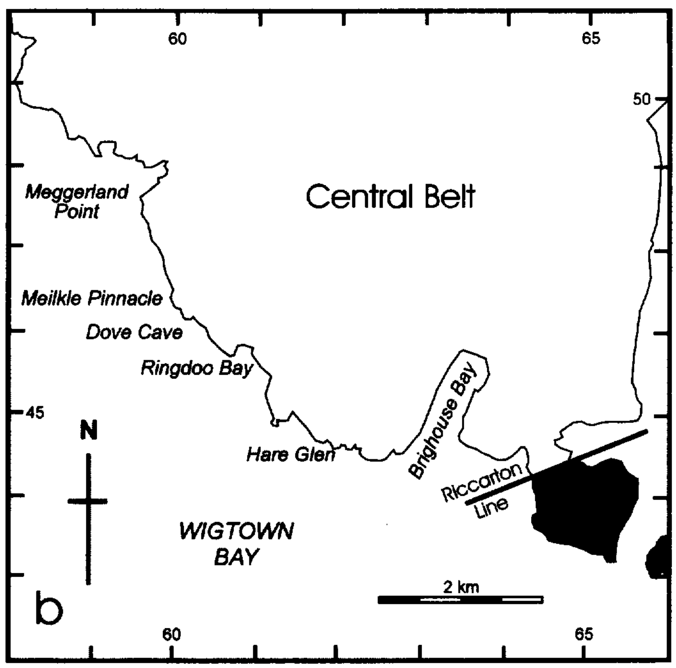


Fig. 4. Map showing localities described in the western part of the Southern Uplands of Scotland. (a) Geological map of the western part of the Southern Uplands. Inset shows location in the U.K. (b) Detailed map showing localities referred to in the text.

modified by strike-slip faults ('wrench-faults' in the local structural terminology) which lie at a high angle to the regional strike within the Southern Uplands.

Stratal disruption in the Central Belt

Stratal disruption is common in the Hawick Rocks on the eastern side of Wigtown Bay. Disrupted units occur interleaved with more coherent, folded sections for a distance of 1 km to the north of the Riccarton Line, the faulted boundary between the Central and Southern Belts. The Riccarton Line represents one of the main accretionary thrusts. Further disrupted zones, which provide the main examples here, lie 2 km to the north (Fig. 4b). The section from Ringdoo Point (NX606456) to Dove Cave (NX604460) shows a gradual northwards transition from coherent to disrupted. In Ringdoo Bay and at Ringdoo Point bedding is coherent and deformed into a series of close to tight, upright asymmetric SE-verging folds typical of much of the Southern Uplands (Stringer & Treagus 1981). Bedding dip decreases northwards as disruption increases although some of the more gently dipping structures are faults with gentle northwesterly dips. Folds axis orientations become more variable and bedding becomes progressively disrupted. This culminates in the presence of a 'broken formation' at Dove Cave. This consists of sandstone blocks, often highly veined by quartz and calcite, in a shaly matrix which is much less veined. The fabric in the shale wraps itself around the blocks which appear to be dismembered sandstone beds with initial thicknesses of less than 10 cm. The blocks vary in size from 5 to 50 cm parallel to their long axes. Layer extension has been accomplished by a range of structures. Riedel R_1 shear fractures separate blocks which exhibit a variable degree of ductile deformation in the adjacent blocks. Symmetrical boudinage and pinch and swell structures are also developed. The blocks are internally fractured. Dilational quartz and calcite cemented fractures perpendicular to the internal bedding of the blocks and their long axes are common. Some fractures with a dilational component of displacement are not perpendicular to block long axes but dip steeply with respect to the internal bedding. These appear to have originated as hybrid (shear-extension) fractures. The beds are also cut by conjugate shear fractures with the bisector of their dihedral angle lying perpendicular to bedding. Displacements on these shear fractures are generally in the order of millimetres. The disrupted zone is cut out on its northern side by a late 'wrench fault'.

Low angle faults that cross-cut steeper bedding and appear to have a top to the southeast sense of movement are also developed. As such they appear to have developed as out of sequence thrusts. Bedding has a sigmoidal geometry in profile between these faults which are generally spaced less than 1 m apart. The sigmoidal bed geometry developed because bedding is locally deflected into parallelism with these faults giving these structures a superficial duplex like appearance. In fact the area between the faults acted as a shear-zone and there are no thrusts linking 'roof' and 'floor' thrusts.

A further disrupted section is found to the north between Meikle Pinnacle (NX600464) and Meggerland Point (NX596476). In this case the disruption decreases northwards grading into the coherent, asymmetrically folded structure. Bed dips reduce into the disrupted zone but remain highly variable. The area is characterized by the development of faults with a Riedel R_1 shear orientation with respect to the main inferred shear plane. These are developed as moderately dipping extensional faults which cut downwards to the south, offsetting either individual beds or packets of beds. There are also SE-directed thrusts and related folds occurring adjacent to many extensional structures. Fold hinges, isolated by these fault sets, can be found. Not all the disruption is brittle in character as some beds show ductile thickness variations such as pinch and swell. The southern margin of the disrupted zone is truncated by a 'wrench fault' although as only 500 m of coherent sequence separates this unit from the Ringdoo Point-Dove Cave zone they may be parts of the same unit now offset by subsequent faulting. Both zones are characterized by a decrease in sandstone bed thickness and an increase in the proportion of shale.

The disrupted zones that lie within 1 km of the Riccarton Line are characterized by steeper dips than those seen in the two areas to the north. They also occur interleaved with coherently bedded units. The transition between these units can be a discrete fault or can be gradational. A good example of a disrupted zone is found just to the south of Hare Glen (NX623446). This zone is 4 m wide and bounded by discrete bedding parallel faults. The zone contains the typical sandstone blocks enclosed in a cleaved shaly matrix. This cleavage anastomoses around the blocks but in map view has a sigmoidal profile across the zone due to reactivation as a sinistral shear-zone (see Needham 1993, fig. 12). Most of the blocks are lenticular in strike and dip profile but some have rectangular outlines due to separation of fractures perpendicular to internal bedding. The source beds appear therefore to have deformed in different ways. The rectangular blocks are suggestive of deformation of a lithified bed whilst the lenticular blocks formed in a more ductile manner and possibly represent less well cemented layers. Internal bedding is preserved in blocks which were probably better lithified and one block even has a series of small sand volcanoes preserved on its upper surface. Other blocks show no internal structure, representing either the initially massive state of the bed or subsequent obliteration due to intergranular flow during extension. Block aspect ratios (short axis:long axis) vary from 0.1 to 1.0, 0.25 being typical. Quartz and calcite filled fractures perpendicular to the block long axes also occur.

SUMMARY: TYPICAL SHEAR-ZONE MÉLANGES

The above descriptions show that shear-zone mélanges have a suite of typical features which have to be explained in any model for the formation of mélanges. These features are summarized in Fig. 5. Mélange blocks may be symmetrical or asymmetrical. Symmetrical block trains lie enclosed within the surrounding mélange matrix fabric and themselves assist in defining that fabric. Asymmetrical blocks tend to be antithetically rotated with respect to the shear direction and external fabric. The blocks show evidence of formation by brittle, semi-brittle or ductile processes. Blocks which have deformed in a mesoscopically ductile manner tend to be more symmetrical with the ductile deformation having been accommodated by grain boundary sliding in a semi-lithified state. Asymmetric ductile boudins may also have developed but this asymmetry tends to be lost with progressive layer fragmentation. Semi-brittle deformation is characterized by the localization of deformation on granular shear-zones, often in an R_1 orientation. Mélange blocks formed in this manner may be characterized by an open sigmoidal form. Brittle deformation in mélange blocks takes two forms. Blocks themselves may be defined by shear fractures. Both asymmetric and symmetric forms are recognized. Additionally the blocks may contain a series of dilational fractures parallel to the block short axis. Exceptionally, these define the block. The blocks themselves may be sourced from single layers, packets of layers or parts spalled from a layer. Most mélanges show evidence of block extension in three-dimensions, usually exhibiting strike-parallel as well as down-dip extension.

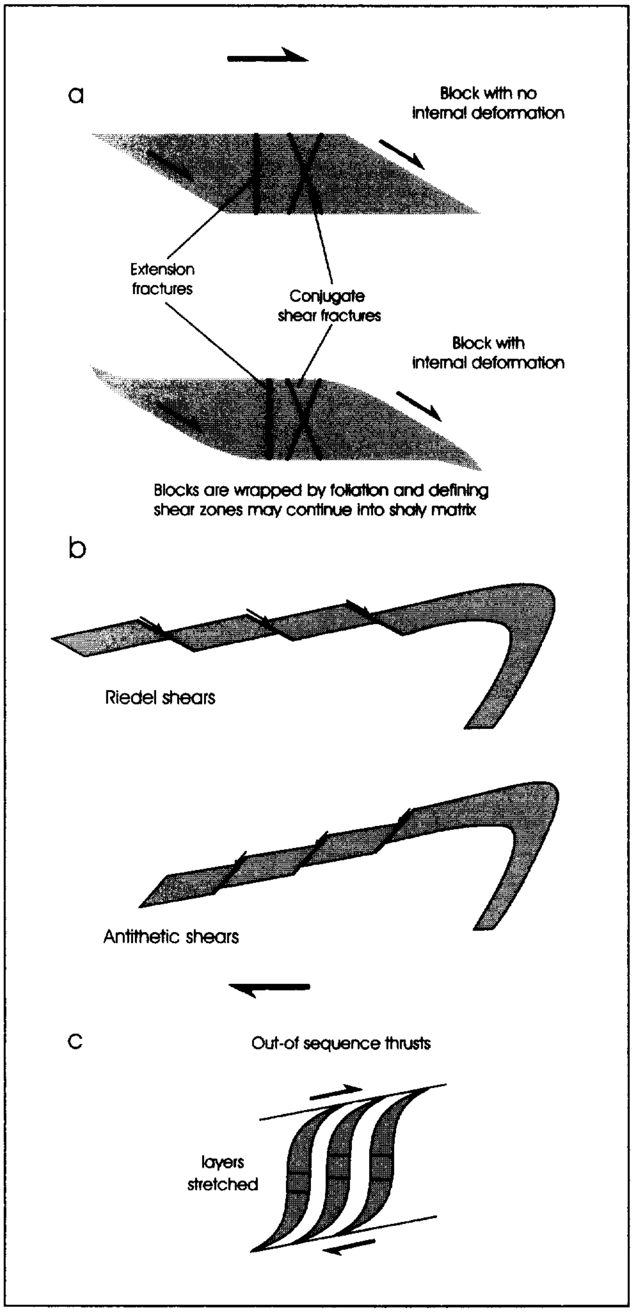


Fig. 5. Summary of features observed in mélanges from SW Japan and southern Scotland. (a) Structures in blocks with and without internal deformation. (b) Stretched fold limbs being dismembered by Riedel shears and antithetic shears. The shear sense is shown for (a) & (b). (c) Layers deformed by out-of-sequence thrusts.

MECHANISMS OF MÉLANGE FORMATION

Riedel shears and shear bands

The importance of Riedel fractures and geometrically identical ductile structures in the formation of mélanges was suggested by Needham (1987). Disruption occurs by the formation of R_1 Riedel shears during layer parallel shear. These fractures cut through the sandstone beds at 30° or less and, as displacement increases, progressively dismember them. The case of layer parallel shear requires that there is a component of extension parallel to the shear-zone, i.e. that the deformation is not simple-shear. It is however possible to disrupt layers during progressive simple-shear. The simple shear case is considered first. For a layer to extend it must lie in the extensional field during simple-shear and this requires rotation of the layer away from parallelism with the shear-zone boundaries. One way of achieving this rotation is to develop folds in the shear-zone. Folds are likely to nucleate at perturbations in bedding, typically those caused by sedimentary structures. The nucleation and development of folds in a layer parallel shear-zone is shown by Lister & Williams (1983). Alternatively, buckling may occur at the tip of a propagating shear-zone. Indeed, low amplitude buckles may be developed well ahead of the prism in the trench-fill sequence. Seismic reflection studies of active margins suggest that barely resolvable deformation occurs in the proto-thrust zone oceanwards of the seismically imaged décollement and other structures at the toe of the prism itself (Karig & Lundberg 1990). Beds therefore may be favourably oriented at the onset of more intense deformation. An alternative to deflecting beds from the shear direction is that any mélange forming extension is 'balanced' by shortening in another part of the shear-zone. This situation was described by Platt & Leggett (1986) albeit in a more coherent accretionary setting. The presence of folds within many mélanges suggests that this is a possible mechanism. Folds were present in all the examples studied often occurring as isolated hinges within the disrupted sequence.

The development of mélanges has been investigated using a simplified 'model mélange'. The investigations centre on the likely strains needed to cause the observed disruption. The amount of stretching $(1 + e)$ in layers inclined at different initial angles to the shear plane was calculated for different values of shear strain (γ) using the equations of Ramsay & Huber (1983) (Fig. 6 and Appendix). A simple rigid domino stretching model (Wernicke & Burchfiel 1982) was then used to estimate the extension $(1 + e)$ in a layer cut by a series of shear

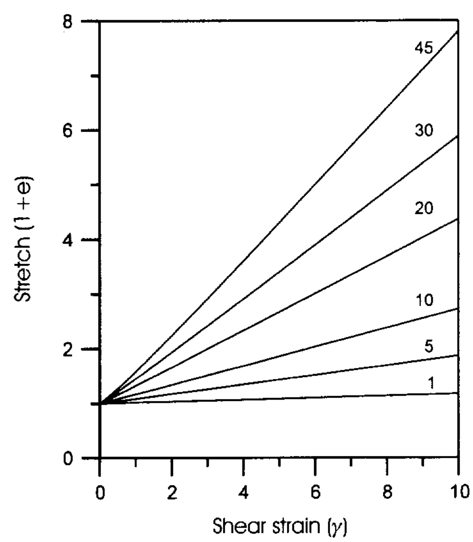


Fig. 6. Graph showing the variation in extension $(1 + e)$ for layers making initial angles of 1, 5, 10, 20, 30 and 45° with the shear plane for increasing values of shear strain (γ).

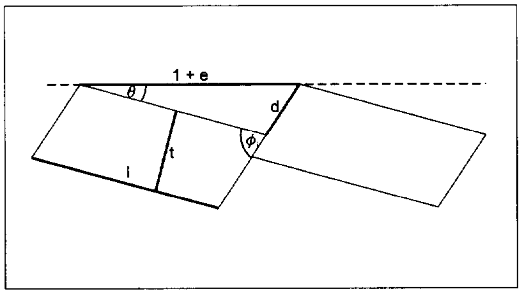


Fig. 7. Rigid domino model showing the parameters used in calculating the extension required to fragment a layer into rhomb shaped mélange blocks.

fractures of displacement d, making an angle (θ) with the layering. The geometry of this model is shown in Fig. 7. The rigid domino model is a simplification, as most mélange blocks are likely to be deformable, but it has the virtue of providing an end-member case which allows an easy assessment of the minimum strain necessary to cause stratal disruption. Blocks showing apparent rigid domino geometry do in fact occur in real mélanges (Korsch 1982). The spacing between the fractures was also varied to give the blocks differing aspect ratios. The results are shown in Fig. 8 in which displacement on the fractures is expressed as a proportion of block length. In all the mélanges studied this aspect ratio was less than 1.0 (length exceeding thickness). Typical values for Southern Uplands blocks range from 0.1 to 1.0 with an average value of 0.3. Similar aspect ratios have also been recorded by Orange (1990) and Kimura & Mukai (1991). Taking the case of a block with an aspect ratio of 0.5 (thickness:length) the displacement required to just separate the layer into blocks is 1.0 for fractures which cut the layer at 30°. This critical displacement value corresponds to a layer parallel stretch of 1.94. The shear strain required to generate such a stretch is variable dependent upon layer orientation but, for the case of bedding deflected away from the shear plane by 10°, is 2.0. Cowan (1990) records shear strains of at least 3.0

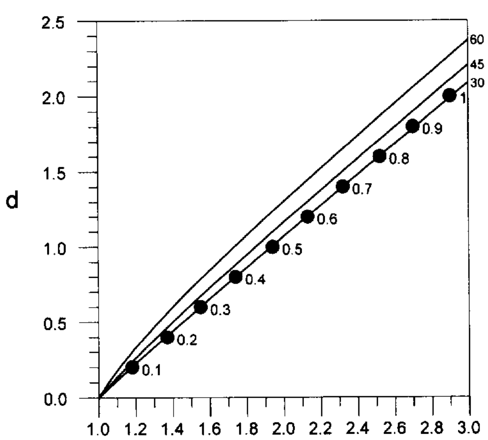


Fig. 8. Graph showing variation in displacement (d) with longitudinal strain ($1 + e$), expressed as a proportion of block length, for fractures making angles of 30, 45 and 60° with the layer. Values on the 30° curve indicate the critical displacement values for blocks with aspect ratios (thickness/length) of 0.1 to 1.0. The values on the other curves are omitted for clarity.

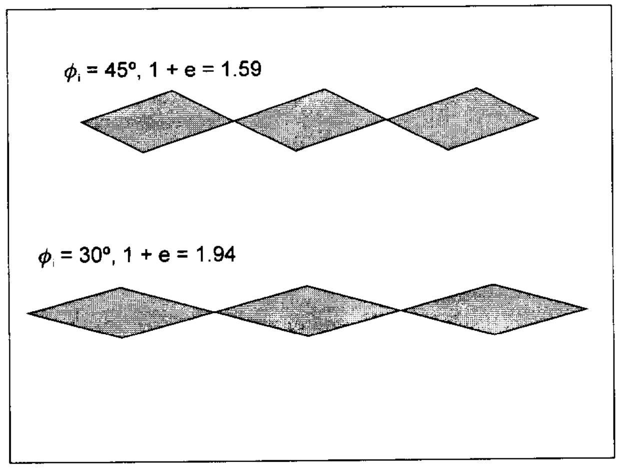


Fig. 9. Two examples of a 'model mélange'. The blocks have aspect ratios of 0.5 are segmented by fracture with initial dips of 30 and 45°, respectively. Note how symmetrical the blocks appear, especially for the 30° example.

from mélanges in the Shimanto Belt. Low amplitude buckles with inter limb angles in the region of 160° would produce this kind of deflection away from the shear plane and could be easily generated within a shear-zone or ahead of the propagating tip. Folds considerably tighter than this are found within all the examples studied and, if their enveloping surface is used to define the shear plane, suggest that deflections considerably larger than 10° can be achieved. Disruption will therefore occur at lower strains. However the folds are finite strain features and it is likely that disruption occurred prior to the folds reaching their final form. Note that in the example shown that once the critical displacement value is reached the blocks appear much more symmetrical (Fig. 9) even when they are rigid and internally undeformed. Deformable blocks are likely to show a higher degree of symmetry suggesting that this geometry is not always easily recognizable in nature.

The critical displacement at which the blocks just become dissociated has been assessed for blocks with aspect ratios varying from 0.1 to 1.0 (Fig. 8). The required displacement and consequently the longitudinal and shear strains increase with block aspect ratio, i.e. with decreasing fracture spacing. For fractures dipping at 30° a longitudinal strain of 2.9 is required to separate a block with a 1.0 aspect ratio compared with 1.19 for a block with a 0.2 aspect ratio. The areas studied show that blocks do not have a uniform aspect ratio within any particular mélange. This implies that the fractures which extend the layers in a mélange are not regularly spaced. Such an observation accords with the findings of Gillespie *et al.* (1993) who studied the spacing of extensional faults and found them to have a fractal distribution. Future studies of mélange forming mechanisms should investigate the size and shape characteristics of blocks in mélanges.

A rigid domino model requires that all the blocks rotate by the same amount at the same rate. This would not be possible in a layer with non-uniformly spaced fractures without internal deformation of the block or variable displacement on the fractures. In this case a layer may extend by separation of the blocks so that their bounding fractures have a dilational component of displacement. This situation is analogous to that described by Jordan (1991) for shale layers pulled apart in evaporite shear-zones. In that case the dilational fractures become filled with sulphates. In a mélange the shale matrix is liable to flow into the space created by the separation of the blocks or mineral veins develop.

The separation of rigid rhomb shaped inclusions was studied by Mandal & Khan (1991) who carried out analogue modelling using asymmetric wooden blocks embedded in paraffin wax. They found that the separation of the blocks was controlled by the block aspect ratio and the dip of the bounding fractures. They also showed that separation occurs when block aspect ratios are uniform. Their analysis was for layer normal compression and the behaviour of blocks when subjected to a component of non-coaxial deformation may be more complex. Figure 10 shows the behaviour of mélange blocks with aspect ratios of less than 1.0, the range which appears to be the norm. The plot is derived from the analysis of Mandal & Khan (1991, equation 27). Layers fragmented by Riedel R_1 shears, which typically make an angle of 30° to the layering, should undergo no separation. Fragmentation should occur purely by shear displacement on the fractures. Layers cut by fractures at angles exceeding 35° will fragment with a component of block separation, i.e. dilation on the bounding fractures. This is for the situation of layer normal compression and the exact position of the 'separation' and 'no separation' fields may change when the deformation is non-coaxial. However, if strain is partitioned between the sand and shale layers, the pure shear case described here will accurately model the fragmentation of a sandstone bed. Deformation in the sandstone layer would be coaxial but the layer would rotate with slip along its bounding surfaces. The likelihood of strain partitioning and some of the resulting structures is discussed below.

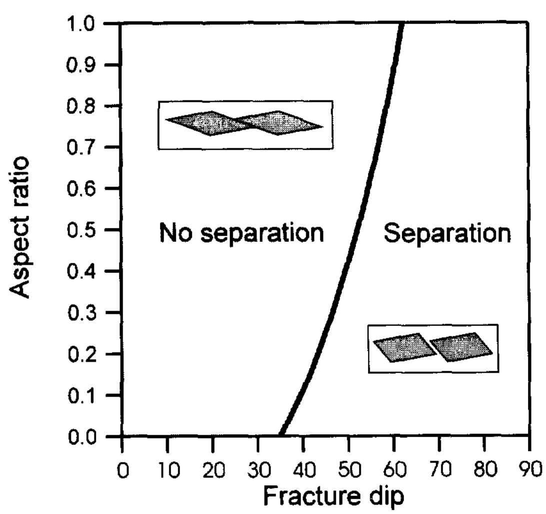


Fig. 10. Plot of fracture dip against block aspect ratio showing derived from the analysis of Mandal & Khan (1991, equation 27). The field in which blocks separate by dilation across their bounding fractures is shown. In the 'no separation' field deformation is accomplished by shear displacement on the bounding fractures.

Once the blocks are dissociated the domino-type model ceases to be applicable unless deformation continues to be localized on to Riedel shear-zones within the shale matrix. In some of the examples studied the deformation remains localized and the scaly shale fabric is cut by a synthetic Riedel shear band. Sandstone blocks continue to be dispersed along these shear-zones. In other cases the deformation of the shale matrix is much more distributed and no shear band is developed. In this latter case the deformation is more likely to be of the type predicted for inclusions in a flowing matrix (Ghosh & Ramberg 1976, Freeman 1985).

Such a model of rotation away from the shear plane may also be applicable to mélange blocks which show evidence of coaxial stretching. Strain partitioning allows a layer to internally stretch and rotate (Platt 1984). This would allow the formation of symmetrical boudins, dilational fractures perpendicular to block long axes and conjugate shear/hybrid fractures at a high angle to bedding. All these structures are present within the mélanges studied. To allow the coaxially deforming layer to rotate and stretch there must be failure and slip at the layer boundary. This is likely to occur in mélanges with slip concentrated at sandstone–shale boundaries. Blocks exhumed from mélanges often have polished or striated surfaces suggesting slip (Moore & Allwardt 1980, Byrne 1984). The scaly fabrics common in the shaly mélange matrix show that inter-layer slip has occurred on a microstructural scale (Agar *et al.* 1989). The presence of layer parallel veins in some of the mélanges studied suggests decoupling between layers probably under conditions of elevated fluid pressure. In the eastern Kyushu example these veins have themselves become disrupted by Riedel shears during progressive deformation.

So far the consideration has been restricted to mélanges formed under conditions of simple-shear. There is however evidence that deformation in mélanges departs from simple-shear (Cowan 1990). One of the major lines of evidence for this is that of strike-parallel extension as indicated by the oblate three-dimensional nature of the blocks in mélanges, a non-plane strain precluding simple-shear. The more symmetrical nature of structures in some mélanges also indicates a component of flattening across the shear-zone, including strike-parallel extension. Previously this has been used to indicate that deformation took place in a near surface slump sheet environment where lateral spreading may occur (Cowan 1982). Possible causes of strike-parallel extension are discussed in a later section. Analysis of deformation in deeper level settings suggests that flattening can occur across a basal shear-zone to a thrust sheet, in the shear direction, the 'dynamic spreading' of Holdsworth & Grant (1990). Whilst reducing the need for a deflection of the layering away from the shear plane it is likely that this is still an applicable mechanism particularly as folds are developed in such zones. The likely cause of a flattening component across the basal shear-zone of an accretionary prism is the shape change in the prism induced by the need to maintain a 'critical taper' (Davis *et al.* 1983, Waldron *et al.* 1988). Evidence for extension within an actively accreting prism has been documented by McIntosh *et al.* (1993). There is evidence for both extension and shortening after the main deformation in the Shimanto Belt. The refolded folds and deformation of the mélange fabric of eastern Kyushu along with the discrete minor thrust faults at Kono on Shikoku indicate shortening. The late stage normal faults on Kyushu indicate extension. These structures may reflect changes in the wedge taper due to variations in subduction rate. Alternative causes may be more local in nature, related to uplift of the Shimanto Belt in this area by partial subduction of the Palau–Kyushu Ridge or by outer-arc bending due to opening of the Sea of Japan marginal basin. When its taper is too low a prism shortens to increase the surface slope. This is possibly achieved by the development of out of sequence thrusts which cut already folded and imbricated units. These thrusts are also important in the disruption of strata and this is considered in the next section. When the taper is too high for the basal shear stress the prism extends. Stretching and spreading of the prism would be accommodated on the basal shear-zone as this decouples it from the subducting plate beneath. The component of pure shear within the basal shear-zone would lead to the development of more symmetrical structures. Layer extension might occur by symmetrical boudinage, Riedel shears with bedding initially lying parallel to the shear plane or steeper conjugate extensional or hybrid shear fractures. Under these circumstances the magnitude of shear strain required to produce a given layer stretch is reduced.

The situation of a layer experiencing a component of pure shear during progressive deformation is modelled and the results shown in Fig. 11. Values of longitudinal strain $(1 + e)$ were calculated for progressive non-coaxial deformation where for every rotational strain increment of 2 (i.e. 2, 4, 6, 8 and 10) there was a stretch parallel to the shear plane of 10 and 20% (Figs. 11a & b, respectively). Using the example of the block with a 0.5 aspect ratio, bounded by 30° fractures forming in a layer inclined at 10° to the shear plane, a critical displacement value of 1.0 to dissociate it from other blocks formed from the layer is predicted. This critical displacement requires a longitudinal strain of 1.94 which is generated by a shear strain of 2.0 in simple-shear. Corresponding rotational plane strains of 1.95 and 1.75 are needed to fragment the layer when there is extension (e) parallel to the shear-zone of 0.1 and 0.2 for every rotational strain increment of 2.0, i.e. less than in simple-shear. Some mélange belts appear to be devoid of folds, (e.g. Cowan 1982) and it is possible that these in particular formed in such circumstances.

One further fracture type which causes stratal disruption is the high-angle (>45°) antithetic fracture. Such fractures have dips opposed to the shear direction and gradually dismember layers during progressive deformation. Examples of these 'bookshelf-sliding' fractures were observed in the disrupted beds at Kono. Such fractures are developed in the longer, more gently

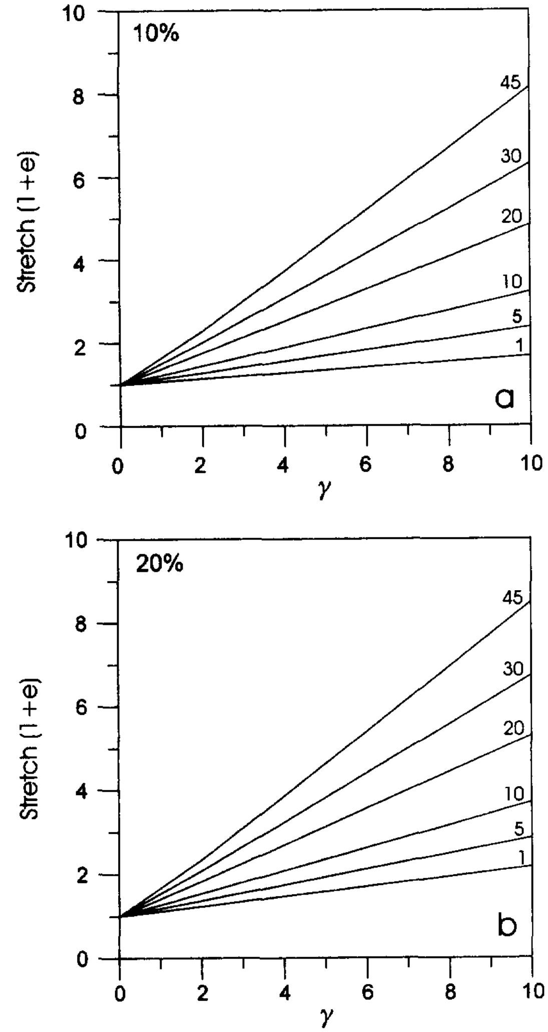


Fig. 11. Graph showing the variation in longitudinal strain $(1 + e)$ for layers making initial angles of 1, 5, 10, 20, 30 and 45° with the shear plane for increasing values of shear strain (γ) but incorporating (a) an increment of 10% and (b) an increment of 20% flattening perpendicular to the shear plane for each increment of shear deformation (2.0).

dipping limb of asymmetric folds during progressive sub-horizontal simple-shear.

'Out-of-sequence thrusts'

'Out-of-sequence' is here defined as relating to a thrust that develops within the prism behind of the active deformation front and cuts through a previously imbricated sequence. These thrusts can be recognized as they may place younger on to older rocks and truncate fold structures. Such thrusts are considered likely in accretionary prisms as they act to shorten the prism and so maintain the critical taper of the wedge in response to changes of basal shear stress (Davis *et al.* 1983, Platt 1986). The suggestion that mélanges may form within out-of-sequence thrust zones was made by Nell (1990) who described such structures from Alexander Island in the Antarctic. In this case the out-of-sequence thrust forms a broad shear-zone through steeply dipping beds which are favourably oriented to undergo extension during progressive shear. Other features in such mélanges include layer normal fractures developed during high fluid pressure episodes. Similar structures, albeit on a smaller scale, are also seen in the Southern Uplands in the disrupted units near Ringdoo Point and Meikle Pinnacle. Bedding can be disrupted in this manner even when there is a high proportion of sandstone in the sequence. Beds within the out-of-sequence thrust zones develop pinch and swell type structures, layer-normal, dilational fractures and conjugate shear fractures with the bisector of their dihedral angle perpendicular to bedding. The small scale structures on Kyushu and Shikoku described above indicate that post-mélange shortening has also occurred in the Shimanto Belt.

Strike-parallel extension

The evidence for strike-parallel extension in mélanges is overwhelming but the mechanism by which it occurs is much less clear. Needham (1987) suggested that differential displacement along parts of the same thrust zone may be a mechanism whereby this strike-parallel extension occurs. One problem with this is the widespread nature of strike-parallel extension. Mélanges occur in long linear belts all of which may show such extension. The cause therefore has to be a much more general one. There is some evidence for arc parallel stretching above active subduction zones (Geist *et al.* 1987, McCaffrey 1991, 1992, Armijo *et al.* 1992). At the surface this manifests itself in the development of normal faults at a high angle to the trench axis. In the case of the Hellenic arc, described by Armijo *et al.* (1992), the extension is thought to be related to changes in plate convergence vector and the onset of collision.

Seismological data reveal extension of the Sumatran forearc and this is ascribed to oblique convergence which causes stretching. The magnitude of this extension appears to be small (McCaffrey 1991, 1992) and the general applicability of the observations to other forearcs is not yet clear. Possibly this deformation is more distributed within the accretionary prism. Whatever the mechanism, it must take place simultaneously with the operation of the accretionary shear-zones (i.e. be part of the strain history of the shear-zones) so that the characteristic oblate blocks form. Presumably any extension of the forearc 'sliver' would be detached from the downgoing plate and therefore transferred onto the basal shear-zone of the accretionary prism. So far, the three-dimensional strain state of mélanges is virtually unknown, mainly due to the lack of suitable markers. Kimura & Mukai (1991) analysed deformed radiolaria and found that the strain they recorded differed from that suggested by the mélanges block shapes. The possibility remains that there may be sufficient lateral spreading in an accretionary prism to allow a component of strike parallel extension. This spreading may be particularly marked and more easily accommodated at outwardly convex continental margins.

CONCLUSIONS

Mélanges exhibit a wide variety of structures indicative of their development in shear-zones. The strains involved in the formation of these structures are within the reasonable range given the displacements on accretionary thrust faults, particularly the basal shear-zone. They also are in accord with the few strain measurements from accretionary prisms. The mechanisms of layer fragmentation are varied, showing that there is no unique mechanism for the formation of mélanges. The mechanisms of fragmentation may vary even within an individual mélange. The degree to which fragmentation occurs and the magnitude of strain required to accomplish this are a function of block aspect ratio and bounding fracture dip. Fragmentation can be accomplished entirely by shear displacement on the bounding fractures/shear-zones but can also involve dilation and separation across these structures. Fracture spacing will decrease and displacement increase with progressive strain causing blocks to be dismembered themselves. The wide variety of mélange structures, even within a single accretionary complex, indicates the operation of a number of controlling factors. Mélanges forming along the basal shear-zone to the prism may experience changes in deformation style as the prism taper reacts to variations in basal shear stress. These changes are triggered by variations in plate convergence rate and direction. Periods of non-coaxial strain including a component of shear-zone parallel extension during taper decrease may be interspersed with increments of simple-shear and even shear-zone thickening. In this situation the deformation history experienced by any mélange would reflect conditions in the prism whilst that shear-zone was active. Once slip was transferred onto a new shear-zone segment by footwall collapse the only deformation experienced would be due to stacking and back-rotation within the prism. Only part of the basal shear-zone will remain active throughout the development of a prism. The other controlling factors are variations in lithification and pore-fluid pressure which will influence the nature and orientation of the mélange block defining fractures/granular shear-zones. Fluid pressure is undoubtedly of great importance but the focus here has been on some of the other processes involved in mélange formation.

Mélanges can also be developed by out-of-sequence thrusts suggesting that their formation can occur during all stages of prism growth. Stable slip on the basal shear-zone and extensional spreading of the prism favour the formation of mélanges in the basal shear-zone itself. Internal shortening of the prism may lead to the formation of out-of-sequence thrust related mélanges. These mélanges would only develop during part of the prism's deformation history and therefore cannot entirely reflect the plate convergence vector. Recognition of mélanges formed in these different settings may provide valuable clues to the evolution of exposed on-land accretionary prisms. For instance, determining the sequence of mélange development within a prism might allow the reconstruction of the plate convergence history.

The recognition that the internal structure of a mélange is not chaotic and is amenable to analysis using the concepts developed during the study of deeper level ductile shear-zones is important. The common but not exclusive association of mélanges with accretionary complexes reflects the nature of sediments in the forearc setting, i.e. interlayered sandstones and shales. Given these starting materials, high pore fluid pressures, high strains and strain rates the disruption of layers to form mélanges along accretionary faults/shear zones becomes very likely.

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APPENDIX

Stretching of layers

The relationship between longitudinal $(1 + e)$ and shear strain (γ) for a line making an initial angle (α) with the shear plane is given by:

$$1 + \mathbf{e} = \sqrt{-\tfrac{1}{2}\gamma^2 \cos 2\alpha + \gamma \sin 2\alpha + \tfrac{1}{2}\gamma^2 + 1}. \qquad \text{(A1)}$$

For simple shear (Ramsay & Huber 1983 p. 285).

Fault displacement–domino model

Displacement (d) on a fault with initial dip (ϕ_i) and length (l) is given by:

$$d = \frac{l \sin \theta}{\cos \{180 - [\phi_i + (90 - \theta)]\}}. \qquad \text{(A2)}$$

Where θ is the dip of the layer. In a rigid domino model this dip is related to the longitudinal strain $(1 + e)$ by:

$$1 + e = \frac{\sin \phi_i}{\sin (\phi_i - \theta)}. \qquad \text{(A3)}$$

Conditions for block separation

The analysis of Mandal & Khan (1991) shows that the ratio (K_r) between the rate of layer segment displacement with respect to an adjacent segment and the rate of layer segment centre displacement as a consequence of rotation is given by:

$$K_r = \frac{R\sec^2(90 - \phi_i) + \tan(90 - \phi_i)}{2[1 - R \tan (90-\phi_i)]} \tan (90 - \phi_i). \qquad \text{(A4)}$$

R is the block aspect ratio (width: length). For values of $K_r \geq 1$ there is no separation between the segments.