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The anatomy and evolution of a transpressional imbricate zone, Southern Uplands, Scotland

Enrico Tavarnelli^{a,*}, Robert E. Holdsworth^b, Phillip Clegg^b,
Richard R. Jones^c, Kenneth J.W. McCaffrey^b

^a*Dipartimento di Scienze della Terra, Università di Siena, Siena I-53100, Italy*

^b*Reactivation Research Group, Department of Earth Sciences, University of Durham, Durham DH1 3LE, UK*

^c*e-Science Research Institute, University of Durham, Durham DH1 3LE, UK*

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Abstract

This paper describes in detail a spectacularly exposed transpressional imbricate zone from the Southern Uplands of SE Scotland. A highly heterogeneous assemblage of contemporaneous structures is preserved and is interpreted to have formed during bulk inclined triclinic sinistral transpression in an obliquely convergent thrust wedge. The resulting structures include a piggy-back imbricate system of closely related strike-slip detachments, highly curvilinear folds, oblique thrust faults and a clockwise-transecting cleavage. A series of sub-domains are recognised, which are interpreted to result from imperfect kinematic partitioning of the bulk transpression into either contraction- or wrench-dominated strains. In this case, the partitioning appears to be controlled by pre-existing lithological anisotropy and how this was subsequently modified by processes such as folding once deformation began. Our findings demonstrate that transpressional deformation zones can develop structural patterns *geometrically* very similar to those found in dip-slip fold and thrust belts. Such geometries are likely to occur in many other obliquely convergent wedges because deformation zone boundaries are very often inclined and lie at low-angles or sub-parallel to regional bedding. Imbricate systems inevitably form because the sedimentary anisotropy is a key mechanical control in their development. Our observations illustrate, therefore, the fundamental importance of measuring fault movement directions in the field using fault slickenline lineations in imbricate systems. It is possible that a number of 'imbricate zones' identified in other thrust wedges may turn out to be transpressional features.

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Keywords: Transpression; Strain partitioning; Fault kinematics; Southern Uplands

1. Introduction

The deformation of much of the Earth's crust is characteristically heterogeneous across a wide range of scales, with displacements typically being localised within interconnected systems of faults or shear zones that bound blocks or lozenges of less deformed material (e.g. Dewey et al., 1986). In orogenic deformation belts where convergence directions are significantly oblique, an additional kinematic partitioning of the transpressional strain into fault-bounded domains dominated by orogen-parallel strike-slip simple shear and orogen-normal shortening strains has now been widely documented (e.g. Oldow

et al., 1990; Molnar, 1992; Tikoff and Teyssier, 1994; Jones and Tanner, 1995; Teyssier et al., 1995; Dewey et al., 1998; Jiang et al., 2001; Jones et al., 2004). It has been variously proposed that such strain partitioning is controlled either by the lithosphere-scale boundary conditions (e.g. Oldow et al., 1990; Molnar, 1992; Teyssier et al., 1995; Tikoff et al., 2002), or by the rheology of the orogenic wedge (Platt, 1993) or due to the presence of weak, pre-existing heterogeneities such as faults (e.g. Mount and Suppe, 1987; Zoback and Healy, 1992; Jones and Tanner, 1995; Vauchez et al., 1998), or by proximity to an obliquely converging indenter (Jezek et al., 2002). Most of these mechanisms refer primarily to crustal-scale processes, but it is pertinent to ask whether a lower limit in scale exists for kinematic partitioning. A number of recent studies have documented such partitioning on mesoscopic (tens of

* Corresponding author. Tel.: +39-577-233984; fax: +39-577-233938.
E-mail address: tavarnelli@unisi.it (E. Tavarnelli).

metres) scales in transpression zones (e.g. Goodwin and Williams, 1996; Tikoff and Greene, 1997; Lin et al., 1998; Holdsworth et al., 2002a). In this paper we document a spectacularly exposed transpressional imbricate zone in the Southern Uplands of SE Scotland, in which strike-slip and shortening displacements are partitioned on metre to centimetre scales. The distribution of strain and evolution of this imbricate zone provide new insights into kinematic partitioning processes, emphasising the all-important controlling influences of pre-existing mechanical anisotropies, especially bedding, on all scales.

2. Geological setting

2.1. The Southern Uplands terrane

The Lower Palaeozoic rocks of the Southern Uplands comprise deformed turbidite sequences divided into elongate, NE–SW-trending tracts by steeply-dipping faults that mostly originated as top-to-the-SE thrusts (Fig. 1; McKerrow et al., 1977). The steeply-dipping rocks generally young northwestwards in each fault-bounded slice, but the age range of strata within each tract gets

younger to the southeast. Complex systems of mainly SE-verging folds and associated top-to-the-SE thrusts occur throughout much of the Southern Uplands (e.g. Knipe and Needham, 1986; Knipe et al., 1988). These structures are associated with very low grade metamorphic assemblages (diagenetic to prehnite–pumpellyite facies: Oliver and Leggett, 1980; Kemp et al., 1985), suggesting that deformation occurred at relatively shallow crustal depths (< 10 km).

Two regional tectonic models have been proposed to explain the development of the Southern Uplands thrust wedge. Many authors favour an accretionary prism hypothesis in which the imbricated fault tracts are derived from off-scraping of sediments from the down-going plate at a long-lived subduction zone on the northern margin of the Early Palaeozoic Iapetus Ocean (e.g. McKerrow et al., 1977; Leggett et al., 1979; Leggett, 1987). Other authors suggest that the region forms part of a back-arc to foreland basin thrust system related to late Ordovician to early Silurian arc–continent collision (e.g. Hutton and Murphy, 1987; Stone et al., 1987; Armstrong and Owen, 2001). Irrespective of their relative merits, both models recognise that the thrust-related structures in the NW tracts formed significantly earlier than those to the SE. This is supported

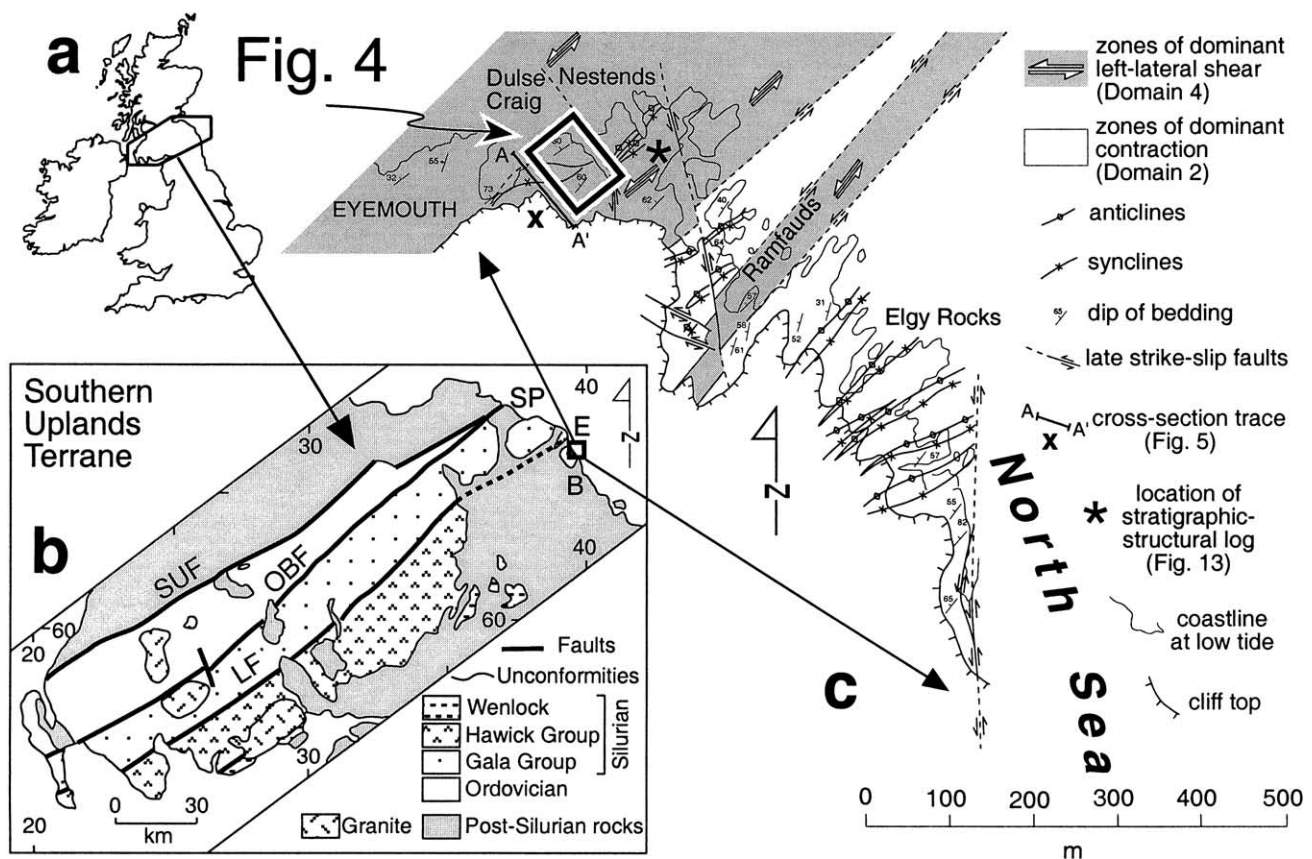


Fig. 1. Location of study area. (a) General sketch of the British Isles, showing the position of the Southern Uplands Terrane. (b) Regional map of the Southern Uplands Terrane showing main tectonostratigraphic units and tract-bounding faults. OBF, Orlock Bridge Fault; SUF, Southern Uplands Fault; LF, Laurieston Fault; SP, Siccar Point; E, Eyemouth; B, Burnmouth. Box shows the location of Fig. 2c. (c) Simplified structural map of the northern part of the Eyemouth–Burnmouth section, between Eyemouth Harbour and Elgy Rocks.

by existing biostratigraphic and radiometric data, which suggest that the onset of thrusting ranges from the Ashgill in the NW through to Wenlock in the SE (Barnes et al., 1989). An additional regional component of sinistral shear becomes important during deformation from the late Llandovery onwards (Anderson and Oliver, 1986; Anderson, 1987; Barnes et al., 1989). In NW tracts, sinistral faults and shear zones, often with associated steeply-plunging minor folds ('F3') are superimposed upon pre-existing thrust-related structures ('F1–F2'). In contrast, in the southeastern parts of the thrust wedge, sinistral shear is contemporaneous with primary deformation ('F1'). This leads to the development of transpressional deformation patterns, often with a distinctively heterogeneous, domainal distribution of structures (Fig. 2; e.g. Holdsworth et al., 2002a, and references therein).

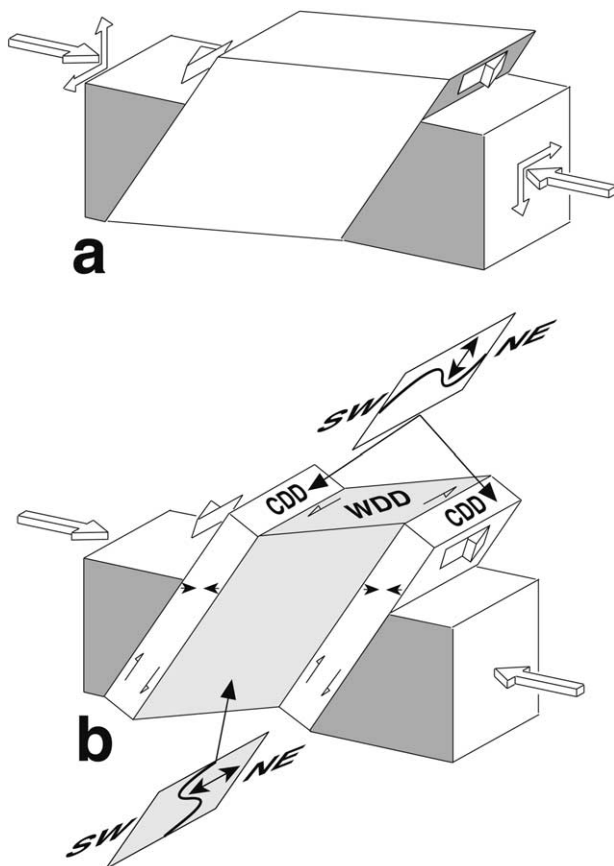


Fig. 2. (a) Schematic 3D model for non-partitioned triclinic transpressional strain. (b) Schematic 3D model where the triclinic transpressional strain is partitioned into end-member wrench dominated (WDD, shaded) and contraction dominated (CDD, unornamented) domains. The panels show fold axial planes and differing curvilinear fold hinge-bedding/cleavage intersection lineation patterns (bold black lines) and inferred stretching axes (double-headed arrows) observed in contraction- and wrench-dominated domains. Orientation provides a reference frame for structures investigated in this study.

2.2. The Lower Palaeozoic rocks of SE Scotland

In SE Scotland, the predominantly Silurian strata of the Southern Uplands terrane crop out in two main areas, both of which are exposed along the Berwickshire coast (Fig. 1; Greig, 1988; Holdsworth et al., 2002a,b). The rocks are all typical turbidite deposits, predominantly comprising inter-layered sequences of greywacke sandstones, siltstones and mudstones. They form the regional basement in SE Scotland and are often bounded by later, steeply-dipping faults, although unconformable relationships with overlying Devonian and younger rocks are locally preserved (e.g. Hutton's unconformity at Siccar Point; Fig. 1).

The most accessible, southernmost coastal section from Eyemouth to Burnmouth (Fig. 1) preserves an apparently unfossiliferous, ca. 2.5-km-thick homoclinal sequence of turbidites that is generally correlated with Upper Llandovery age rocks of the Hawick Group in SW Scotland (MacKenzie, 1956; Sheills and Dearman, 1966; Greig, 1988). Structurally, these rocks display a highly domainal system of sinistral transpressional strain, with zones of steeply-plunging curvilinear folds, clockwise cleavage transection and bedding-parallel sinistral detachment faults (Dearman et al., 1962; Treagus, 1992; Holdsworth et al., 2002a; Jones et al., 2004). Just 5 km to the north, a very different ca. 1.2-km-thick, highly folded turbidite succession is exposed between Siccar Point and Pettico Wick. These rocks are thought to be of Llandovery age based on preserved graptolite fauna and are correlated with the Gala Group in SW Scotland (Greig, 1988). A series of hundreds of metre-scale upright to NW-verging folds consistent with NW–SE shortening affects this sequence and there is no evidence for sinistral shear (Sheills and Dearman, 1966; Greig, 1988; Holdsworth et al., 2002b). The contrast in stratigraphic age and structural style observed in the rocks of these two coastal sections suggests that they must be separated by the along-strike projection of the major tract boundary, the Laurieston Fault seen in SW Scotland (Fig. 1; Akhurst et al., 2001). It seems very likely that this structure corresponds to, and was reactivated by, the normal fault that separates the Silurian rocks south of Eyemouth Harbour from Devonian and Carboniferous strata to the north (Holdsworth et al., 2002b).

The following section summarises the geometric and kinematic characteristics of the well-exposed structures seen in the northern part of the Eyemouth–Burnmouth section between Eyemouth Harbour (National Grid Reference NT 946 645) and Elgy Rocks (NT 952 644) (Figs. 1 and 3). The main body of the paper then focuses on one particularly well-exposed part of that section around Dulse Craig (NT 949 646) (Figs. 4 and 5, for location see Fig. 1). Lithologically, the rocks comprise units of greywacke sandstone, siltstone and shale interlayered on metre to centimetre scales. They preserve abundant way-up criteria, such as graded bedding, cross-laminations, sole markings (flutes and grooves), load casts, ripple marks etc., which

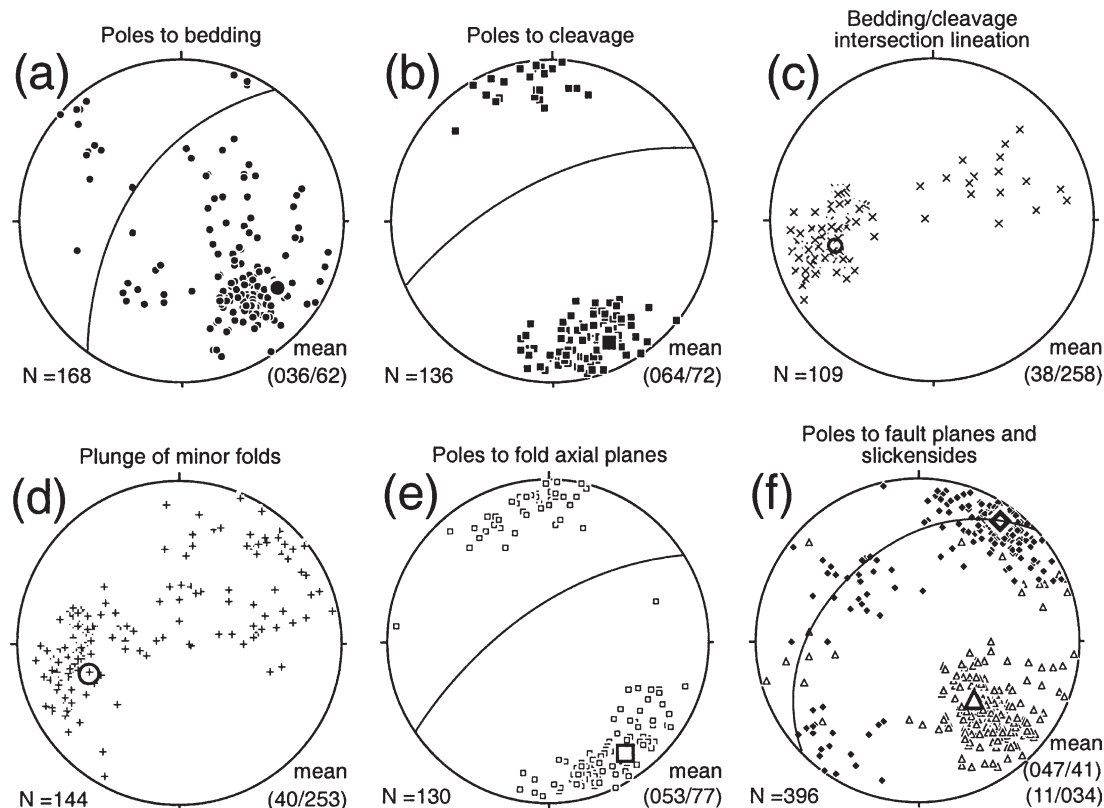


Fig. 3. Generalised orientation data from the wrench-dominated Domain 4 (see Holdsworth et al., 2002a) along the coast between Eyemouth Harbour and Ramfauds (see Fig. 1c for location). Equal area projection, lower hemisphere.

allow structural facing directions to be assessed. Facing is here defined (following Shackleton, 1957; Holdsworth, 1988) as ‘the direction, normal to the fold axis/cleavage-bedding intersection lineation, along the fold axial/cleavage plane and towards the younger beds’. Holdsworth et al. (2002a,b) used fold and cleavage facing directions to highlight the profoundly different structural geometries that exist both between structures developed in the Fast Castle–Pettico Wick and Eyemouth–Burnmouth sections and how these may be used to recognise kinematic partitioning in transpression zones.

2.3. Mesoscopic structures between Eyemouth Harbour and Elgy Rocks

The NNW–SSE-trending coastline to the south of Eyemouth Harbour preserves an almost completely exposed section through a generally NW-dipping, right-way-up sequence of turbidites. Holdsworth et al. (2002a) demonstrated that the deformation patterns are heterogeneous, defining a number of NW–SE-trending, often fault-bounded domains (labelled 1–4) in which geometrically and kinematically different sets of structures—all of broadly the same age—are recognised on centimetre to hundreds of metre scales.

In the northernmost part of the section, between Eyemouth Harbour and Elgy Rocks (Fig. 1), very different

structural geometries occur within two alternating zones corresponding to Domains 2 and 4 of Holdsworth et al. (2002a). These are summarised in Table 1.

The upright to slightly SE-vergent, upward-facing whaleback folds of Domain 2 are interpreted by Holdsworth et al. (2002a) to result from predominantly sub-horizontal NW–SE shortening with a subordinate component of top-to-the-SE dip-slip shear, i.e. a contraction dominated strain. In contrast, the dominance of interlinked sinistral detachments in Domain 4 was taken to indicate an overall wrench-dominated strain. Thus, it was proposed that in this northerly part of the section, the regional bulk triclinic sinistral transpressional strain (Fig. 2a) was kinematically partitioned into monoclinic end-member domains of strike-slip simple shear and non-coaxial dip-slip shortening (Fig. 2b; see Holdsworth et al., 2002a; Jones et al., 2004). The preservation of small components of sinistral shear associated with NW-dipping thrusts and bedding-parallel flexural slip slickenlines in Domain 2 (see Table 1) were taken as evidence that the partitioning of strain was not perfect. It was also noted that metre-scale partitioning of strain could be recognised within Domain 4 (see below).

Late, cross-cutting structures include steeply-dipping, possible conjugate strike-slip faults that everywhere post-date the folds and detachments (e.g. Figs. 1 and 4). These are often associated with prominent zones of white, carbonate-cemented breccia up to 1 m wide and metre-scale brittle

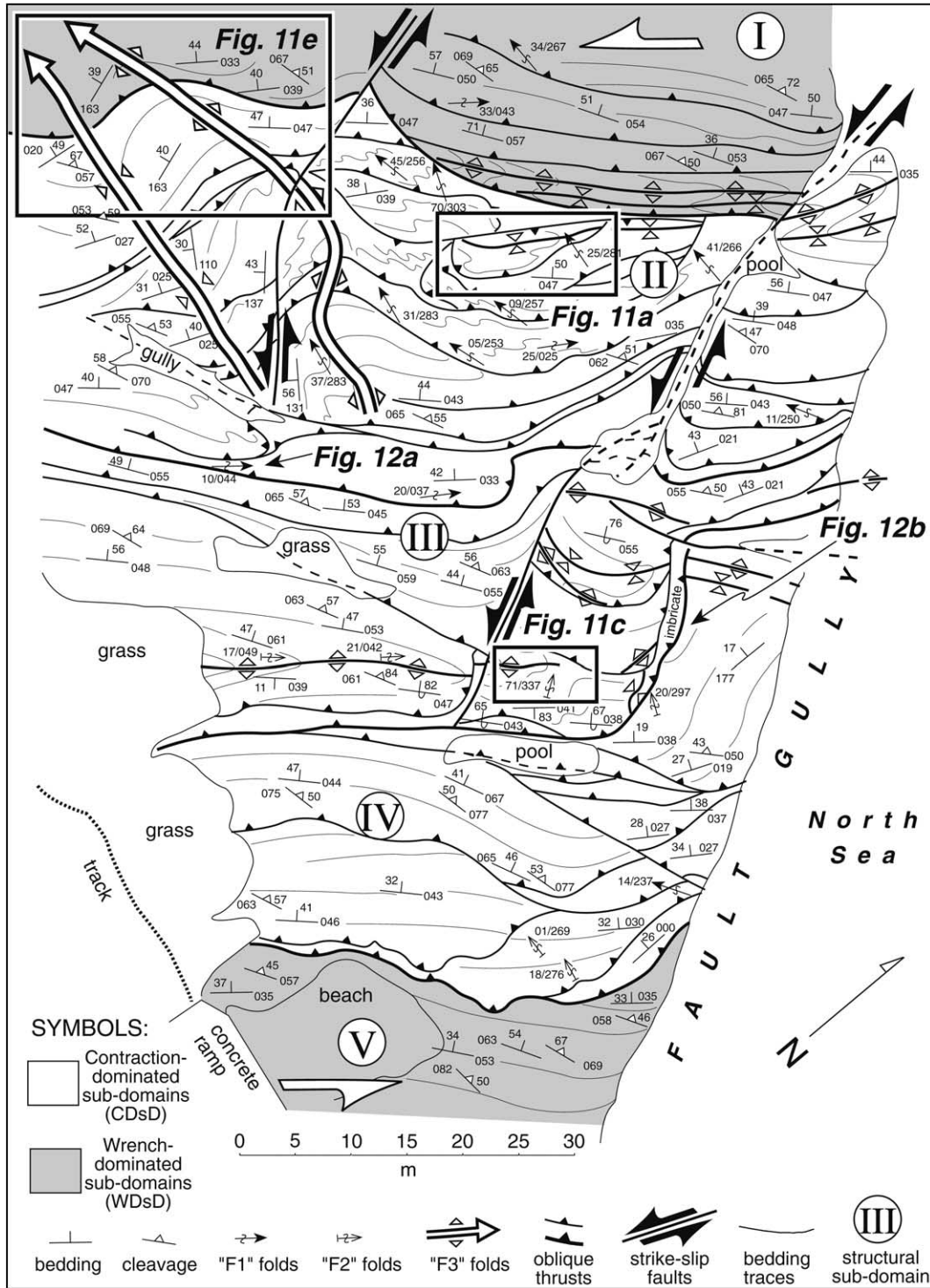


Fig. 4. Detailed structural map of Dulse Craig (centred around NT 949 646; see Fig. 1c for location). Sub-domains I–V in this study are indicated.

kink folds. Sinistral faults trend mainly N–S whilst dextral faults trend NW–SE and, collectively, they appear to be consistent with NNW–SSE contraction. These faults may individually accommodate displacements in excess of 10 m, and have locally influenced the present coastal morphology, controlling the location and trend of many prominent gullies (Figs. 1 and 4). The age of the steep faulting is uncertain and

may be related to younger deformation episodes (see Holdsworth et al., 2002a).

A compilation of orientation data from Domain 4 is provided in Fig. 3. Right way-up bedding dips mainly towards the NW (mean 036/62 NW; Fig. 3a) and is cross-cut in a predominantly clockwise sense by a generally more steeply-dipping slaty to spaced pressure-solution cleavage

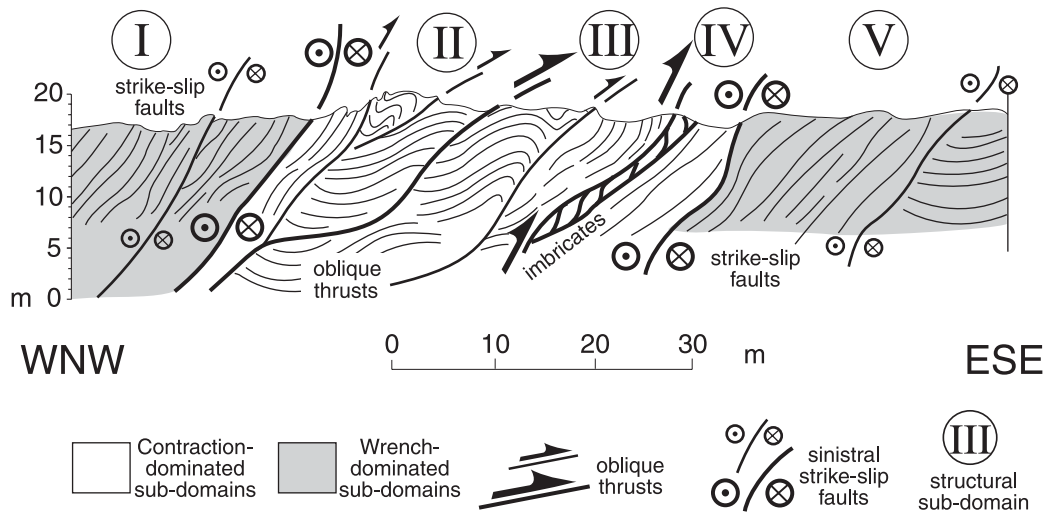


Fig. 5. Composite cross-section constructed along the SW edge of the detailed map of Fig. 4 (see Fig. 1c for location).

(mean 064/72 NW; Fig. 3b). Bedding/cleavage intersection lineations are well preserved on bedding surfaces, with a predominant WSW plunge (mean 38/258; Fig. 3c), although this is locally variable. Similarly, a majority of minor folds plunge moderately towards WSW (mean 40/253; Fig. 3d) and face obliquely upwards to the SW. Fold hinges are often markedly curvilinear, locally displaying almost 180° of curvature on metre- to centimetre-scales, passing through the horizontal, where they face upwards and to the SE, round into steeply plunging, sideways to slightly downward SW- or NE-facing orientations (see fig. 6d of Holdsworth et al., 2002a). Statistically, minor fold axial surfaces (mean 053/77 NW; Fig. 3e) are clockwise transected by the cleavage, and transected folds are well exposed in a number of localities (see below). Brittle detachment faults are one of the characteristic and dominant structures in this domain, lying sub-parallel to bedding or cross-cutting at low angles (mean 047/41 NW; Fig. 3f). The great majority of associated slickenline lineations plunge predominantly shallowly NE (mean 11/034; Fig. 3f) and are everywhere associated with sinistral, top-to-the-SW shear sense indicators, with a slight reverse slip component.

In their original analysis, Holdsworth et al. (2002a) tentatively suggested that the bulk triclinic transpressional strain in Domain 4 had partitioned into metre-scale domains of contraction-dominated strain with generally SE-verging curvilinear folds, which were bounded by an interconnected system of sinistral strike-slip detachments. In the next section, we document the structural relationships in more detail in order to test the validity of this proposal and gain insights into what might cause strain partitioning to occur on such a small scale.

3. The structural architecture of Dulse Craig

Structures and rocks typical of Domain 4 are best

exposed in a wave-cut platform between Dulse Craig and Nestends, ca. 500 m east of Eyemouth Harbour (Fig. 1). Fig. 4 shows a detailed geological map originally surveyed by cairn mapping at 1:200 scale, centred around map reference NT 949 646. To further illustrate the three-dimensional geometry and inter-relationships of the various structures preserved, Fig. 5 shows a composite ESE–WNW cross-section constructed in the field along the SW edge of the mapped area (see Fig. 1 for location), whilst Fig. 6 presents separate maps of the four main structural elements: bedding, cleavage, folds and faults. In common with much of the Eyemouth section on a regional scale, the Dulse Craig area can be conveniently divided into five smaller-scale sub-domains (labelled I–V), each of which is characterised by internally consistent structures in terms of their style and orientation (Fig. 7). All domains are bounded by sinistral-oblique detachment faults parallel to, or cross-cutting, bedding at low angles. Overall, this well exposed area (Fig. 8a) is characterised by asymmetric folds (Figs. 8b and c and 11a), a cleavage, which is best developed in shale units (e.g. Figs. 8c and d, 9a and 11b and c), and interlinked, imbricate systems of sinistral oblique thrusts (Figs. 8b, e and f, 9b–f, 11b and 12a and b), extension faults and pull-aparts (Fig. 10a–f). With the sole exception of sub-domain V, where folds were not found, most of the aforementioned structures occur within all five sub-domains. Two distinct types of sub-domains are recognised: wrench-dominated (I, V) and contraction-dominated (II, III, IV).

3.1. Wrench-dominated sub-domains

Wrench dominated sub-domains are predominantly homoclinal regions of moderately to steeply NW-dipping right-way-up strata (Fig. 7ai and ei), uniformly cross-cut in a clockwise sense by the cleavage (Figs. 7aii and eii and 9a) with mainly WSW-plunging intersection lineations (Fig. 7aiii and eiii). Cleavage facing directions are predominantly

Table 1
Summary of structures in Domains 2 and 4 in the Eyemouth section

	Domain 2	Domain 4
General structure	Right way-up sequence folded by NW–SE-trending folds.	Homoclinal, dipping moderately and younging to NW.
Fold geometry and scale	Slightly asymmetric, SE overturned folds. 10 m- to metre-scale.	Mainly asymmetric, SE overturned folds. Mainly metre-scale.
Fold/cleavage–bedding intersection plunge pattern	Mainly shallow SW to locally NE plunges, passing through horizontal; minor curvature ($< 30^\circ$).	Moderate SW to moderate NE plunges, passing through horizontal; up to 180° curvature.
Fold–cleavage relationship	Clockwise transected.	Clockwise transected.
Facing patterns	Mainly SW and steeply upwards.	Mainly sideways SW or NE or upwards to SE.
Bedding-parallel faults	ACW oblique flexural slip.	Not distinguished from detachments.
Detachment geometry and kinematics	Conjugate thrusts in hinge regions of some folds, with component of sinistral shear on NW-dipping thrusts. Bedding-parallel set absent.	Generally bedding-parallel with well-defined R and P ramps. Dominantly sinistral with subordinate set showing dip-slip NW-side-down movements.

sideways and to the SW. Refraction is common, so cleavage traces typically lie clockwise of bedding between 10° in shales and 40° in sandstone units, with curved cleavage trajectories well-displayed in graded units. Compared with the contraction-dominated sub-domains, relatively few minor folds are found in wrench-dominated sub-domains, and where present (sub-domain I), they tend to be small, steeply-plunging, sideways SW-facing structures (Fig. 7*ai* and *av*).

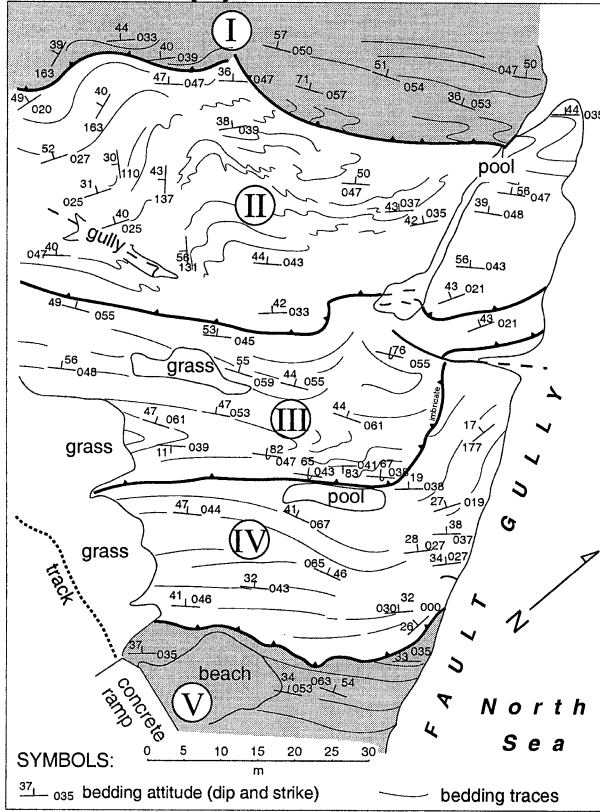
The predominant structures in sub-domains I and V are sinistral detachment faults (Figs. 7*avi* and *evi*, 9*b–d* and 10*a–f*) where the trends of the mean detachments are exactly parallel to the mean bedding trends (039 and 043 in sub-domains I and V, respectively; Fig. 7*ai*, *avi*, *ei* and *evi*). Most detachments are associated with pink carbonate mineralization which occurs either as slickenfibres along detachment surfaces or as infills of Mode I tensile veins and sinistral pull-apart features lying at high angles to bedding (e.g. Fig. 10*b–e*). The mean slip vectors inferred from slickenfibres along detachment surfaces plunge shallowly NE suggesting a slight reverse component of slip in addition to the dominant left-lateral sense of movement (Fig. 7*avi* and *evi*). Adjacent bedding-parallel detachment surfaces are often linked by arrays of short ramps that lie either clockwise (e.g. Fig. 9*b–f*) or anticlockwise (Fig. 10*a*, *e* and *f*) of layering, respectively, shortening or extending bedded units. Geometrically, these features appear to correspond to contractional and extensional duplexes as defined by Woodcock and Fischer (1986).

The relative abundance of sinistral detachments is well illustrated by a graphic log (Fig. 13) measured in a 100% exposed section through the along-strike continuation of sub-domain V, 40 m to the NE of the area mapped in detail (see location in Fig. 1). In this 50-m-thick section, 92 detachments are recognised. The general parallelism of detachments with bedding often makes it difficult to estimate the amount of strike-slip offset along many of these faults. Bedding cutoffs are more easily recognised across ramps, with individual faults typically showing offsets in the range 10–100 cm (e.g. Figs. 9*b* and *e* and 10*a* and *f*). If these values are representative of all 92 faults logged in the 50-m-section, it would suggest that collectively they display predominantly sinistral displacements of between approximately 10 and 100 m. In reality, however, it seems likely that the displacements along the bedding-parallel faults are significantly higher, perhaps by an order of magnitude or more.

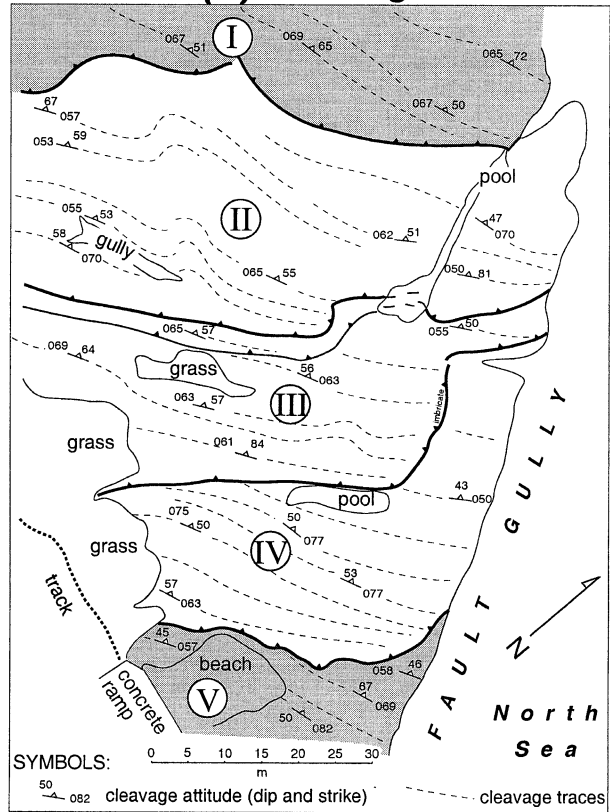
3.2. Contraction-dominated sub-domains

The structures found in contraction-dominated sub-domains II, III and IV are mainly folds (on centimetre- to metre-scales) and sinistral-reverse detachments (Figs. 8*b–f*, 11*a–d* and 12*a* and *b*). Bedding once again is overall homoclinal dipping to the NW, but poles are typically spread out along a girdle due to the effects of folding

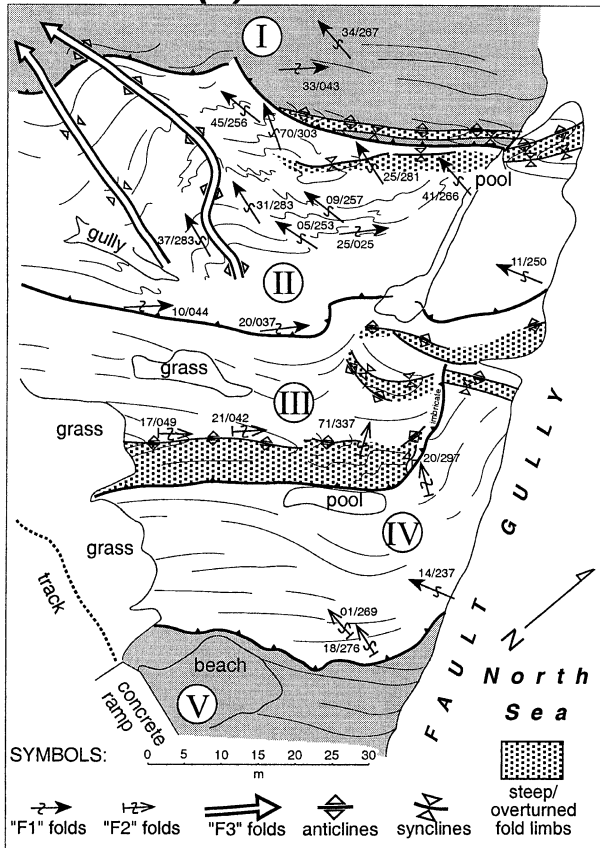
(a) - Bedding



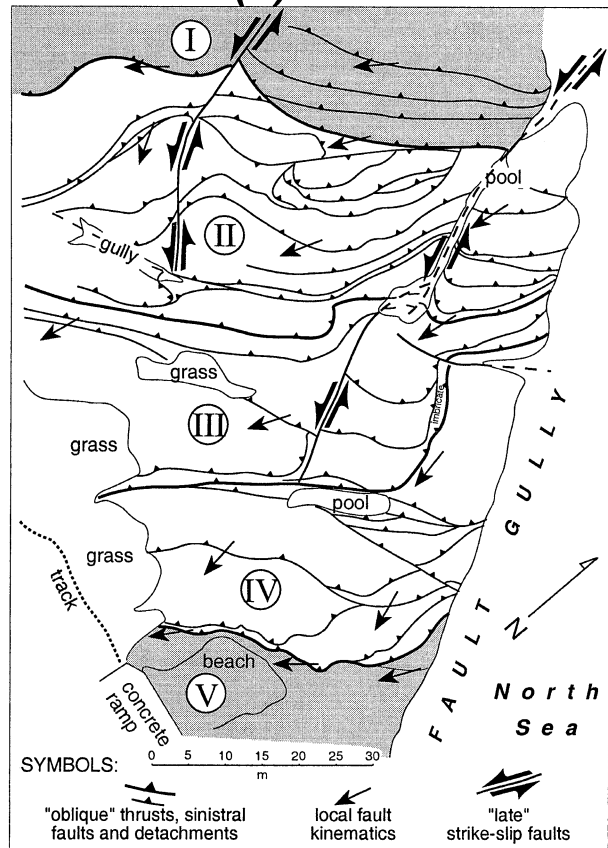
(b) - Cleavage



(c) - Folds



(d) - Faults



(Fig. 7bi, ci and di). Cleavage is well-developed (e.g. Figs. 8c and d, 11b and c and 12a and b) particularly in the shale intervals separating sandstone beds. Compared with the wrench-dominated domains, cleavage dips more steeply and clockwise transects both bedding and fold axial planes (Fig. 7b–d). Detachment faults dip mostly NW, with mean trends close to that of bedding (Fig. 7bvi, cvi, dvi). All detachment faults are characterised by sinistral oblique-reverse kinematics, but compared with the wrench-dominated sub-domains, the pitch of the pink carbonate slicken-fibre lineations is significantly (25–30°) steeper (compare Fig. 7avi and evi with Fig. 7bvi, cvi and dvi; see also Fig. 6d) suggesting a greater degree of dip-slip movement. Hereafter, we refer to these faults as *oblique thrusts*.

Folds range in wavelength from several centimetres to 10 m or more (Figs. 4, 5 and 6c). They are typically SW–NE-trending anticline–syncline pairs (e.g. Figs. 8b and 12a and b), that may be traced for over 40 m in map view (e.g. Figs. 4 and 6c). Mean minor fold axes plunge shallowly WSW in all three sub-domains (Fig. 7biv, civ and div). In detail, however, the fold hinges are markedly curvilinear on centimetre- to metre-scales, passing through the horizontal, where they face upwards and to the SE, swinging round into steeply plunging, sideways to slightly downward SW- or NE-facing orientations (e.g. Figs. 4, 6c and 11a). Normal fold limbs dominate over steep-to-overturned limbs (shown ornamented in Fig. 6c), illustrating the overall SE-vergence sense of the folds. Many folds are clockwise transected at low angles (<10°) by their associated cleavage. Folds and oblique thrusts are often intimately related. For example, oblique thrusts are often preserved branching from bedding-parallel décollements and terminating upwards in tip points within asymmetric fold pairs (e.g. Fig. 8b and e). The geometry of these structures is consistent with that predicted by tip-line folding (Elliott, 1976) or fault-propagation folding (Suppe, 1985) models.

The relative age relationships between folds, cleavage and oblique thrusts are locally complex and variable in sub-domains II–IV. Thus it is possible to separate three sequentially younger fold sets, here termed 'F1', 'F2' and 'F3'. The main structural features of each fold set, illustrated in both map and cross-sectional views, are summarised in Fig. 11. F1 folds occur throughout sub-domains II, III and IV, but are most common in sub-domain II. In cross-section views the cleavage appears parallel to minor fold axial surfaces (Figs. 8c and 11b) and only clockwise transects in plan view. F2 folds are most abundant in sub-domain III, and to a lesser extent in sub-domain IV, where they locally re-fold the main cleavage (e.g. Figs. 8d and 11c and d). In both cases, F2 folds show a close spatial association with the sub-domain basal detachments (e.g. Fig. 6c). In sub-domain II, examples of both F1

and F2 minor structures are re-folded by an E–W-trending, steeply W-plunging pair of F3 folds (Figs. 6a–d, 8f and 11e and f). These F3 folds also overprint oblique-thrusts in sub-domain II and sinistral detachments in the overlying sub-domain I (Fig. 11e). Similar locally polyphase deformation sequences have been described elsewhere in the Southern Uplands (e.g. Knipe and Needham, 1986; Fig. 11).

As with the folds, structural overprinting relationships make it possible to infer local polyphase sequences of fault propagation, especially where multiple detachments are located at different stratigraphic levels. In these cases, structurally higher detachments are usually folded by structures rooting downward into blind oblique thrusts emanating from lower detachments (e.g. Fig. 12a). Sometimes shallow, low-angle detachments are breached by steeper, deeper thrusts (Fig. 9e). These observations collectively indicate that younger oblique thrusts typically developed in piggy-back sequences.

The boundary between sub-domains III and IV corresponds to a well-exposed imbricate thrust stack bounded by gently NW-dipping detachments (Figs. 4, 5 and 12b). The imbricate thrust stack (Fig. 12b) consists of minor contractional structures, such as S-verging minor folds (Fig. 8e), NW-dipping oblique thrusts and subsidiary SW-dipping backthrusts (Fig. 10a). The contractional imbricate structures are locally truncated by sub-horizontal or gently SE-dipping, locally extensional faults, that produce top-to-the-S displacements.

3.3. Summary

Despite the generally homoclinal, NW-dipping nature of the sequence, the Dulse Craig section preserves a highly heterogeneous and complex assemblage of structures. An interlinked system of generally bedding-parallel sinistral detachments and oblique thrusts are developed on centimetre to tens-of-metre scales, imbricating bedding and isolating generally SE-verging, upward-facing fold pairs with locally highly curvilinear hinge zones. In most of the area, a single set of folds is recognised, clockwise transected at low angles by a well-developed cleavage. However, very localised refolding of cleavage and detachments is also preserved. In at least some cases, these features can be shown to result from sequential propagation along oblique thrusts at different structural levels, with several examples of piggy-back relationships preserved. Collectively, all of the structures suggest important components of top-to-the-SW sinistral shear, NW–SE shortening and top-to-the-SE thrusting, i.e. an inclined bulk triclinic sinistral transpression (cf. Fig. 2). The deformation appears to be partitioned into fault-bounded sub-domains of wrench- or contraction-dominated deformation characterised by imbricates of,

Fig. 6. Thematic maps of Dulse Craig, based on the structural map of Fig. 4, showing the distribution of bedding (a), cleavage (b), folds (c) and faults (d). Wrench-dominated sub-domains I and V are shaded, whereas contraction-dominated sub-domains II–IV are unornamented.

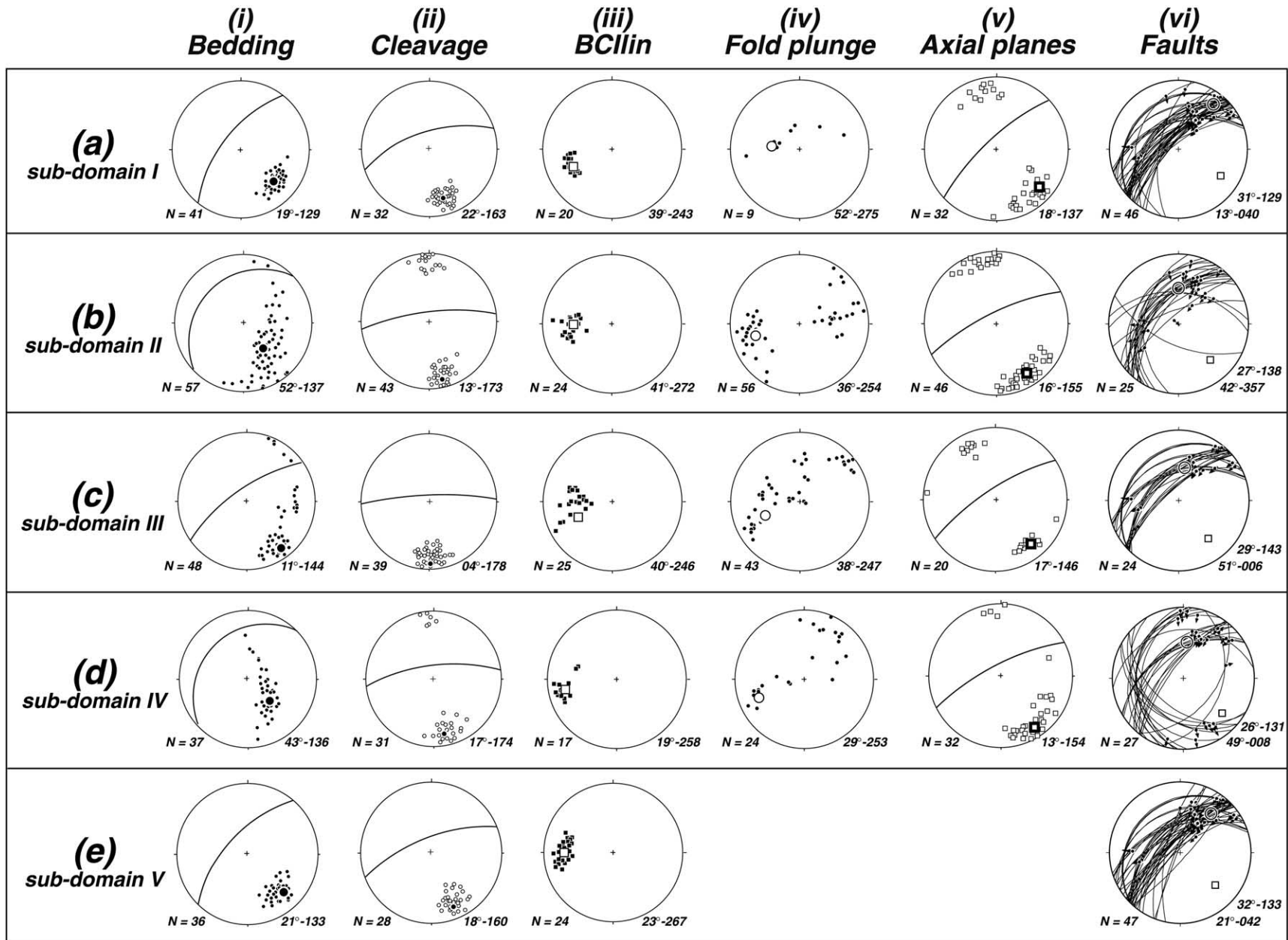


Fig. 7. Orientation data from sub-domains I–V at Dulse Craig. Equal area projection, lower hemisphere.

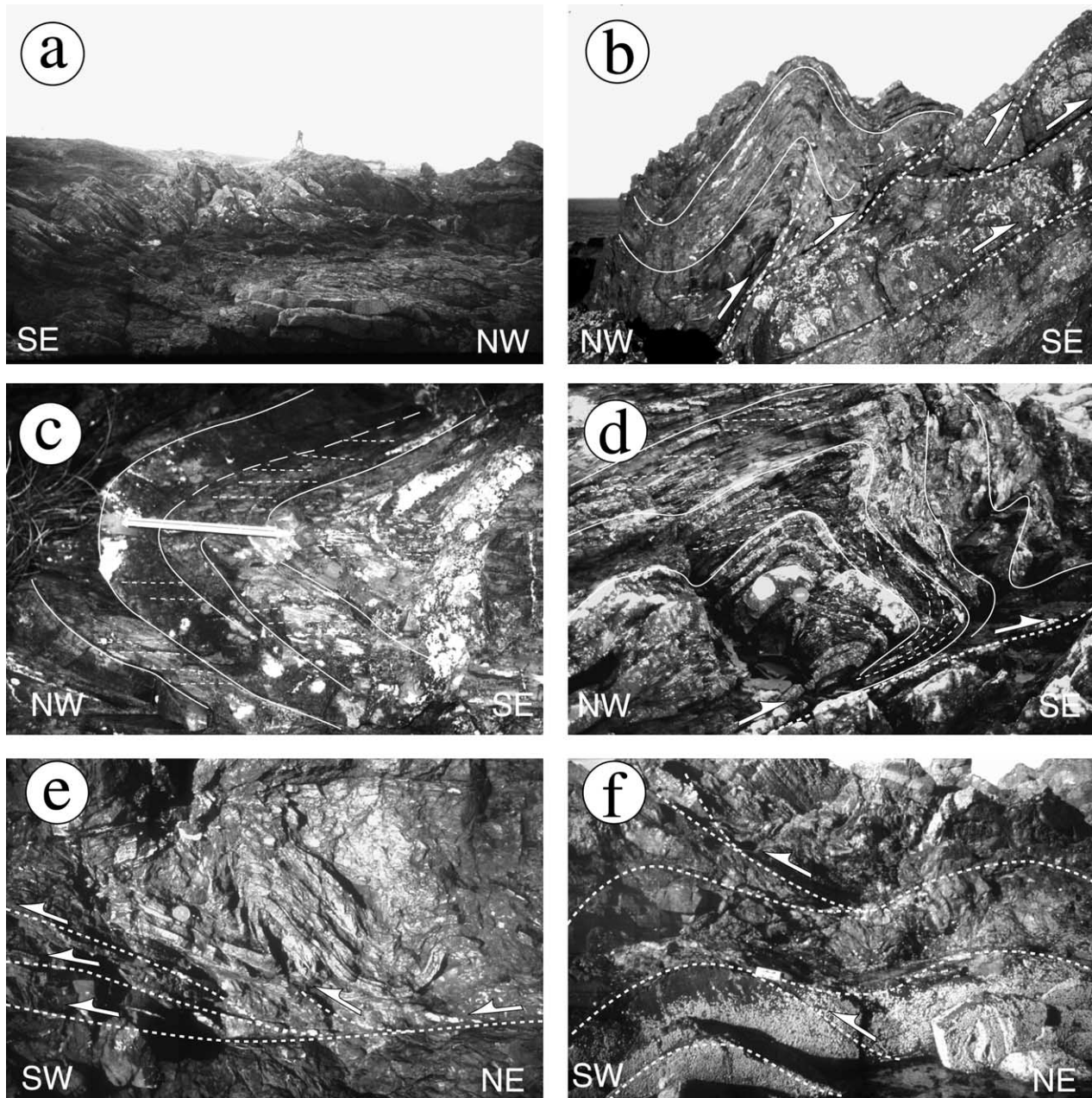


Fig. 8. Structural features of folds at Dulce Craig. (a) General overview of the area mapped in Fig. 4. (b) Asymmetrical, SE-verging and upward-facing $F1$ thrust-related folds in sub-domain II. (c) Cleavage distribution in the hinge of a minor $F1$ fold in sub-domain II. (d) Cleavage refolding in the hinge of a minor $F2$ fold in sub-domain III. (e) Minor folds developed above sinistral detachment faults (part of the imbricate structure illustrated in Fig. 12b). (f) Detachment faults deformed by $F3$ steeply NW-plunging folds.

respectively, top-to-the-SW sinistral detachments and top-to-the-S sinistral oblique thrusts and curvilinear, generally SE-verging folds.

4. Discussion

4.1. Transpressional imbricate zones

Linked, imbricate fault systems have long been recognised in both thrust and extensional settings (e.g. Boyer and

Elliott, 1982; Gibbs, 1984). Despite some attempts to extend these concepts into strike-slip settings on a regional scale (e.g. Woodcock and Fischer, 1986), relatively few strike-slip or transpressional imbricate zones have been described on a mesoscopic (i.e. outcrop) scale (e.g. see Laney and Gates, 1996). The traditional view is that most strike-slip faults will form as sub-vertical structures and will therefore lie at high angles to layering in most bedded sequences (e.g. Woodcock and Fischer, 1986). Thus, many strike-slip fault zones (s.l.) are thought to be characterised by faulting patterns more typical of rheologically isotropic materials

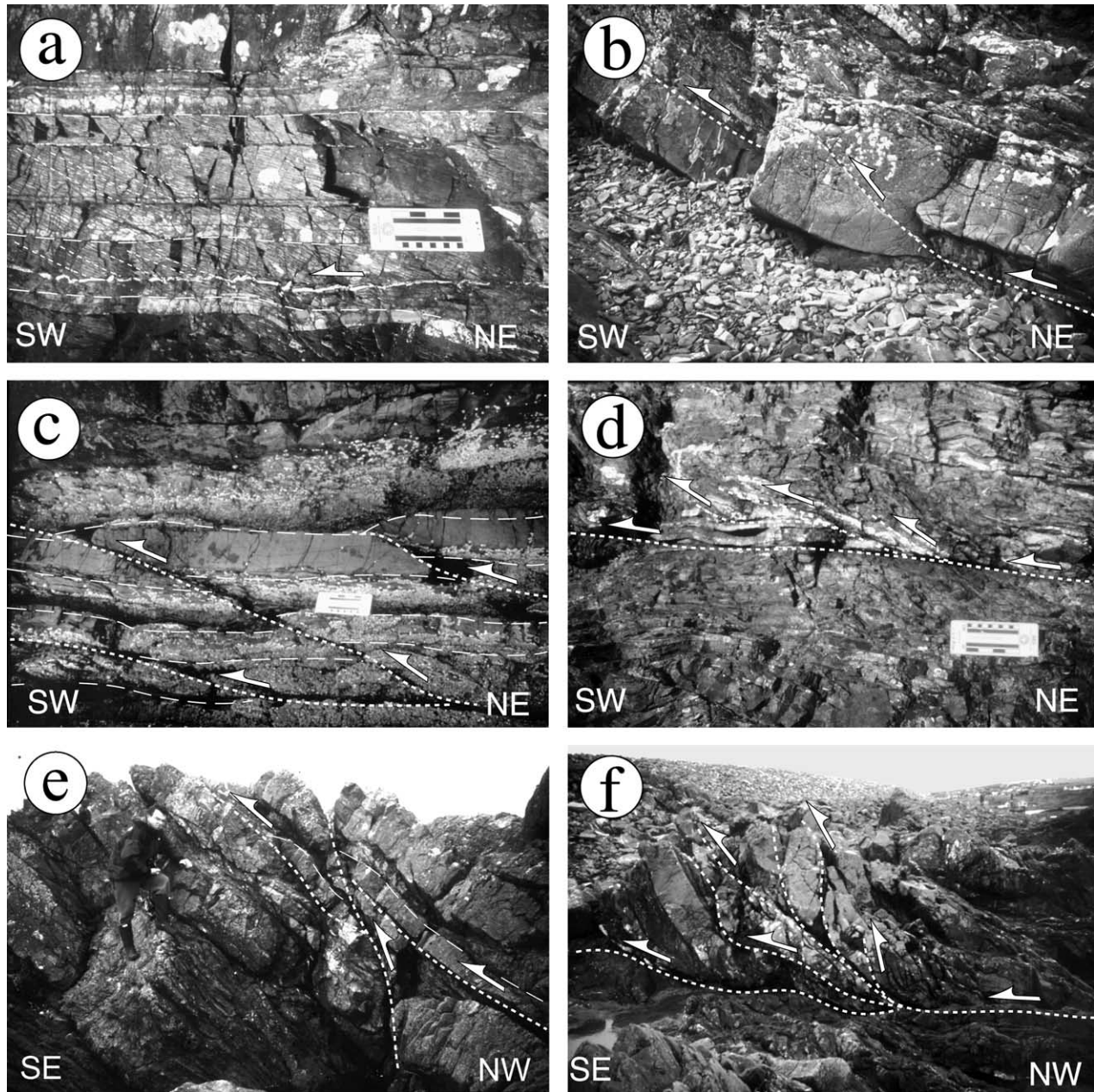


Fig. 9. Structural features of faults at Dulce Craig. (a) Cleavage (finely dashed) and bedding-parallel detachments (dashed) developed within steeply-dipping mudstone layers in sub-domain V. (b) Minor ramp developed across a sandstone bed, connecting two bedding-parallel flats localised within mudstone horizons in sub-domain V. (c) Minor sinistral strike-slip duplex. (d) Minor sinistral oblique thrusts emanating from a bedding-parallel detachment. (e) Breaching of a bedding-parallel oblique thrust by a steep reverse fault. (f) Minor oblique thrust array: the geometrically highest faults are systematically steeper than the geometrically lower faults, indicating a general piggy-back sequence of detachment propagation.

(e.g. Tchalenko, 1970; Wilcox et al., 1973). Once displacements begin to accumulate, kinematic controls related to strain compatibility arise, eventually leading to the development of disorganised braided geometries or more diffuse, domainally-distributed conjugate strike-slip fault systems in which differential block rotations about vertical axes occur (e.g. Garfunkel and Ron, 1985; Woodcock, 1987; Dewey, 2002).

The linked detachment faults and associated folds of the Dulce Craig area clearly formed in a transpressional

deformation system with very significant amounts of sinistral strike-slip displacement, yet they show many geometric similarities with fold-and-thrust systems found in dip-slip thrust belts. The overall parallelism of the detachment systems with the well-defined bedding demonstrates that sedimentary anisotropy is a central mechanical control in the development of imbricate fault systems. In our view, this parallelism is not simply fortuitous—it is almost inevitable in any obliquely convergent accretionary thrust wedge where deformation zone (e.g. thrust tract) boundaries

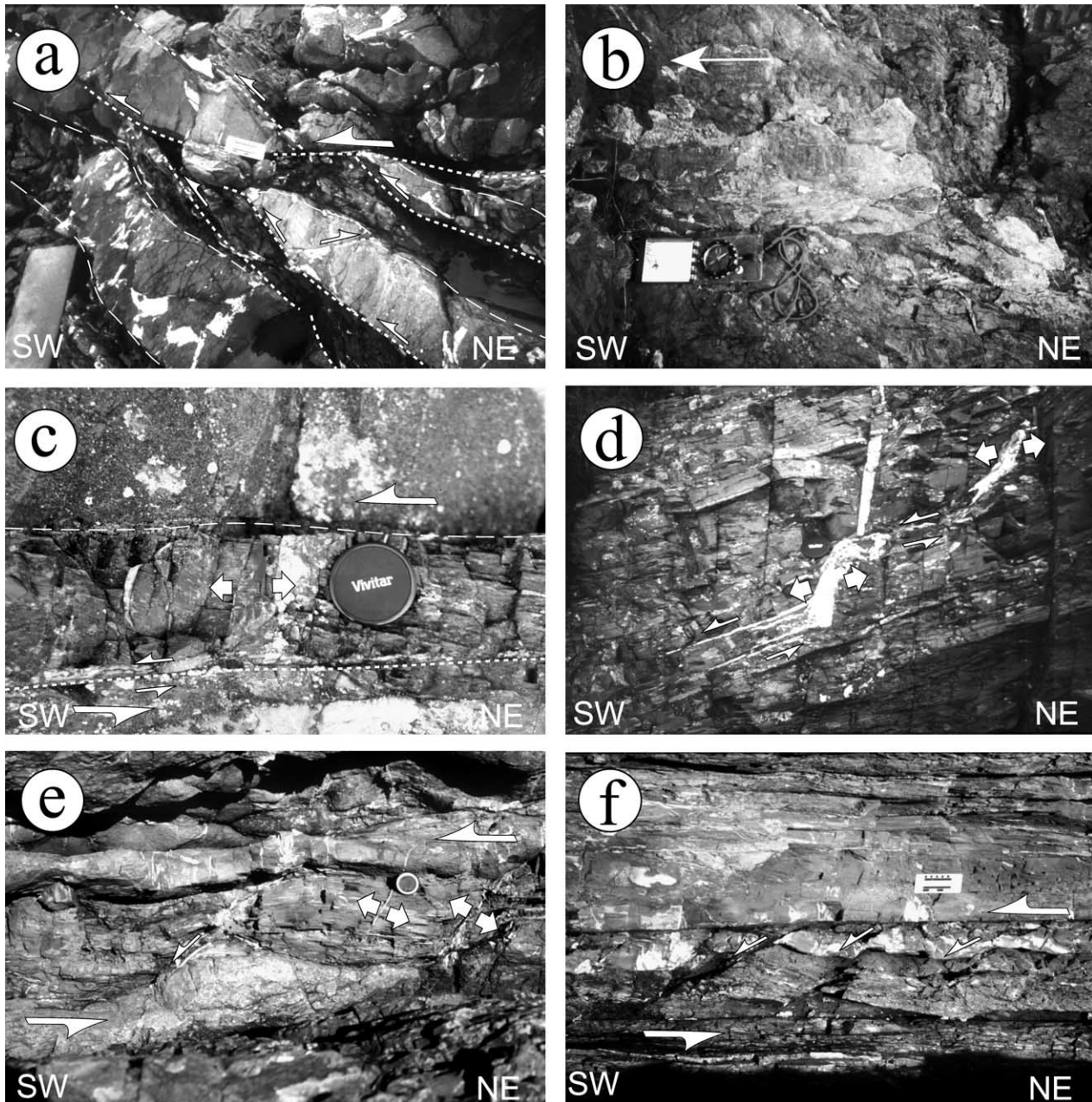


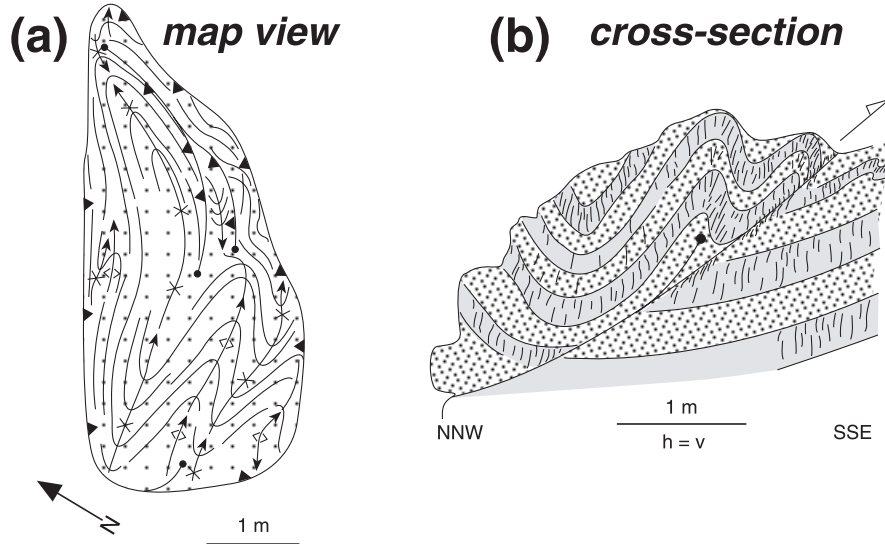
Fig. 10. Kinematic features of faults at Dulce Craig. (a) Complex fault array, resulting from the superposition of later sinistral faults onto a pre-existing imbricate. The former faults lie anticlockwise, whilst the latter faults lie clockwise of layering, respectively, extending and duplicating bedding (particularly of the structure illustrated in Fig. 12b). (b) Mechanical striations and slickenlines on a fault surface, indicating sinistral strike-slip kinematics. (c) Mode I tensile veins developed across a sandstone bed, and passing downwards into a sinistral, bedding parallel shear vein developed within a mudstone horizon. (d) Mode I tensile vein linking two sinistral strike-slip faults and defining a pull-apart structure. (e) Sinistral asymmetric boudinage developed within sandstone and mudstone layers: note that the sandstone bed (above) appears truncated by brittle tensile Mode I veins, whereas the mudstone layer (below) is affected by shear-induced thickness variations. (f) Bedding-parallel detachment faults bounding an extensional strike-slip duplex. View down dip to the NW.

are inclined and lie at low-angles or sub-parallel to bedding. This has two important consequences:

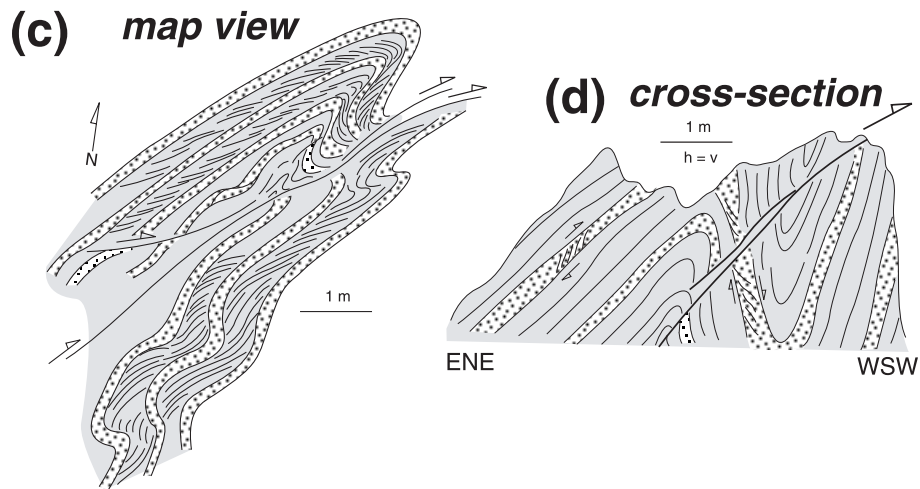
- (1) The great majority of transpressional strain models follow Sanderson and Marchini (1984) by considering an upright deformation zone with vertical deformation zone boundaries. Our study illustrates that non-

vertical, or inclined transpression models (Fig. 2a; cf. Dutton, 1997) are more appropriate in obliquely convergent settings like the Southern Uplands thrust wedge. Note that such boundary conditions will inevitably lead to triclinic bulk strains (see Jones et al., 2004). In addition, the inclined orientation means that gravitational forces will be acting at high angles to the deformation zone boundaries (cf. Boyer and Elliott,

"F1" folds



"F2" folds



"F3" folds

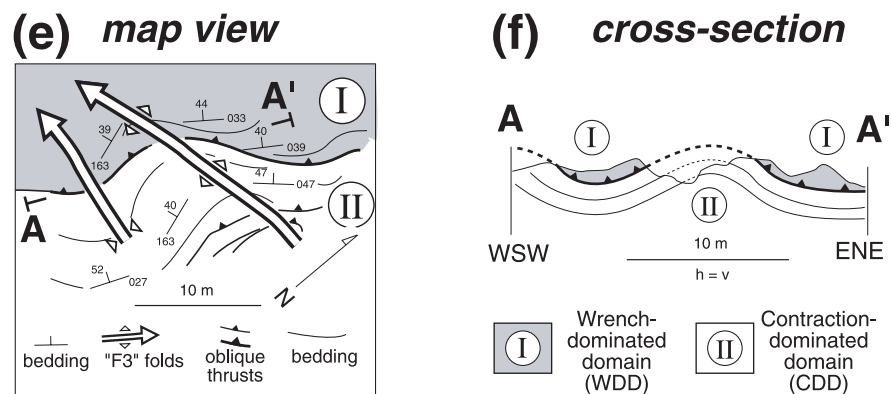


Fig. 11. Summary features of F1 ((a) and (b)), F2 ((c) and (d)) and F3 ((e) and (f)) folds at Dulse Craig, as seen in map pattern and cross-section, respectively.

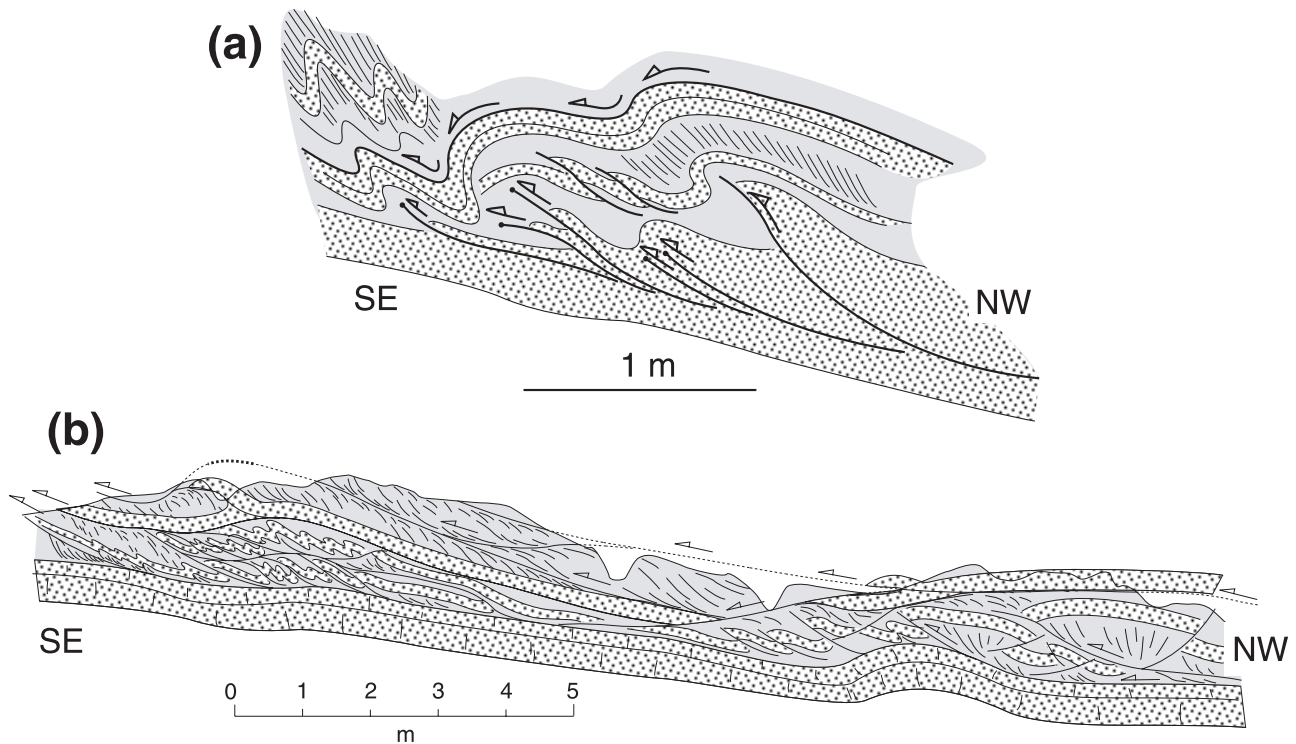


Fig. 12. Cross-section view of minor imbricate structures at Dulse Craig, across sandstone (stippled) and mudstone (shaded) layers. (a) An upper detachment is folded due to development of late, steep oblique thrusts, a feature indicating a piggy-back propagation. (b) Complex imbricate zone at the base of the contraction-dominated sub-domain III. Earlier top-to-the-SW oblique thrusts are truncated by extensional faults confined within the imbricate zone.

1982) and this likely explains the recognition of sequential piggy-back faulting and folding in the Dulse Craig area.

- (2) Our findings suggest that transpressional deformation zones can develop structural patterns *geometrically* very similar to those found in dip-slip fold-and-thrust belts. Were it not for the very widespread development of slickenline lineations on fault planes at Dulse Craig, the transpressional component of the deformation might easily have gone unnoticed. Geometric techniques for ascertaining displacement directions such as the ‘bow and arrow rule’ (Elliott, 1976) or use of bedding normals on a stereonet (Elliott and Johnson, 1980) are not valid in transpressional imbricates of this kind. Other structural relationships also independently point to a component of sinistral shear. These include the predominance of apparently sinistral bedding offsets across detachment ramps (e.g. Figs. 8d–f and 9b–f) and the slight clockwise-transsecting cleavage. In the absence of slickenline data, however, such criteria cannot be considered as conclusive proof of sinistral transpression. This emphasises the importance of properly ascertaining fault movement directions from lineation or slickenline measurements along faults in imbricate systems.

4.2. Possible controls on kinematic partitioning

Two styles of kinematic partitioning of the bulk triclinal

transpressional strain are recognised in the Dulse Craig area. Firstly, on centimetre- to metre-scales, strike-slip displacements are preferentially taken up along detachment faults, whilst contractional strains with a subordinate component of dip-slip overthrusting are accommodated by folding of strata in the intervening fault bounded blocks. A second tens-of-metre-scale partitioning is highlighted by the division of the sub-domains I–V into wrench-dominated zones—with top-to-the-SW sinistral detachments and sideways-facing structures—and contraction-dominated zones with SE-verging, upward facing folds and top-to-the-S sinistral oblique thrusts. The latter is directly equivalent to the domainal partitioning recognised on hundreds-of-metre-to kilometre-scales in the Eyemouth–Burnmouth section by Holdsworth et al. (2002a). On all scales, the degree of partitioning is never 100%. Thus, the sinistral detachments in the wrench-dominated regions always retain a component of reverse movement, whilst the folds in the contraction-dominated domains are clockwise transected, with SW-vergence and facing often prevalent.

What controls the observed partitioning of displacement and strain? Holdsworth et al. (2002a) suggest that the hundreds-of-metre- to kilometre-scale partitioning in the northern part of the Eyemouth–Burnmouth section (e.g. between Domains 2 and 4, Fig. 1) may be determined by proximity to the main tract bounding fault which lies just to the north. The smaller scales of partitioning recognised in the Dulse Craig area, point to additional more localised

controls, such as lithology. The overwhelming majority of sinistral detachments and oblique thrusts occur in mudstone units, while sandstones are unfaulted, except where they are imbricated by ramps, or cut by tensile vein arrays or pull-aparts (e.g. Fig. 13). This could indicate that the detachments preferentially develop in mudstones as they are less competent, easy-slip horizons. An additional factor may be the presence of an overpressured fluid phase since all detachments and oblique thrusts carry syn-tectonic carbonate mineralization. Many bedding-parallel detachments are located in shale suggesting that these fine-grained, presumably low permeability argillaceous units were able to trap fluids internally and become overpressured, possibly due to the effects of compaction. Diagenetic dewatering may have further contributed to preferential overpressuring of the shales. A majority of detachments characteristically lie 1–2 cm from a contact with an adjacent sandstone bed (e.g. Fig. 13). This could indicate that pressure seals in shales were only effective in preventing fluid migration at

scales greater than 2 cm. The localisation of displacements onto brittle detachments—as opposed to ductile folds and cleavage—could then be controlled by anisotropies in both mechanical strength and fluid pressure, both of which are determined by pre-existing lithological variations in the bedded sequences of the turbidites. The high pore fluid pressures would additionally lead to weakening of the detachment faults, which could then preferentially accommodate strike-slip movements, despite their mechanically unfavourable, inclined orientations (e.g. Sibson, 1985, 1995).

The relative lack of widespread metre-scale or larger folds in the wrench-dominated sub-domains compared with the contraction-dominated regions is striking. The nucleation and growth of such SE-verging folds would tend to rotate bedding in hinge and short common limb regions towards the horizontal, increasingly out of orientations favourable to bedding-parallel strike-slip movement. It is significant that the mean bedding dips in two of the

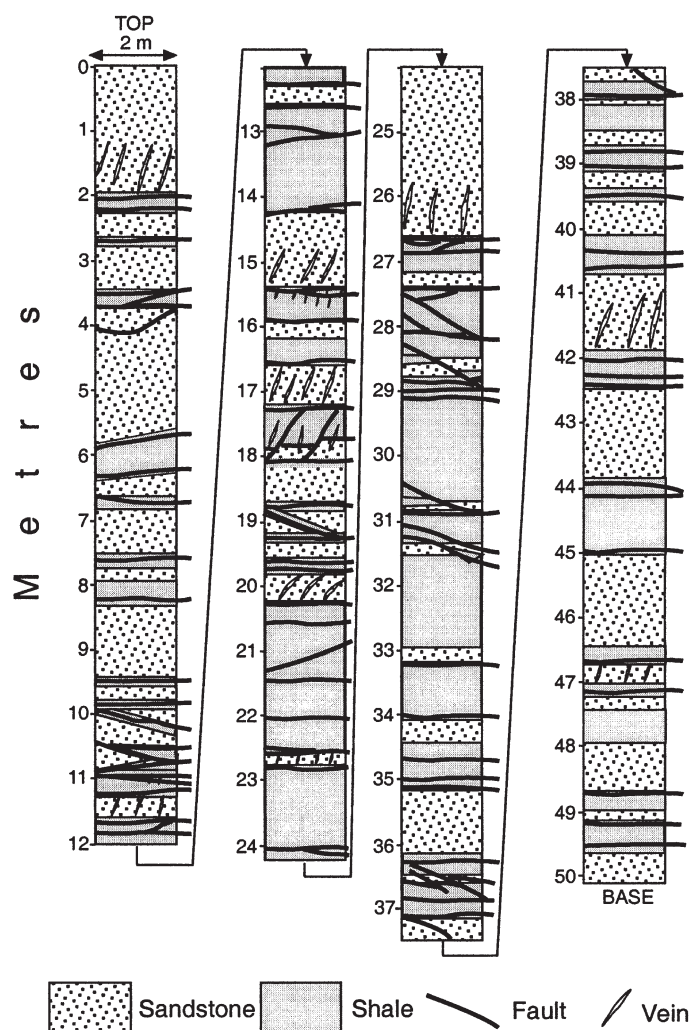


Fig. 13. Ca. 50-m-long stratigraphic–structural log located 40 m NE of the area mapped in Fig. 4 (see asterisk in Fig. 1c). The section consists of alternating sandstones and mudstones affected by sinistral detachments. Note that most detachments are located within the mudstone layers, and/or in close proximity to mudstone–sandstone contacts. The detachments are all associated with syn-tectonic carbonate mineralization.

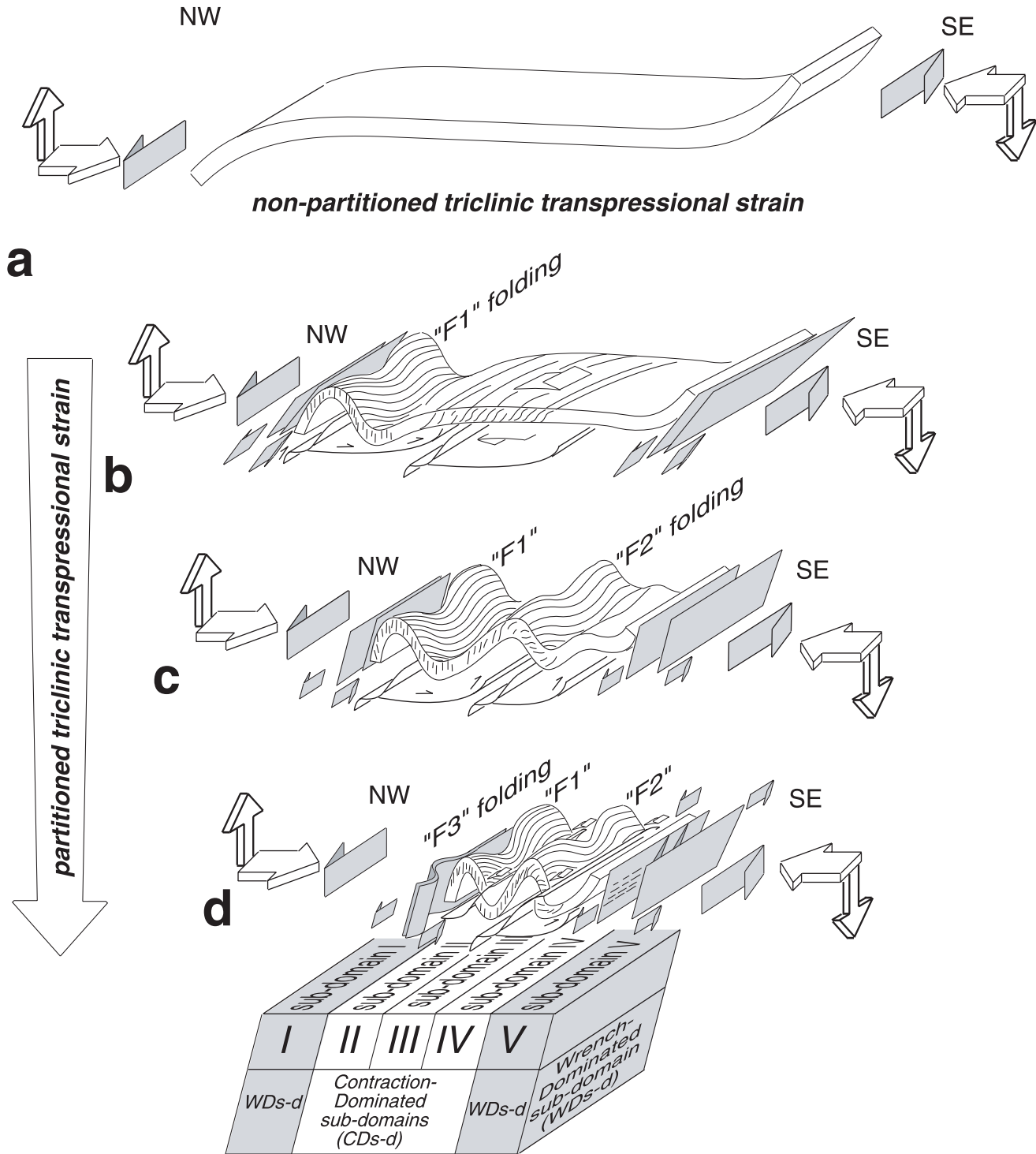


Fig. 14. Schematic kinematic model (a–d in time) to account for development of the structures investigated in this study within the framework of a bulk triclinic transpressional deformation. The relative positions of the recognised sub-domains I–V are also illustrated. Following the formation of a gentle S-verging fold pair (stage a), the bulk transpressional triclinic strain is partitioned into contractional (unornamented) and strike-slip (shaded) components, that dominate in the zones of flat-lying and steeply-dipping bedding, respectively (stages b–d). *F1* folds are developed during stage b, along with a steeply NW-dipping cleavage. *F2* folds are developed during stage c, and refold the previously formed NW-dipping cleavage. *F3* folds eventually deform the steep faults that bound sub-domains I (wrench-dominated) and II (contraction-dominated).

contraction-dominated sub-domains (II and IV) are 20–30° shallower than those in the adjacent wrench-dominated zones (Fig. 7). These folded regions could therefore become pre-disposed to the accommodation of non-coaxial dip-slip contractional strains, inevitably leading to kinematic partitioning on tens-of-metre- or larger scales, i.e. as seen in the sub-domains of Dulse Craig or even in larger regions such as Domain 2 in the Eyemouth section (see Holdsworth et al., 2002a). Following Ramsay (1974), it is possible that the nucleation points of such larger-scale folds may ultimately be controlled by pre-existing lithological factors such as thickness and packing distances of competent sandstone units in the multilayer sequence. Further work is required to test this hypothesis.

Overall, we propose that much of the observed strain partitioning on scales less than hundreds of metres is controlled firstly by pre-existing lithological anisotropy and secondly by how this anisotropy is reoriented by processes such as folding once deformation begins. This suggests that in common with many orthogonal thrust belts, the structural character and evolution of many transpressional deformation zones is also very strongly influenced by the mechanical interactions of deformation processes with highly anisotropic, layered stratigraphies.

4.3. A kinematic model for the Dulse Craig structures

A speculative model (Fig. 14a–c) is now presented to account for the observed structural geometries, evolution and strain partitioning seen on the scale of the sub-domains recognised in the Dulse Craig area. We propose that the current sub-domains II–IV initially developed due to the nucleation of one or more, tens-of-metre- or larger scale, SE-verging fold pair(s) (Fig. 14a) in a bulk sinistral triclinic transpressional strain regime. Outwith from these folded regions (e.g. sub-domains I and V), the subsequent deformation involved the predominant development of generally bedding-parallel sinistral detachments and strike-slip dominated imbricates (Fig. 14a–c). A SW-facing cleavage developed, cross-cutting bedding in a clockwise sense, with only relatively minor, mainly sideways SW-facing curvilinear folds forming. In sub-domains II–IV, we suggest that a rather different sequence of events occurred. Following the arguments of Treagus and Treagus (1981, 1992), it is assumed that the early fold hinges formed in generally sub-horizontal orientations, parallel to the long-axes of the 2-D sectional strain ellipse in gently to moderately NW-dipping bedding planes. The trend of these hinges is uncertain, but may have been more E–W (in present-day coordinates) given the overall sinistral sense of shear. Folding rotated the bedding in sub-domains II–IV out of orientations favourable to the accommodation of strike-slip shear, so the region became a focus for further NW–SE shortening. This led to tightening and possibly rotation of the fold hinges about a steeply-dipping axis

into more NE–SW orientations and to the development of top-to-the-S sinistral oblique thrust imbricates (Fig. 14b). The latter structures formed in mainly piggy-back sequences, leading to local refolding of structurally higher detachment surfaces, folds and cleavage (Fig. 14c). The final phase of *F3* folding in sub-domains I and II is then attributed to a final, highly localised phase of late NE–SW sinistral shear (Fig. 14c).

A number of uncertainties and problems exist in this speculative model. One of the most important concerns the highly curvilinear nature of the minor fold hinges, a striking feature of the Eyemouth section. Holdsworth et al. (2002a) concluded that these curvilinear structures cannot be sheath folds as there is no evidence of intense ductile strains in these rocks—little-modified sedimentary structures are ubiquitously preserved. Similarly, there is little evidence to suggest that they result from constrictional strains or irregular bedding orientations prior to folding. Holdsworth et al. (2002a) show that the arcs of fold hinge curvature are consistently bisected by directions parallel to the predicted orientations of the finite strain axes in wrench and contraction-dominated domains. This is also the case in the Dulse Craig area. In sub-domains II–IV, for example, the arcs of curvature are bisected by a down-dip direction of extension consistent with a non-coaxial NW–SE shortening. In contrast, the arc of hinge curvature is bisected by a sub-horizontal NE–SW axis in wrench dominated zones such as sub-domain I (Fig. 2b). This suggests that the development of these curvilinear geometries is most likely linked in some way to the process of strain partitioning. We currently do not fully understand why this should occur, but the observed hinge curvatures are most likely to reflect severe problems in lateral hinge propagation during fold amplification (cf. Dubey and Cobbold, 1977). Significantly, Holdsworth and Pinheiro (2000) have recently documented a similar association between strain partitioning and the development of ‘low-strain’ highly curvilinear fold geometries in a shallow crustal transpression zone in Brazil.

5. Conclusions

The Dulse Craig area preserves a highly heterogeneous assemblage of contemporaneous structures formed during bulk triclinic sinistral transpression in an inclined, obliquely convergent thrust wedge. The resulting structures include a piggy-back imbricate system of closely related strike-slip detachments, highly curvilinear folds, oblique thrust faults and a clockwise transecting cleavage. A series of sub-domains are recognised which are interpreted to result from kinematic partitioning of the bulk transpressional strain into contraction- and wrench-dominated end-members. In this case, the partitioning appears to be controlled by pre-existing lithological anisotropy and how this is subsequently modified by processes such as folding once deformation begins.

Overall, our findings suggest that transpressional deformation zones can develop structural patterns *geometrically* very similar to those found in dip-slip fold and thrust belts. In our view, this is very likely to occur in many obliquely convergent wedges where deformation zone (e.g. thrust tract) boundaries are typically inclined and lie at low-angles or sub-parallel to regional bedding. Imbricate systems will inevitably form because the sedimentary anisotropy is a central mechanical control in their development. Our findings therefore emphasise the fundamental importance of properly ascertaining fault movement directions from lineation or slickenline measurements along faults in imbricate systems. Many other so-called ‘thrust imbricates’ identified in previous studies, both in the Southern Uplands and elsewhere, may in reality be transpressional in origin.

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