Geol. Mag. **139** (6), 2002, pp. 707–717. © 2002 Cambridge University Press
DOI: 10.1017/S0016756802006854 *Printed in the United Kingdom*

The nature and regional significance of structures in the Gala Group of the Southern Uplands terrane, Berwickshire coast, southeastern Scotland

R. E. HOLDSWORTH*‡, E. TAVARNELLI† & P. CLEGG*

*Reactivation Research Group, Department of Geological Sciences, University of Durham, Durham DH1 3LE, UK
†Dipartimento di Scienze della Terra, Università di Siena, Siena, Italy

(*Received* 12 March 2002; *accepted* 18 July 2002)

Abstract – Structures deforming Llandovery turbidites of the Gala Group in the Southern Uplands terrane are spectacularly exposed in the Berwickshire coastal section, southeastern Scotland. The upward-facing, upright to NW-vergent folds and associated structures appear to record a single regional phase of subhorizontal NW–SE contractional deformation, with a steeply dipping direction of bulk finite extension. These structures are markedly different from those developed in rocks correlated with the Upper Llandovery Hawick Group exposed some 5 km to the south in the Eyemouth–Burnmouth coastal section. Here a highly domainal system of sinistral transpressional strain occurs, with zones of steeply plunging curvilinear folds, clockwise cleavage transection and bedding-parallel sinistral detachment faults. The markedly different bulk strain patterns in the Berwickshire coastal sections are thought to reflect the regionally diachronous nature of transpressional deformation in the Southern Uplands terrane. There are striking similarities in the structures recognized in the Berwickshire coastal sections and those developed in stratigraphically equivalent units along strike in southwestern Scotland and Northern Ireland. This confirms the lateral structural continuity and correlation of tracts and tract boundaries along the entire length of the Southern Uplands terrane. The regional structure suggests that a phase of top-to-the-NW backthrusting and backfolding associated with the southern margin of the Gala Group outcrop marks the transition from orthogonal contraction to sinistral transpression in the Southern Upland thrust wedge during late Llandovery times.

Keywords: Southern Uplands, Caledonides, folding, transpression, tectonic wedges.

1. Introduction

The widely studied Southern Uplands terrane in the Caledonian orogen of Scotland (Fig. 1a) forms part of a broad belt of Palaeozoic deformation that resulted from the sinistral oblique closure of the Iapetus Ocean (Dewey & Shackleton, 1984; Soper & Hutton, 1984; Soper *et al.* 1992). Numerous studies have documented the structures present in this terrane in some detail, notably in Northern Ireland (e.g. Anderson & Cameron, 1979; Anderson & Oliver, 1986; Anderson, 1987), southwestern Scotland (e.g. Stringer & Treagus, 1980, 1981; Anderson & Oliver, 1986; Kemp, 1986, 1987; Barnes, Anderson & McCurry, 1987; Stone, 1995, 1996; Lintern & Floyd, 2000) and inland regions of the Southern Uplands (e.g. Barnes, Phillips & Boland, 1995; Phillips *et al.* 1995; Stone, 1996). However, with the exception of the detailed BGS memoir (Greig, 1988), there are few modern published accounts of the well-exposed section of deformed Silurian rocks exposed along the Berwickshire coastline in southeastern Scotland (Fig. 1b). Holdsworth *et al.* (2002) have recently published a detailed description of the structural geology of the Eyemouth to Burnmouth section (Fig. 1b) where they document evidence for strain partitioning during bulk sinistral transpression leading to a complex and highly domainal style of deformation. The present paper gives an account of the structures in the northernmost coastal section of Berwickshire between Fast Castle & Pettico Wick. The relatively simple pattern of neutral- to slightly NW-verging, cylindroidal folding contrasts sharply with the more complex transpressional deformation seen in the Eyemouth–Burnmouth section that lies only 5 km to the south. These findings have implications concerning the structural and tectonostratigraphic continuity of the Southern Uplands terrane and shed further light on the regional significance of NW-directed movements in this otherwise SE-directed zone of overthrusting.

‡ Author for correspondence: R.E.Holdsworth@durham.ac.uk

2. Regional setting

2.a. The Southern Uplands terrane

The Lower Palaeozoic rocks of the Southern Uplands are predominantly turbidite deposits that are subdivided into a series of elongate NE–SW-trending tracts

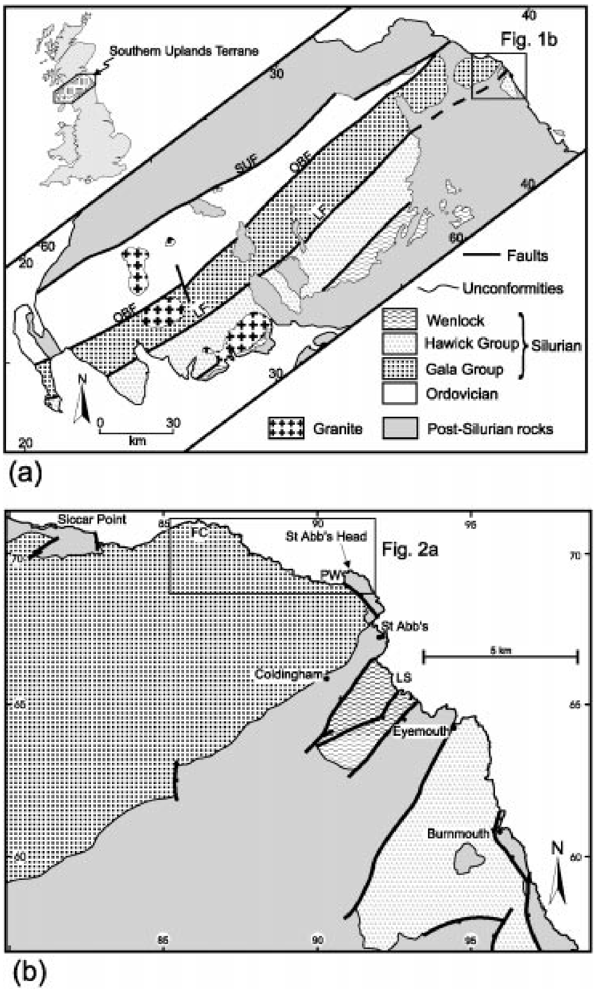

Figure 1. (a) Regional map with national grid markings of the Southern Uplands Terrane showing main tectonostratigraphic units and tract-bounding faults. The likely correlations between the Berwickshire outcrops and the main outcrop to the southwest are also shown. Box indicates location of Figure 1b. SUF – Southern Uplands Fault; OBF – Orlock Bridge Fault; LF – Laurieston Fault. (b) Simplified sketch geological map with national grid markings of southeastern Scotland between Siccar Point and Burnmouth (after BGS map). Box shows location of Figure 2a. FC – Fast Castle; PW – Pettico Wick; LS – Linkim Shore.

by steeply dipping faults that mostly originated as top-to-the-SE thrusts (Fig. 1a; McKerrow, Leggett & Eales, 1977). In general, the younging direction of the steeply dipping rocks entrained within each thrust slice is to the northwest, whilst the age range of strata within each fault-bounded tract becomes progressively younger to the southeast. Thus the Northern Belt of the Southern Uplands comprises exclusively Ordovician rocks whilst the Central and Southern belts are mainly or exclusively Silurian strata (Fig. 1a; Peach & Horne, 1899). Complex systems of mainly SE-verging folds and associated top-to-the-SE thrusts are recognized throughout much the Southern Uplands (e.g. Knipe & Needham, 1986; Knipe *et al.* 1988) and are thought to have formed at relatively shallow crustal depths (< 10 km) based on the relatively low metamorphic grade (diagenetic to prehnite–pumpellyite facies) (Oliver & Leggett, 1980; Kemp, Oliver & Baldwin, 1985).

Two main regional tectonic models have been proposed to explain the development of the thrust wedge: (1) an accretionary prism hypothesis in which the imbricated fault tracts are progressively scraped off the down-going plate at a long-lived subduction zone on the northern margin of the Lower Palaeozoic Iapetus Ocean (e.g. McKerrow, Leggett & Eales, 1977; Leggett, McKerrow & Eales, 1979; Leggett, 1987); and (2) a model in which the region forms part of a back-arc to foreland basin thrust system related to early Silurian arc–continent collision (e.g. Stone *et al.* 1987; Hutton & Murphy, 1987). Both models require that the thrust-related structures are regionally diachronous, with those in the northwest forming significantly earlier than those in the southeast. This is supported by existing biostratigraphic and radiometric data which suggest that the onset of thrusting ranges from the Ashgill in the northwest through to the Wenlock in the southeast (Barnes, Lintern & Stone, 1989). In addition to the contractional deformation, a regional component of sinistral shear becomes important during deformation from the late Llandovery onwards (Anderson & Oliver, 1986; Anderson, 1987; Barnes, Lintern & Stone, 1989).

2.b. The Lower Palaeozoic rocks of southeastern Scotland

In southeastern Scotland, the mainly Silurian strata of the Southern Uplands terrane crop out in three areas, all of which are exposed along the Berwickshire coast (Fig. 1b; Greig, 1988). The rocks are all typical turbidite deposits, predominantly comprising interlayered sequences of greywacke sandstones, siltstones and mudstones. They form the regional basement in southeastern Scotland and are often bounded by later, steeply dipping faults, although unconformable relationships with overlying Devonian and younger sedimentary rocks and extrusive lavas are locally preserved (e.g. Hutton's unconformity at Siccar Point; Fig. 1b).

The turbidites exposed in the northernmost coastal section from Siccar Point to Pettico Wick are thought to be of Llandovery age based upon preserved graptolite fauna (Greig, 1988). The present study focuses on the best exposed part of this section between Fast Castle and Pettico Wick (Fig. 2). To the north and west of Fast Castle, much of the coastal section is parallel to strike, is poorly exposed or disrupted by later faulting. All the Silurian rocks exposed along the northernmost coastal section are correlated by Greig (1988) with the Gala Group in the southwestern part of the Southern Uplands outcrop (Fig. 1a, b). Some 5 km to the south, the coastal section from Eyemouth to Burnmouth preserves an apparently unfossiliferous turbidite sequence that is generally correlated with the

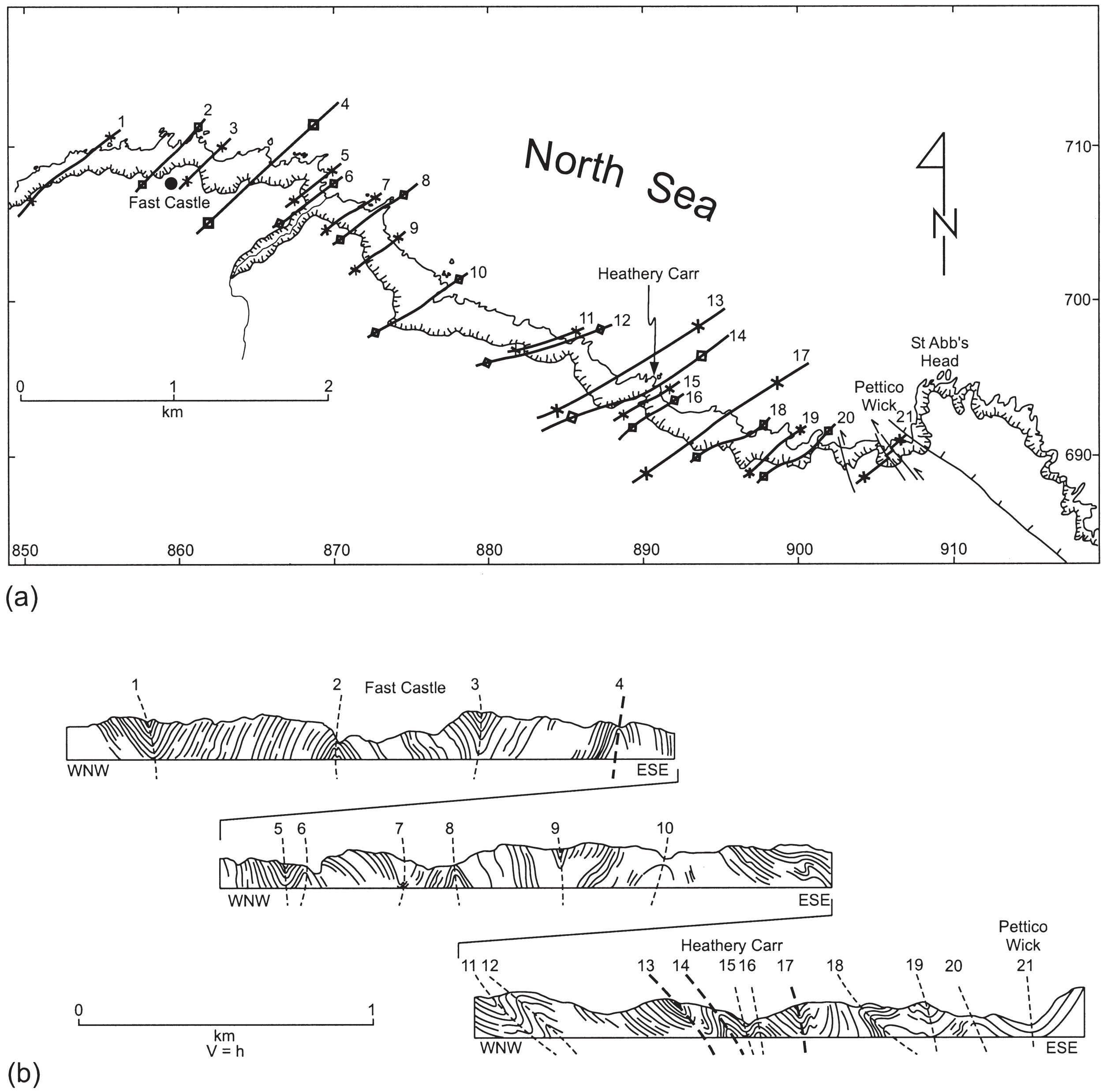

Figure 2. (a) Simplified structural map and (b) cross-section of the Fast Castle–Pettico Wick coastal section, with axial traces of major folds indicated.

Upper Llandovery age rocks of the Hawick Group in southwestern Scotland (Greig, 1988). An intervening central coastal section centred around Linkim Shore (Fig. 1b) exposes greywackes and shales of the Coldingham and Linkim beds which are thought to be of Wenlock age based on poorly preserved faunal and microfaunal evidence (e.g. see Molyneux, 1987). These rocks are highly disrupted by soft-sediment deformation structures and are of significantly lower metamorphic grade compared to the Silurian rocks in the adjacent coastal sections (Oliver *et al.* 1984). This suggests that these rocks may have formed in a very shallow part of the thrust wedge where the effects of down-slope, gravity-induced deformation were dominant. They are not considered further in the present study.

A major tract boundary must lie somewhere to the south of the Fast Castle–Pettico Wick section to separate these rocks correlated with the Gala Group from those of the Eyemouth–Burnmouth section correlated with the Hawick Group (e.g. Fig. 1b). This structure presumably corresponds to the along-strike projection of the Laurieston Fault which is recognized in southwestern Scotland (Fig. 1a; Akhurst *et al.* 2001). The normal fault that currently separates the Silurian basement south of Eyemouth from the Devonian and Carboniferous rocks to the north (Fig. 1b) may well reactivate this tract-bounding structure.

In the following section, the geometric and kinematic characteristics of the well-exposed structures seen in the Fast Castle–Pettico Wick section are summarized and interpreted. All the Silurian rocks are typical

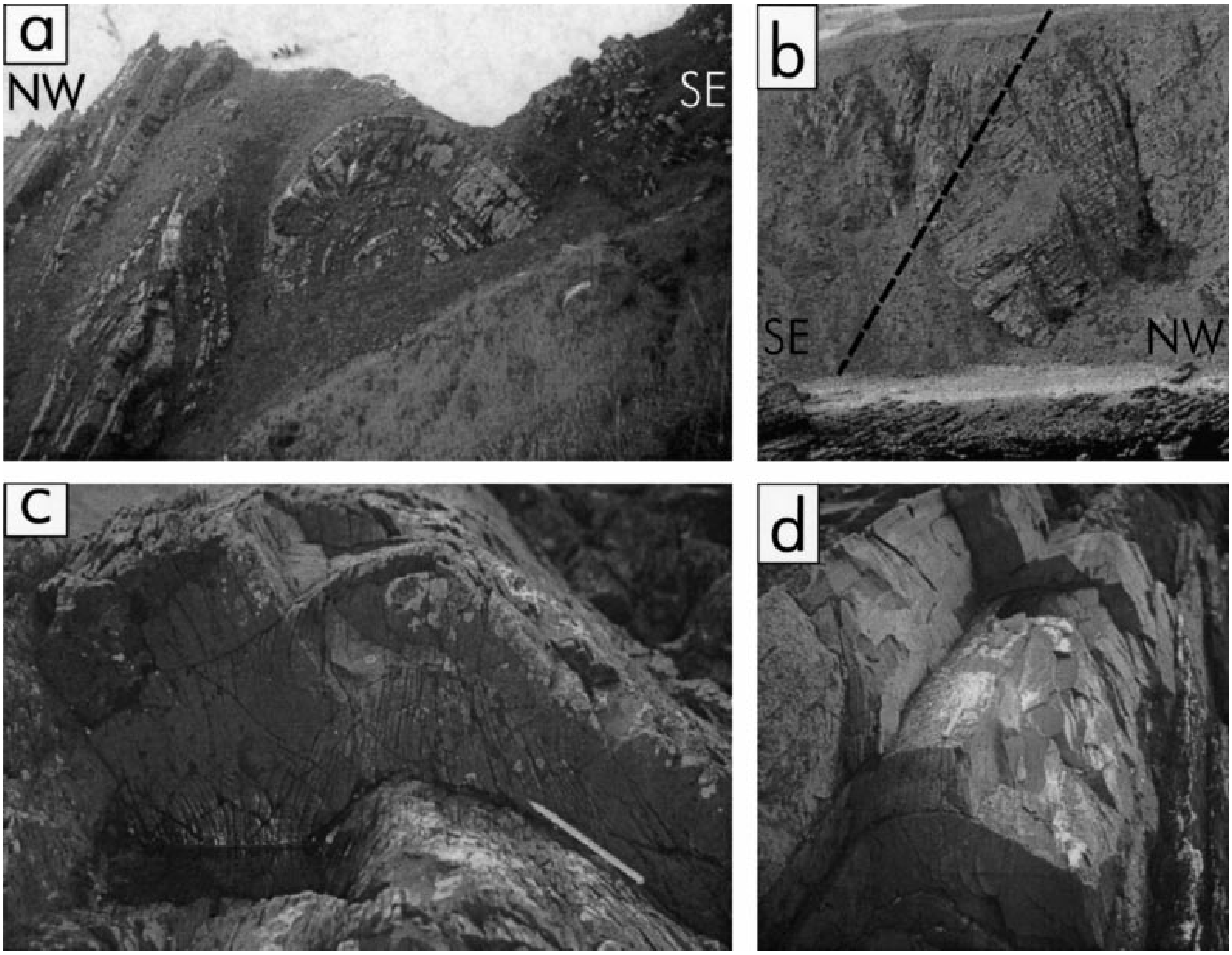

Figure 3. Folds and associated structures of the Fast Castle–Pettico Wick coastal section. (a) Upright, subhorizontally plunging anticline typical of northwest end of coastal section, just west of Souter (fold 4 in Fig. 2). View looking northeast, horizontal field of view 50 m. The oldest rocks exposed in the section are found in the core of this fold. (b) NW-verging, subhorizontally plunging syncline typical of southeast end of coastal section, Heathery Carr (fold 13 in Fig. 2). View looking south, with cliffs approximately 70 m in height. Dotted line corresponds to axial trace of synform in cliff. (c) Typical gently fanning and refracted nature of spaced solution cleavage in folded interlayered mudstones and greywacke sandstones; note how cleavage development picks out upwards fining nature of graded sandstones, indicating that the folds face steeply upwards. View looking southwest, with pencil 160 mm long, foreshore west of Fast Castle. (d) Upright fold and cleavage showing cleavage-bedding intersection (in line with pencil) parallel to the gently SW-plunging fold hinge. View looking southwest, with pencil 160 mm long, foreshore west of Fast Castle.

turbidite sequences with units of greywacke sandstone, siltstone and shale interlayered on a metre to centimetre scale. They preserve abundant way-up criteria, including graded bedding, cross-laminations, sole markings (mainly flutes and grooves), load casts and ripple marks (Greig, 1988). This is significant as it allows a detailed analysis and comparison of fold and cleavage facing patterns to be carried out in addition to a standard orientation analysis using stereographic projections. 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'. We use these facing directions and orientation data to highlight the profoundly different geometries that exist between the structures developed in the Fast Castle–Pettico Wick section and the Eyemouth–Burnmouth section recently described by Holdsworth *et al.* (2002).

3. The Fast Castle–Pettico Wick section

3.a. Description of structures

The 6 km long steep cliffs forming much of the WNW–ESE-trending coastline preserve an almost completely exposed, though often inaccessible, section through a highly folded, uniform sequence of turbidites with an estimated total stratigraphic thickness of at least 1200 metres (Fig. 2a, b; see also Sheills & Dearman, 1966; Greig, 1988).

A single set of open to tight folds is developed, exhibiting gentle whaleback-geometry hinges typically

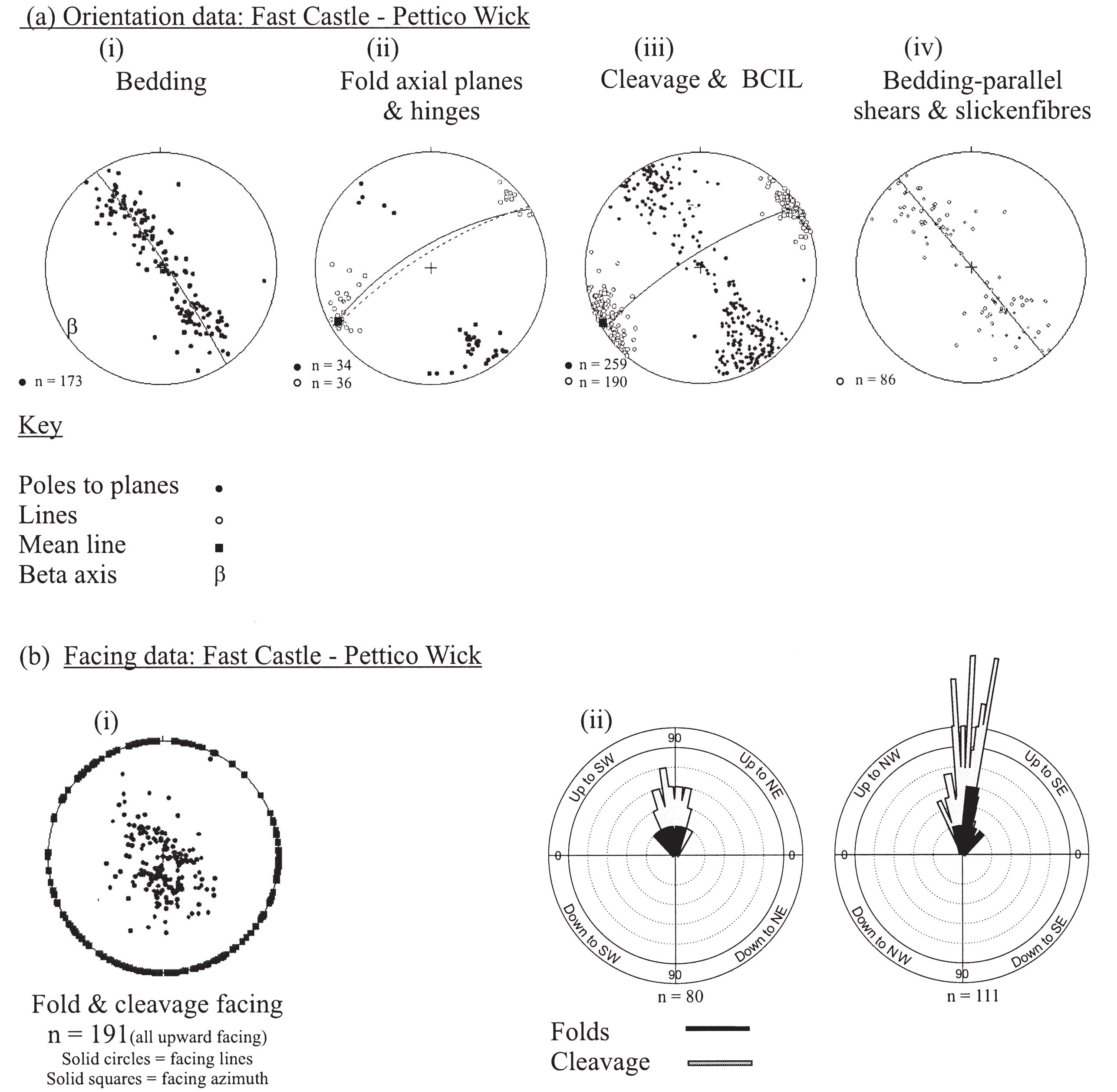

Figure 4. (a) Stereoplots of structural orientation data from the Fast Castle–Pettico Wick area shown in Figure 2a. (i) Poles to bedding, with best-fit great circle (146/86NE) and regional β axis (04/236). (ii) Poles to fold axial planes and fold hinges, with mean fold hinge (08/240), axial plane (solid, 059/75NW) and cleavage plane (dashed, 058/80NW) shown. (iii) Poles to cleavage and bedding-cleavage intersection lineations (BCIL), with mean BCIL (03/241) and cleavage plane shown. (iv) Slickenfibre lineations from bedding-parallel shears with best-fit great circle shown (141/89NE) (b) Facing data from the Fast Castle–Pettico Wick section. (i) Fold and cleavage facing lines and azimuths plotted using the construction method of Holdsworth (1988). (ii) Plots showing the pitch of fold and cleavage facing directions in planes parallel to the fold axial/cleavage planes in which they were measured. Note that facing data are omitted from the region of folded cleavage associated with the synform at Pettico Wick (fold 21 on Fig. 2). In addition, the scarcity of NW-facing fold data reflects the relatively inaccessible nature of the south-eastern part of the cliff section where most NW-verging folds occur (see Fig. 2b).

plunging shallowly towards the NE or SW (Fig. 3a–d; stereoplots i and ii in Fig. 4a). All folds and the associated cleavage face steeply upwards (Fig. 4b). The relative simplicity of the folding is illustrated by the clear girdle distribution of poles to bedding (stereoplot i, Fig. 4a) that defines a subhorizontal, NE–SW regional β axis which corresponds closely with the mean fold hinge orientation. Associated axial surfaces have NE to ENE trends and dip steeply to the NW or SE (stereoplot ii, Fig. 4a). The folds in the western–northwestern part of the section are more upright and symmetric (Fig. 3a), whilst those to the east–southeast are more asymmetric and overturned northwestwards (Figs 2b, 3b; Sheills & Dearman, 1966). The structurally lowest and presumably oldest rocks are exposed in a major anticlinal closure near Souter (fold 4 in Fig. 2a, b),

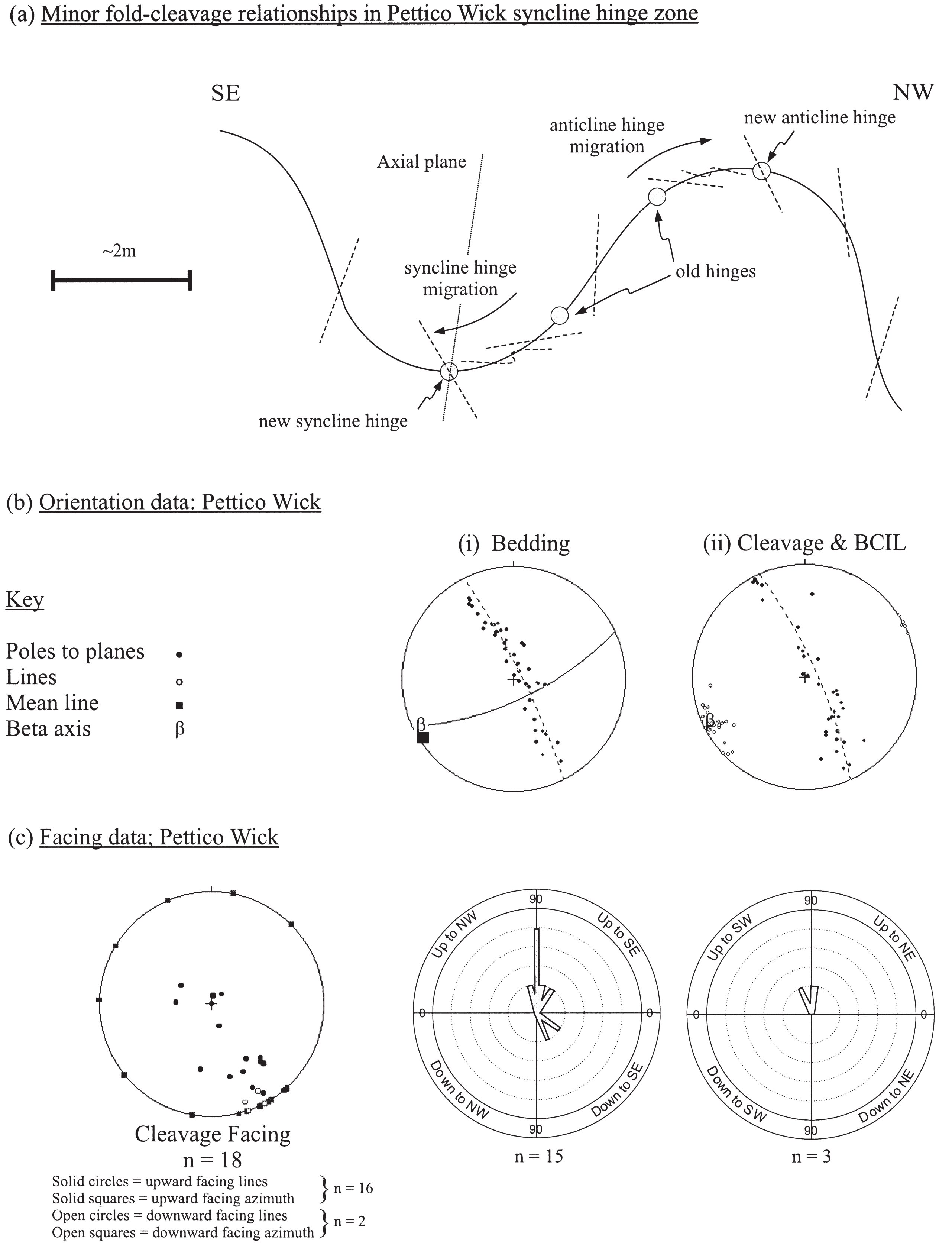

Figure 5. (a) Diagrammatic sketch showing cleavage (S1; dashed)–bedding (So; solid curved line) relationships around minor synclines and anticlines seen in the larger synclinal fold hinge zone exposed along the foreshore at Pettico Wick (fold 21 in Fig. 2). The bedding is right way-up. Viewed in fold profile plane. It is suggested that the cleavage is locally coaxially refolded due to migration of the fold hinges to produce local downward facing relationships in S1; note also minor SE-vergent folding of cleavage in regions of hinge migration. (b) Stereoplots of structural orientation data from the syncline at Pettico Wick. (i) Poles to bedding, with best-fit great circle (153/84NE; dashed) and β axis (06/243). Mean fold hinge (02/240) and axial plane (061/73SE)

whilst the structurally highest, presumably youngest strata crop out in a broad synclinorium centred around Heathery Carr (folds 13–17 in Fig. 2a, b). On a regional scale, the folds verge slightly to the NW, with approximately 60 % of the exposed strata younging to the SE. In the less accessible, southern part of the section (e.g. south of fold 10 in Fig. 2b), the proportion of southerly younging strata rises to near 75 % and almost all of the folds verge markedly NW.

A weakly developed slaty to spaced-solution cleavage is present in many mudstone and siltstone horizons (Fig. 3c). No mineral lineations are visible in exposed cleavage surfaces. Over much of the outcrop, the cleavage exhibits an axial planar or gently fanning relationship to the folds. There are no clear examples of transection and cleavage–bedding intersection lineations are regionally and locally parallel to fold axes (Fig. 3d; stereoplot iii in Fig. 4a). The synclinal fold at Pettico Wick (fold 21 in Fig. 2) exhibits a more complex relationship to the cleavage in which the present fold hinge zone does not correspond to the location where the cleavage–bedding relationship changes (Fig. 5a). As a result the cleavage is locally coaxially refolded around SE-dipping parts of the fold hinge region, hence spreading poles to cleavage planes along a girdle normal to the regional fold axis (stereoplots i and ii, Fig. 5b). Thus, the cleavage locally faces sideways or downwards to the SE (Fig. 5a, c). These relationships are attributed to hinge migration during fold tightening (as indicated in Fig. 5a). It is unclear why this feature appears to be restricted entirely to the extreme east–southeast of the coastal section.

Faults are widespread, but are generally minor structures in terms of displacement and are often associated with minor amounts of carbonate mineralization. Conjugate thrust faults dipping NW and SE are common in some disrupted fold hinge regions (see Greig, 1988, pp. 11–13 for details). In all fold limb regions, bedding-parallel shears with well-defined carbonate slickenfibres are ubiquitous and are distributed along a girdle orthogonal to the regional fold axis and parallel to the fold profile plane (stereoplot iv, Fig. 4a). Senses of shear deduced from slickenfibre steps and offsets of markers are reversed on opposite fold limbs and are everywhere consistent with a flexural slip model (e.g. Ramsay & Huber, 1987, fig. 21.11). The youngest group of structures are steeply dipping, possible conjugate, strike-slip faults that everywhere cross-cut the folded bedding. Sinistral faults trend mainly NNE–SSW whilst dextral faults trend NW–SE. Collectively, the faults appear to be consistent with NNW–SSE bulk contractional strain (Greig, 1988). The age of this faulting is uncertain and may be late Caledonian (cf. Stone, 1995) or be related to younger deformation episodes such as the Variscan inversion of the Northumberland basin that lies to the south (e.g. Roper, 1997).

3.b. Interpretation of structures and comparison with regions along strike

The upward-facing, upright to slightly NW-vergent folds and associated structures of the Fast Castle–Pettico Wick section appear to be consistent with subhorizontal NW–SE contractional deformation. A steeply dipping direction of bulk finite extension can be inferred by bisecting the arc of the slightly curvilinear subhorizontal fold hinges. There is no evidence for cleavage transection of the folds that also exhibit bedding-parallel shears with hinge-normal slickenfibre lineations thought to be related to flexural slip during folding. Faults are relatively unimportant features compared to folds and many small-scale conjugate thrust faults appear to have formed during flexural-slip folding of local multilayer sequences in which the thickness of individual competent sandstone units is variable leading to strain compatibility problems (cf. Ramsay, 1974).

The slight NW vergence of the folds and predominance of SE-younging directions in the Fast Castle–Pettico Wick section, particularly in its southern part (Figs 2b, 3b), is atypical of the general NW-younging and markedly SE structural vergence recognized throughout much of the Southern Uplands terrane (e.g. McKerrow, Leggett & Eales, 1977; Knipe & Needham, 1986). However, very similar structural assemblages, with significant areas of SE-younging strata, are seen in units of the Gala Group rocks of the Wigtown, Rhins of Galloway (southwestern Scotland) and Ards peninsula (Northern Ireland) areas (e.g. Barnes, Anderson & McCurry, 1987; McCurry & Anderson, 1989; Stone, 1995). Significantly, these regions lie directly along strike of the Fast Castle–Pettico Wick section, an observation that seems to confirm the general along-strike structural continuity and correlation of tracts and tract boundaries along this part of the Southern Uplands terrane (e.g. Fig. 1a).

4. Discussion

4.a. Comparison with the Eyemouth–Burnmouth section

Lying some 5 km to the south of the Fast Castle–Pettico Wick section, the 4 km long coastline to the south of Eyemouth harbour (Fig. 1b) preserves an

orientations also shown. (ii) Poles to cleavage and bedding-cleavage intersection lineations, with best fit great circle (156/81N), mean BCIL (07/243) and β axis (09/246) shown. (c) Facing data from the syncline at Pettico Wick. (i) Fold and cleavage facing lines and azimuths plotted using the construction method of Holdsworth (1988). (ii) Plots showing the pitch of fold and cleavage facing directions in planes parallel to the fold axial/cleavage planes in which they were measured; note the local downward facing due to refolding of the cleavage as shown in Figure 5a.

almost completely exposed section through a generally NW-younging sequence of uniform turbidites with an estimated total structural thickness of at least 2500 metres (Geikie, 1864; MacKenzie, 1956; Dearman, Shiells & Larwood, 1962; Sheills & Dearman, 1966; Holdsworth *et al.* 2002). The rocks are apparently devoid of fossils, but are generally assigned to the Upper Llandovery Hawick Group based on lithological similarities with these rocks in their type locality in southwestern Scotland (Greig, 1988).

The structure of the Eyemouth–Burnmouth section is described in some detail by Holdsworth *et al.* (2002). In overview, this section differs from the Fast Castle–Pettico Wick section in several important respects:

(1) Compared to the highly folded Fast Castle–Pettico Wick section (Fig. 2b; stereoplot i in Fig. 4a), the Eyemouth–Burnmouth sequence is a more homoclinal NW-dipping and -younging sequence with local regions of generally S-vergent folding (Sheills & Dearman, 1966; Holdsworth *et al.* 2002).

(2) In contrast to the subhorizontal NE–SW whaleback-geometry folds of the Fast Castle–Pettico Wick section (stereoplot ii, Fig. 4a), fold hinges are markedly curvilinear, particularly in more northerly parts of the section close to Eyemouth, where they locally exhibit in excess of 110° of plunge variation within their axial surfaces (Dearman, Shiells & Larwood, 1962; Treagus, 1992; Holdsworth *et al.* 2002).

(3) The weakly developed, steeply dipping slaty to spaced solution cleavage is axial planar to the folds in the Fast Castle–Pettico Wick section (stereoplots ii and iii, Fig. 4a). In the Eyemouth–Burnmouth outcrop, however, both bedding–cleavage intersection lineations and poles to cleavage planes exhibit local clockwise transection in the northern parts of the section near to Eyemouth harbour (Holdsworth *et al.* 2002).

(4) In stark contrast to the simple upward facing patterns of the Fast Castle–Pettico Wick section (Fig. 4b), fold and cleavage facing directions in the Eyemouth–Burnmouth section collectively exhibit approximately 270° of variation from sideways NE-, through upward- to SW sideways- and downward-facing (Holdsworth *et al.* 2002). This is a direct consequence of the locally highly curvilinear character of the folds (cf. Dearman, Sheills & Larwood, 1962).

(5) Flexural-slip slickenlines associated with bedding-parallel shears are parallel to the profile plane in the Fast Castle–Pettico Wick section (stereoplot iv, Fig. 4a), whilst those from folded regions in the Eyemouth–Burnmouth area lie in a common plane significantly anticlockwise of the profile plane (see Holdsworth *et al.* 2002, fig. 4). This seems to suggest that oblique flexural-slip occurred during folding in most, if not all of, that section.

(6) Faults are more widespread in the Eyemouth–Burnmouth section and include conjugate thrust faults in disrupted fold hinge regions, bedding-parallel shears in fold limbs and interlinked networks of detachment faults lying at low-angles or sub-parallel to bedding. Carbonate slickenfibres along all of these shears and faults exhibit variable and locally complex movements, but those lying at low angles to strike always display a sinistral sense of movement (Holdsworth *et al.* 2002).

(7) Holdsworth *et al.* (2002) delimit a number of NE–SW-trending fault-bounded domains in the northern part of the Eyemouth coastal section that exhibit very different assemblages of structures which appear to be broadly all of the same age. This pattern contrasts markedly with the uniformly folded structure observed between Fast Castle and Pettico Wick.

Collectively, all the features of the Eyemouth–Burnmouth section are interpreted by Holdsworth *et al.* (2002) to indicate components of NW–SE contraction, top-to-the-SW sinistral shear and lesser amounts of top-to-the-SE thrusting, that is, bulk triclinic sinistral transpression. The domains exhibiting different structural assemblages are thought to represent regions of contraction- and sinistral wrench-dominated strain. Such features are widely recognized in transpression zones and are thought to form due to kinematic partitioning of strain into orogen-parallel and orogen-normal components (e.g. Dewey, Holdsworth & Strachan, 1998, and references therein). Similar structural assemblages have been described along-strike and to the southwest in the Southern Uplands terrane, notably in the Hawick Group rocks of the Wigtown Peninsula and Kirkcudbright areas of southwestern Scotland (e.g. Kemp, 1987; Barnes, Anderson & McCurry, 1987; Stone, 1995, 1996; Lintern & Floyd, 2000). Once again, this seems to confirm the structural continuity and correlation of tracts along the entire length of the Southern Uplands terrane (e.g. Fig. 1a).

4.b. Regional implications

In addition to the contractional deformation recognized throughout the Southern Uplands terrane, a regional component of sinistral shear becomes important during deformation from the late Llandovery onwards (Anderson & Oliver, 1986; Anderson, 1987; Barnes, Lintern & Stone, 1989). In the northwestern parts of the thrust wedge, sinistral fault- and shear-zones, often with associated, steeply plunging late folds ('F3') are superimposed upon pre-existing contractional structures ('F1–F2') including tract-bo unding early thrusts such as the Orlock Bridge Fault (Fig. 6; Anderson & Oliver, 1986). However, in the frontal parts of the thrust wedge developed from the mid- to late Llandovery onwards (Hawick Group rocks and younger; Fig. 6), the sinistral shear becomes increasingly synchronous with initial accretion as a result of the diachronous nature of the deformation.

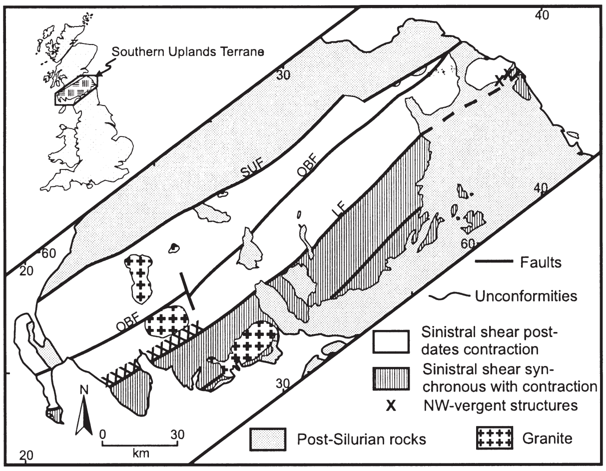

Figure 6. Regional map of the Southern Uplands terrane showing general distribution of timing of sininstral shear relative to primary phase of contraction. This changes across the Laurieston Fault (LF) and a regionally recognized zone of NW-vergent backthrusting and backfolding (after Barnes, Anderson & McCurry, 1987, and McCurry & Anderson, 1989, in southwestern Scotland) is consistently located in Gala Group rocks immediately north of this boundary, including those in Berwickshire. OBF – Orlock Bridge Fault, SUF – Southern Uplands Fault.

Thus, rocks in the most southeasterly fault tracts in the Southern Uplands, including those of the Eyemouth–Burnmouth section in Berwickshire, are often characterized by sinistral transpressional primary ('F1') fold belts with clockwise cleavage transection and local steeply plunging hinges with sinistral fold vergence (e.g. Stringer & Treagus, 1980; Anderson, 1987; Kemp, 1987; Holdsworth *et al.* 2002).

The absence of any clear evidence for sinistral shear in the Fast Castle–Pettico Wick section has two possible explanations. Either these structures formed prior to the onset of regional sinistral transpression in the Southern Uplands, or the transpressional strain was highly partitioned so that the Gala Group rocks of the Fast Castle–Pettico Wick section lie in a large domain of contraction-dominated deformation. The latter explanation requires that these structures have an equivalent history to those in the regions of contraction-dominated deformation in the Hawick Group rocks of the Eyemouth–Burnmouth section (e.g. domain 2 of Holdsworth *et al.* 2002). Whilst the folds in the latter domains are upright NE–SW structures with gentle whaleback hinges, they are clearly clockwise transected by the cleavage, and the bedding-parallel flexural slip slickenline lineations lie in a plane significantly anticlockwise of the profile plane. These characteristic features are not observed in the Fast Castle–Pettico Wick section and we suggest, therefore, that the main fold structures in the Gala Group rocks of Berwickshire formed prior to the onset of regional sinistral shear in the Southern Uplands.

The Southern Uplands terrane is dominated by structures that verge towards the SE. However, NW-vergent folds have been recognized in several locations adjacent to the southern margin of the Gala Group in both Northern Ireland and southwestern Scotland (Fig. 6; Barnes, Anderson & McCurry, 1987; McCurry & Anderson, 1989; Stone, 1995). Barnes, Anderson & McCurry (1987) and Stone (1995) propose that the geometry of these structures is consistent with a short-lived phase of backthrusting that may have occurred due to changes in the rheology of the thrust wedge or its basal detachment. In contrast, McCurry & Anderson (1989) suggest that the onset of NW-directed shearing reflects a switch from subduction (with SE-directed shear) to obduction, possibly in response to increased sedimentation rates in the late Llandovery. This explanation seems to be at odds with the biostratigraphical relationships (see Stone, 1995, pp. 52–3). Our findings do not resolve this controversy, although they seem to confirm the regional extent of this NW-directed deformation event in rocks adjacent to the southern margin of the Gala Group (Fig. 6). We suggest, however, that the timing of deformation events may also be significant because the backthrusting occurs in Gala Group rocks that were likely deformed immediately prior to the onset of regional sinistral shear in the late Llandovery (Fig. 6; Stone *et al.* 1987; Barnes, Lintern & Stone, 1989; Stone, 1996; Holdsworth *et al.* 2002). Thus the phase of backthrusting in the Southern Uplands thrust wedge coincides with a change in kinematic boundary conditions from a regime of orthogonal contraction to one of sinistral transpression in a southward migrating deformation system. This change is conceivably linked to the accretion of a microcontinental or arc fragment proposed by Rushton, Stone & Hughes (1996). Our findings, taken together with those of Holdsworth *et al.* (2002), entirely support recent suggestions that the late Llandovery was a key period in the evolution of the Southern Uplands terrane (e.g. Akhurst *et al.* 2001) and further highlight the regional importance of the Laurieston Fault (Fig. 6).

Acknowledgements. The authors would like to thank the Gibson family of St Abbs for providing accommodation and use of their boat during fieldwork. Phillip Clegg very gratefully acknowledges the generous support of both the John Ray Trust and the Annie Greenly Fund of the Geological Society, London. Stereoplots were produced using GEOrient software v.9.0. Phil Stone and Jack Treagus are thanked for helpful and constructive reviews.

References

Akhurst, M. C., McMillan, A. A., Kimbell, G. S., Stone, P. & Merriman, R. J. 2001. Silurian subduction-related assembly of fault-defined tracts at the Laurieston Fault, Southern Uplands accretionary terrane, Scotland, UK. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **91**, 435–46.

Anderson, T. B. 1987. The onset and timing of Caledonian sinistral shear in County Down. *Journal of the Geological Society, London* **144**, 817–25.

ANDERSON, T. B. & CAMERON, T. D. J. 1979. A structural profile of Caledonian deformation in Down. In *The Caledonides of the British Isles – Reviewed* (eds A. L. Harris, C. H. Holland and B. E. Leake), pp. 263–7. Geological Society of London, Special Publication no. 8.

ANDERSON, T. B. & OLIVER, G. J. H. 1986. The Orlock Bridge Fault: a major late Caledonian sinistral fault in the Southern Uplands Terrane, British Isles. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **77**, 203–22.

BARNES, R. P., ANDERSON, T. B. & MCCURRY, J. A. 1987. Along-strike variation in the stratigraphical and structural profile of the Southern Uplands central belt in Galloway and Down. *Journal of the Geological Society, London* **144**, 807–16.

BARNES, R. P., LINTERN, B. C. & STONE, P. 1989. Timing and regional implications of deformation in the Southern Uplands of Scotland. *Journal of the Geological Society, London* **146**, 905–8.

BARNES, R. P., PHILLIPS, E. R. & BOLAND, M. P. 1995. The Orlock Bridge Fault in the Southern Uplands of SW Scotland: a terrane boundary? *Geological Magazine* **132**, 523–9.

DEARMAN, W. R., SHIELLS, K. A. G. & LARWOOD, G. P. 1962. Refolded folds in the Silurian rocks of Eyemouth, Berwickshire. *Proceedings of the Yorkshire Geological Society* **33**, 273–86.

DEWEY, J. F., HOLDSWORTH, R. E. & STRACHAN, R. A. 1998. Transpression and Transtension zones. In *Continental Transpressional and Transtensional Tectonics* (eds R. E. Holdsworth, R. A.Strachan and J. F. Dewey), pp. 1–14. Geological Society of London, Special Publication no. 135.

DEWEY, J. F. & SHACKLETON, R. M. 1984. A model for the evolution of the Grampian tract in the early Caledonides and Appalachians. *Nature, London* **149**, 483–6.

GEIKIE, A. 1864. *The Geology of eastern Berwickshire.* Memoir of the Geological Survey, Scotland.

GREIG, D. C. 1988. *Geology of the Eyemouth District.* Memoir for 1:50 000 geology sheet 34 (Scotland). Keyworth: British Geological Survey.

HOLDSWORTH, R. E. 1988. The stereographic analysis of facing. *Journal of Structural Geology* **10**, 219–23.

HOLDSWORTH, R. E., TAVARNELLI, E., CLEGG, P., PINHEIRO, R. V. L., JONES, R. R. & MCCAFFREY, K. J. W. 2002. Domainal deformation patterns and strain partitioning during transpression: an example from the Southern Uplands terrane, Scotland. *Journal of the Geological Society, London* **159**, 401–15.

HUTTON, D. H. W. & MURPHY, F. C. 1987. The Silurian of the Southern Uplands and Ireland as a successor basin to the end Ordovician closure of Iapetus. *Journal of the Geological Society, London* **144**, 765–72.

KEMP, A. E. S. 1986. Tectonostratigraphy of the Southern Belt of the Southern Uplands. *Scottish Journal of Geology* **22**, 241–56.

KEMP, A. E. S. 1987. Tectonic development of the Southern Belt of the Southern Uplands accretionary complex. *Journal of the Geological Society, London* **144**, 827–38.

KEMP, A. E. S., OLIVER, G. J. H. & BALDWIN, J. R. 1985. Low-grade metamorphism and accretion tectonics; Southern Uplands Terrane, Scotland. *Mineralogical Magazine* **49**, 335–44.

KNIPE, R. J., CHAMBERLAIN, M. I., PAGE, A. & NEEDHAM, D. T. 1988. Structural histories in the SW Southern Uplands, Scotland. *Journal of the Geological Society, London* **145**, 697–84.

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

LEGGETT, J. K. 1987. The Southern Uplands as an accretionary prism: the importance of analogues in reconstructing palaeogeography. *Journal of the Geological Society, London* **144**, 737–52.

LEGGETT, J. K., MCKERROW, W. S. & EALES, M. H. 1979. The Southern Uplands of Scotland: a lower Palaeozoic accretionary prism. *Journal of the Geological Society, London* **136**, 755–70.

LINTERN, B. C. & FLOYD, J. D. 2000. *Geology of the Kirkcudbright-Dalbeattie District.* Memoir of the British Geological Survey, Keyworth, 125 pp.

MACKENZIE, D. H. 1956. A structural profile south of Eyemouth, Berwickshire. *Transactions of the Edinburgh Geological Society* **16**, 248–53.

MCCURRY, J. A. & ANDERSON, T. B. 1989. Landward vergence in the lower Paleozoic Southern Uplands-Down-Longford terrane, British Isles. *Geology* **17**, 630–3.

MCKERROW, W. S., LEGGETT, J. K. & EALES, M. H. 1977. Imbricate thrust model of the Southern Uplands of Scotland. *Nature, London* **267**, 237–9.

MOLYNEUX, S. G. 1987. Probable early Wenlock acritarchs from the Linkim Beds of the Southern Uplands. *Scottish Journal of Geology* **23**, 301–13.

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

OLIVER, G. J. H., SMELLIE, J. L., THOMAS, L. J., CASEY, D. M., KEMP, A. E. S., EVANS, L. J., BALDWIN, J. R. & HEPWORTH, B. C. 1984. Early Palaeozoic metamorphic history of the Midland Valley, Southern Uplands, Longford-Down massif, and the Lake District, British Isles. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **75**, 245–58.

PEACH, B. N. & HORNE, J. 1899. *The Silurian rocks of Britain. Vol. 1 Scotland.* Memoir of the Geological Survey, U.K.

PHILLIPS, E. R., BARNES, R. P., BOLAND, M. P., FORTEY, N. J. & MCMILLAN, A. A. 1995. The Moniaive Shear Zone: a major zone of sinistral strike-slip deformation in the Southern Uplands of Scotland. *Scottish Journal of Geology* **31**, 139–49.

RAMSAY, J. G. 1974. Development of chevron folds. *Geological Society of America Bulletin* **85**, 1741–54.

RAMSAY, J. G. & HUBER, M. I. 1987. *The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures.* London: Academic Press.

ROPER, H. 1997. Origins of the "Berwick Monocline"; geometrical and geophysical considerations. *Scottish Journal of Geology* **33**, 133–48.

RUSHTON, A. W. A., STONE, P. & HUGHES, R. A. 1996. Biostratigraphical control of thrust models for the Southern Uplands of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Science*s **86**, 137–52.

SHACKLETON, R. M. 1957. Downward-facing structures of the Highland Border. *Quarterly Journal of the Geological Society of London* **113**, 361–92.

SHEILLS, K. A. G. & DEARMAN, W. R. 1966. On the possible occurrence of Dalradian rocks in the Southern Uplands of Scotland. *Scottish Journal of Geology* **2**, 231–42.

SOPER, N. J. & HUTTON, D. H. W. 1984. Late Caledonian sinistral displacements in Britain: implications for a three-plate collision model. *Tectonics* **3**, 781–94.

SOPER, N. J., STRACHAN, R. A., HOLDSWORTH, R. E., GAYER, R. A. & GREILING, R. O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society, London* **149**, 871–80.

STONE, P. 1995. *Geology of the Rhins of Galloway District*. Memoir of the British Geological Survey, Keyworth, 102 pp.

STONE, P. 1996. *Geology in south-west Scotland: an excursion guide*. Keyworth, Nottingham: British Geological Survey, 214 pp.

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

STRINGER, P. & TREAGUS, J. E. 1980. Non-axial planar S1 cleavage in the Hawick rocks of the Galloway area, Southern Uplands, Scotland. *Journal of Structural Geology* **2**, 317–31.

STRINGER, P. & TREAGUS, J. E. 1981. Asymmetrical folding in the Hawick rocks of the Galloway area, Southern Uplands. *Scottish Journal of Geology* **17**, 129–48.

TREAGUS, J. E. 1992. Caledonian Structures. In *Caledonian Structures in Britain: south of the Midland Valley* (ed. J. E. Treagus), pp. 9–42. Geological Conservation Series 3. London: Chapman & Hall.