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Non-axial planar S_1 cleavage in the Hawick Rocks of the Galloway area, Southern Uplands, Scotland

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Abstract—S_1 cleavage in the Hawick Rocks of the Galloway area is non-axial planar, cutting obliquely across the F_1 folds in a predominantly clockwise sense. Individual S_1 cleavage planes within cleavage-fans in F_1 folds strike clockwise, locally anti-clockwise, of axial surfaces, and the mean plane to the S_1 cleavage-fans dips predominantly more steeply than the axial surface. F_1 folds investigated at scattered localities in Silurian and Ordovician rocks north of the Hawick Rocks are also transected by the S_1 cleavage, indicating that non-axial planar S_1 cleavage is widespread in the Southern Uplands. The S_1 cleavage is a composite fabric. Objects deformed within sandstones and tuffs indicate oblate strain. F_1 fold plunge varies from NE to SW and fold hinges locally are markedly curvilinear. Steeply plunging and locally downward-facing F_1 folds are present along the southeast margin of the Hawick Rocks. The non-axial planar S_1 cleavage relationships persist in the steeply plunging F_1 folds. Synchronous development of the non-axial planar S_1 cleavage and the variably plunging F_1 folds is proposed.

INTRODUCTION

THE HAWICK Rocks of the Galloway area consist of greywacke sandstones and siltstones, interbedded with minor mudstones and shales. They occupy the southern half of the Central Belt of the Southern Uplands (Peach & Horne 1899), bounded to the south by Llandovery and Wenlock rocks of the Southern Belt and to the north by Silurian rocks with inliers of Ordovician in the northern half of the Central Belt (Fig. 1). The Hawick Rocks are largely unfossiliferous and have been interpreted as Llandovery (Lapworth 1874, 1889, Peach & Horne 1899, Rust 1965a, b) and as late Wenlock or Ludlow (Craig & Walton 1959, Clarkson *et al.* 1975). The Silurian rocks of the Central Belt, therefore, are shown as undivided (Fig. 1).

Intense folding and cleavage in the Hawick Rocks and in the adjacent Silurian and Ordovician rocks of the Southern Uplands have long been recognised (Lapworth 1874, 1889, Peach & Horne 1899). Disparity between the trends of folding and cleavage may be inferred from the observation by Peach & Horne (1899, p. 214) that the strike of the Hawick Rocks in the Borgue area is 036°, whereas the prevalent trend of cleavage planes throughout the area is about ENE–WSW. The folding and cleavage in the Hawick Rocks have been interpreted as polyphase in the Whithorn area (Rust 1965a) and near Gatehouse of Fleet (Weir 1968). F_1 folds and axial planar S_1 cleavage (Rust 1965a, p. 108, Weir 1968, p. 33) were considered to be deformed by monoformal folds ascribed to an F_2 phase. The regional cleavage which transects the F_1 folds in a predominantly clockwise sense in the Whithorn area was attributed to an F_3 phase which also produced steeply plunging folds concentrated along strike zones (Rust 1965a, p. 112). Downward-facing folds were interpreted as F_3 folds which deform bedding in the inverted limbs of F_1 folds (Rust 1963). A fourth phase of deformation produced folds with flat-lying axial surfaces and related cleavage. Structures equivalent to Rust's F_3 and F_4 phases were recognised by Weir (1968) near Gatehouse of Fleet, together with additional folds and cleavages attributed to continuation of existing strains during the earlier F_1 and F_2 phases (Weir 1968, 1979).

The present investigation was undertaken after the initial observation by one of us (J.E.T.) and Dr. S. H. Treagus of F_1 folds transected by S_1 cleavage at two localities in the Galloway area (Treagus 1972), and after the recognition of similar phenomena in the Silurian rocks of New Brunswick (Stringer 1975). The non-axial planar S_1 cleavage needed to be reconciled with the polyphase deformational sequences of Rust and Weir. Folds and cleavage have been mapped in coastal sections of the Hawick Rocks around Wigtown Bay and along the east side of Luce Bay, and at scattered coastal localities in Silurian and Ordovician strata elsewhere in the Galloway area. Exposures inland are inadequate to provide comprehensive three-dimensional data of folds and cleavage. Throughout the sections investigated, predominantly upright F_1 folds of intermediate scale and steep to vertical S_1 cleavage are uniformly developed; the F_1 folds are persistently asymmetrical with a predominantly southeast vergence. The F_1 folds and S_1 cleavage are deformed locally by folds with gently to moderately inclined axial surfaces and associated gently inclined

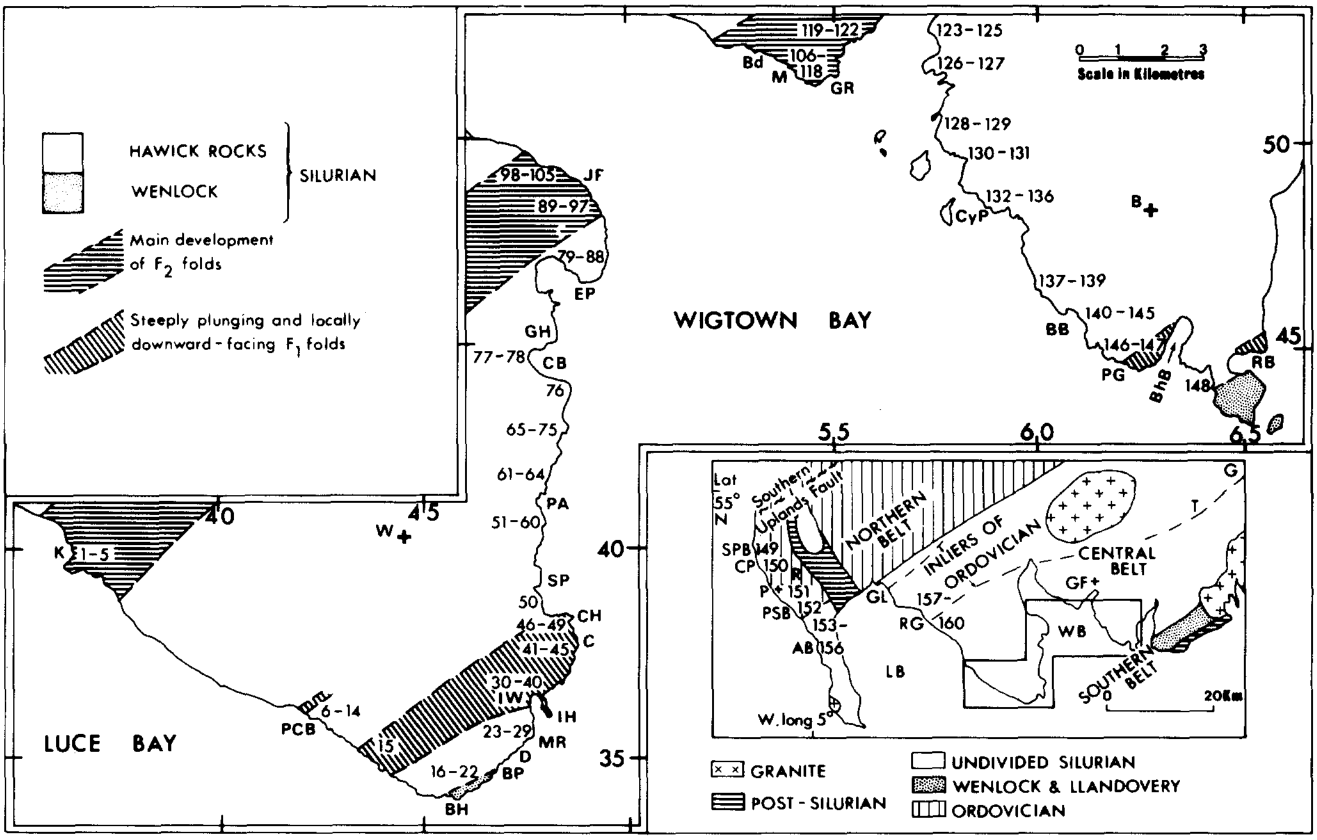

Fig. 1. Geological map of the Wigtown Bay area showing the distribution of the Hawick Rocks and Wenlock rocks (based on Rust 1963, Weir 1968, Clarkson *et al.* 1975), the zone of steeply plunging F_1 folds, and the zone of main development of F_2 folds. Inset is a geological map of the Galloway area showing subdivisions of the Southern Uplands (after Peach & Horne 1899). Numbers refer to F_1 folds in which the relationships of S_1 cleavage to axial surfaces are well exposed (see Appendix for exact locations). Place names: AB Ardwell Bay; B Borgue; BB Borness Bay; Bd Boatdraught; BH Burrow Head; BhB Brighouse Bay; BP Broom Point; C Carrickaboys; CB Cruggleton Bay; CH Cairn Head; CP Cranberry Point; CyP Corseyard Point; D Dykefoot; EP Eggerness Point; G Glen Farm; GF Gatehouse of Fleet; GH Galloway House; GL Glenluce; GR Garvellan Rocks; IH Isle Head; IW Isle of Whithorn; JP Jultock Point; K Kirkmaiden; LB Luce Bay; M Mossyard; MR Mare Rock; P Portpatrick; PA Port Allen; PCB Port Castle Bay; PG Point of Green; PSB Port of Spittal Bay; R Rhinns of Galloway; RB Ross Bay; RG Rocks of Garheugh; SP Shaddock Point; SPB Salt Pans Bay; T Trowdale; W Whithorn; WB Wigtown Bay.

cleavage, apparently formed during a single phase of deformation. The F_2 folds and S_2 cleavage are developed mainly along a NE–SW trending belt 2–3 km wide in the northern part of the Hawick Rocks between Kirkmaiden and Gatehouse of Fleet (Fig. 1). Rare post-F_2 folds and cleavage are of minor significance. The F_1–F_4 sequence of deformations postulated by Rust (1965a) and Weir (1968) in the Hawick Rocks of the Galloway area conflicts with the two phases that we propose; our reinterpretation is discussed in detail elsewhere.

The geometrical relationships of S_1 cleavage to F_1 folds presented in this paper are based on the detailed analysis of 148 well exposed F_1 folds (97 anticlines, 51 synclines) in the Hawick Rocks; the folds are numbered consecutively along the coast from west to east (Fig. 1). F_1 folds and S_1 cleavage have also been investigated north of the Hawick Rocks (see inset map, Fig. 1), in Ordovician strata of the Northern Belt in the Rhinns of Galloway (fold Nos. 149–152), and in Silurian strata in the northern half of the Central Belt at Ardwell Bay (fold Nos. 153–156) and Rocks of Garheugh (fold Nos. 157–160). S_1 cleavage has also been investigated in the Ordovician inliers of the Central Belt. Localities referred to in the text are shown in Fig. 1. The location of the numbered F_1 folds is given in the Appendix by reference to the National Grid.

S_1 CLEAVAGE

The S_1 cleavage is formed by parallel or anastomosing partings, spaced at 1–5 cm intervals in sandstone beds and more closely in mudstone beds. In thin sections of cleaved mudstone beds from the limbs and hinges of F_1 folds, the S_1 cleavage fabric is seen as thin (0.005–0.025 mm) dark domains of fine-grained white mica, opaque minerals and irresolvable material alternating with wider (0.01–0.1 mm) pale domains of fine-grained white mica. Micas within the dark domains commonly lie subparallel to the cleavage direction. The dark domains correspond to the mesoscopic S_1 cleavage partings. Where thin silty quartzose beds are present within the folded mudstones, the dark domains converge towards re-entrants in the silty layer formed by buckles and by reverse microfaults. The dark domains match structures interpreted as pressure solution cleavage planes (Durney 1972, Williams 1972, Gray 1979, Stephens *et al.* 1979, Nickelsen 1979). At the hinges of F_1 folds of mudstone beds, the fine grained micas in the pale domains usually appear variable in orientation, but in places they are aligned subparallel to bedding which is crenulated between the pressure solution planes; some individual flakes are flexed. On the limbs of F_1 folds, micas in the pale

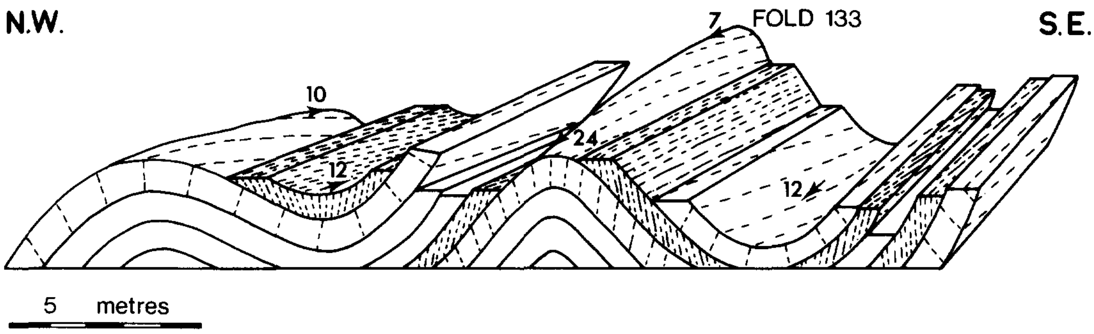

Fig. 2. General fold and cleavage geometry in the Hawick Rocks based on field observations of fold No. 133 and adjacent folds, near Corseyard Point (NX 5835 4865). Cleavage is shown open-spaced in sandstones, narrow-spaced in mudstones and intermediate in one siltstone bed.

domains show a weak to strong orientation parallel to S_1, superimposed upon the variably oriented and crenulated micas.

In thin sections of cleaved sandstone beds, the pale domains commonly display a weak preferred dimensional orientation of clastic quartz and feldspar grains parallel to the S_1 cleavage, with bearded overgrowths in the cleavage direction on some grains. Scattered coarse detrital mica flakes are generally subparallel to bedding. In the 1–5 cm spaced films of fine-grained mica and opaque minerals which form the pressure solution cleavage planes, micas are aligned subparallel to S_1. The S_1 cleavage is, therefore, a composite fabric defined by pressure solution planes, crenulated bedding micas, and incipient mineral orientation parallel to the cleavage direction.

Cleavage-fans

The S_1 cleavage forms divergent fans (Ramsay 1967, p. 405) in folded mudstone beds and convergent fans in folded sandstone beds, centred on the axial surface in both gently (Fig. 2) and steeply (Fig. 3) plunging F_1 folds. The dihedral angle of the cleavage-fans, usually small in tight folds and large in more open folds, ranges from about 5 to 90° in divergent fans (average angle 29° in 128 folds) and from about 5 to 135° in convergent fans (average angle 48° in 74 folds). The S_1 cleavage is refracted from mudstone to sandstone beds, with large angles of refraction in the limbs of the more open F_1 folds. The S_1 cleavage in mudstone beds locally displays a finite neutral point (Ramsay 1967, p. 417) at the hinges of gently or steeply plunging F_1 folds.

Strain indicators

In the northern part of the Hawick Rocks, deformed sand volcanoes flattened within the S_1 cleavage show elliptical cross-sections with axial ratios of about 2 : 1 near Jultock Point (National Grid Reference NX 4893 4893),

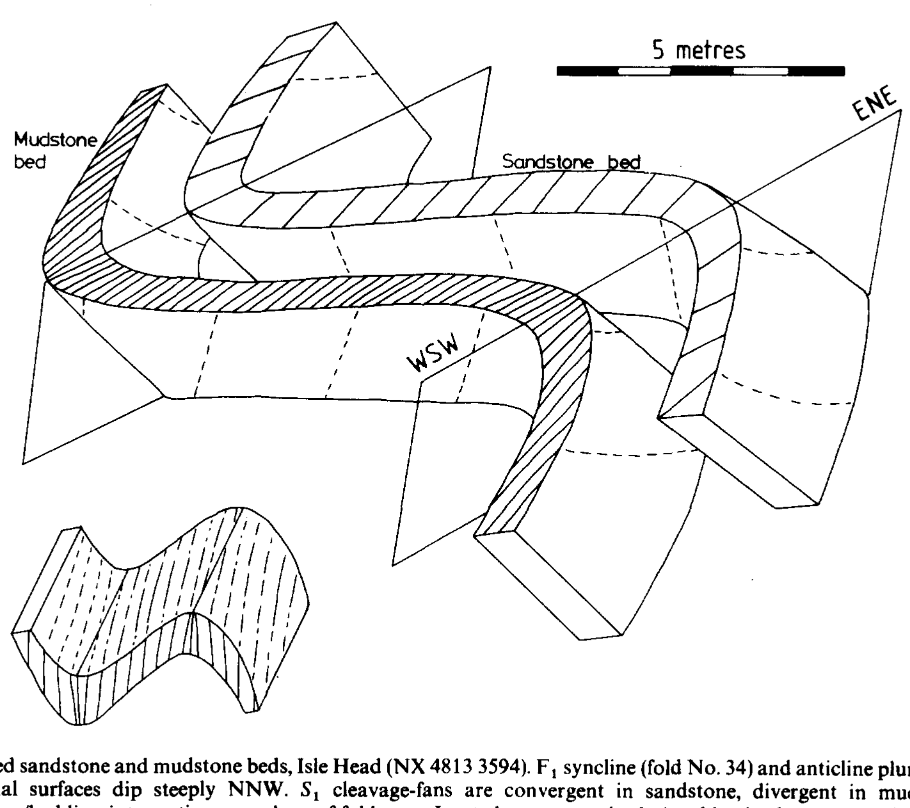

Fig. 3. Folded sandstone and mudstone beds, Isle Head (NX 4813 3594). F_1 syncline (fold No. 34) and anticline plunge steeply NE and axial surfaces dip steeply NNW. S_1 cleavage-fans are convergent in sandstone, divergent in mudstone. S_1 cleavage/bedding intersections are skew of fold axes. Inset shows general relationships in the transected fold.

and near Boatdraught on the opposite side of Wigtown Bay (Fig. 4a). Farther southeast, sand volcanoes near Isle of Whithorn are only slightly deformed (Rust 1965b, plate 1, fig. 1), and near Isle Head sand volcanoes in the short limb of an asymmetrical F_1 fold (Nos. 32 and 33) plunging NE at 60° appear undeformed. The profiles of the deformed sand volcanoes parallel to the S_1 cleavage plane show curvature similar to that of the undeformed sand volcanoes, indicating that the flattening strain is essentially oblate.

Diagenetic carbonate-rich nodules developed parallel to bedding in the greywacke sandstones (Rust 1965b, p. 243) usually appear only slightly deformed in the Hawick Rocks (Figs. 4b & c). In Silurian rocks north of the Hawick Rocks, nodules flattened within the S_1 cleavage show elliptical cross-sections with axial ratios of 2 : 1 in a vertical roadside section north of the Rocks of Garheugh (NX 266 502).

In Ordovician inliers northeast of Gatehouse of Fleet, tuffs near Glen Farm (NX 833 763) and Trowdale (NX 764 688) contain numerous devitrification spots deformed into ellipsoids 1–2 mm long. In thin sections, the elliptical siliceous spots are elongated in the S_1 cleavage with axial ratios up to 2 : 1. Spots in contact exhibit mutual pressure solution boundaries parallel to the cleavage. In thin sections parallel to the cleavage surface, the spots are circular in outline.

The deformed objects observed at scattered localities in the Galloway area in the competent Silurian sandstones and in the Ordovician tuffs indicate oblate flattening strain, apparently greater in the north, coeval with the development of the non-axial planar S_1 cleavage. In the incompetent mudstones deformed objects have not been observed, but a persistent lack of mineral stretching lineations on S_1 cleavage surfaces suggests that the strain is oblate. Some 50 km southwest of Galloway in the Silurian rocks of the Ards, Anderson (1962) recorded a faint stretching fibre in cleaved mudstones, indicating weak extensional strains.

F_1 FOLDS

F_1 folds are persistently asymmetrical in the Hawick Rocks throughout the coastal sections examined, and also in the Silurian and Ordovician rocks north of the Hawick Rocks. The fold pattern viewed towards the northeast is predominantly dextral (Fig. 2); thick sections of steeply inclined or overturned strata decreasing in age to the northwest occupy the long limbs of the F_1 folds. Strata which decrease in age to the southeast in the short limbs of dextral folds, and also in the long limbs of local sinistral F_1 folds, occupy relatively narrow strike zones. Most F_1 folds are intermediate in scale, with amplitudes of about 5–50 m. Sections of southeast younging strata about 250 m thick at a few localities may represent the short limbs of larger scale F_1 folds of about 300–500 m amplitude. For 15 km across the strike of the Hawick Rocks, the local distribution of F_1 fold hinges varies from about 20 to 60 fold hinges in 1 km but the regional distribution is essentially uniform. Sections of strata decreasing in age to the northwest or southeast in which F_1 fold hinges are absent rarely exceed 200 m in width.

The F_1 folds are mostly tight to moderately tight, with interlimb angles between 20 and 70° (Figs. 4c & d and 5a). The few open folds generally involve the more competent beds. Upright folds predominate, with axial surfaces inclined at 65–90° NW or SE. Axial surfaces of open F_1 folds locally dip less steeply at 45–65° NW or SE. F_1 folds are locally recumbent due to rotation by F_2 folds (Fig. 4c). Sandstone beds in many moderately tight F_1 folds maintain constant orthogonal thickness at fold hinges, while interbedded mudstones show only moderate axial thickening. Essentially parallel styles of folding have also been recorded by Weir (1968, p. 35) near Gatehouse of Fleet, and by Anderson (1962) in the Silurian rocks of the Ards. Flattened concentric F_1 folds with up to three-fold axial thickening of mudstone beds and two-fold axial thickening of sandstone beds (Rust 1965a, pp. 116–118; see also Dewey 1969, pp. 314 and 329) have been observed only locally. Significant (10–50%) thickening of sandstone or mudstone beds from one limb to the other, which has been observed in a few F_1 folds, may occur in the short limb or the long limb. The style of folding is essentially the same in both gently plunging and in steeply plunging, locally downward-facing, F_1 folds.

Over short distances, F_1 folds may be cylindrical with rectilinear hinges and constant fold profile, but where exposed extensively along the strike, the fold profile is rarely constant and may change markedly. Thus, the profile of an anticline near Corseyard Point (fold No. 135, and Fig. 6a) changes southwestward, bifurcating to include a syncline, with concomitant changes in plunge, interlimb angle and axial surface orientation. Along the coast northeast of Burrow Head, the axial surface changes in attitude northeastwards from 056°/66° SE to 062°/79° SE in a pericline (fold No. 20) near Broom Point, and from 060°/85° NW to 072°/82° SE in an anticline (fold No. 22) near Mare Rock. Similar variations have been recorded by Craig & Walton (1959, fig. 4).

F_1 fold plunge

The F_1 folds mostly plunge gently or moderately, to the northeast or southwest (Fig. 7a). Adjacent fold pairs commonly plunge in opposite directions (Fig. 2); a consistent direction of plunge in successive F_1 folds has been observed only along the coast for 5 km south of Cruggleton Bay, where the plunge is NE. Individual fold hinges may show slight or moderate axial curvature (Fig. 4d) and in places are periclinal (Fig. 5a). Complementary hinges of fold pairs often display different degrees of plunge, and may plunge in opposite directions; a syncline south of Port Castle Bay plunges 14°/248° and the corresponding anticline (fold No. 14) plunges 15°/079°.

F_1 folds plunge steeply and locally are vertical or downward-facing (Fig. 5b) in the Hawick Rocks within a broad zone which extends subparallel to the 060° regional strike along the southern margin of the Central Belt (Fig.

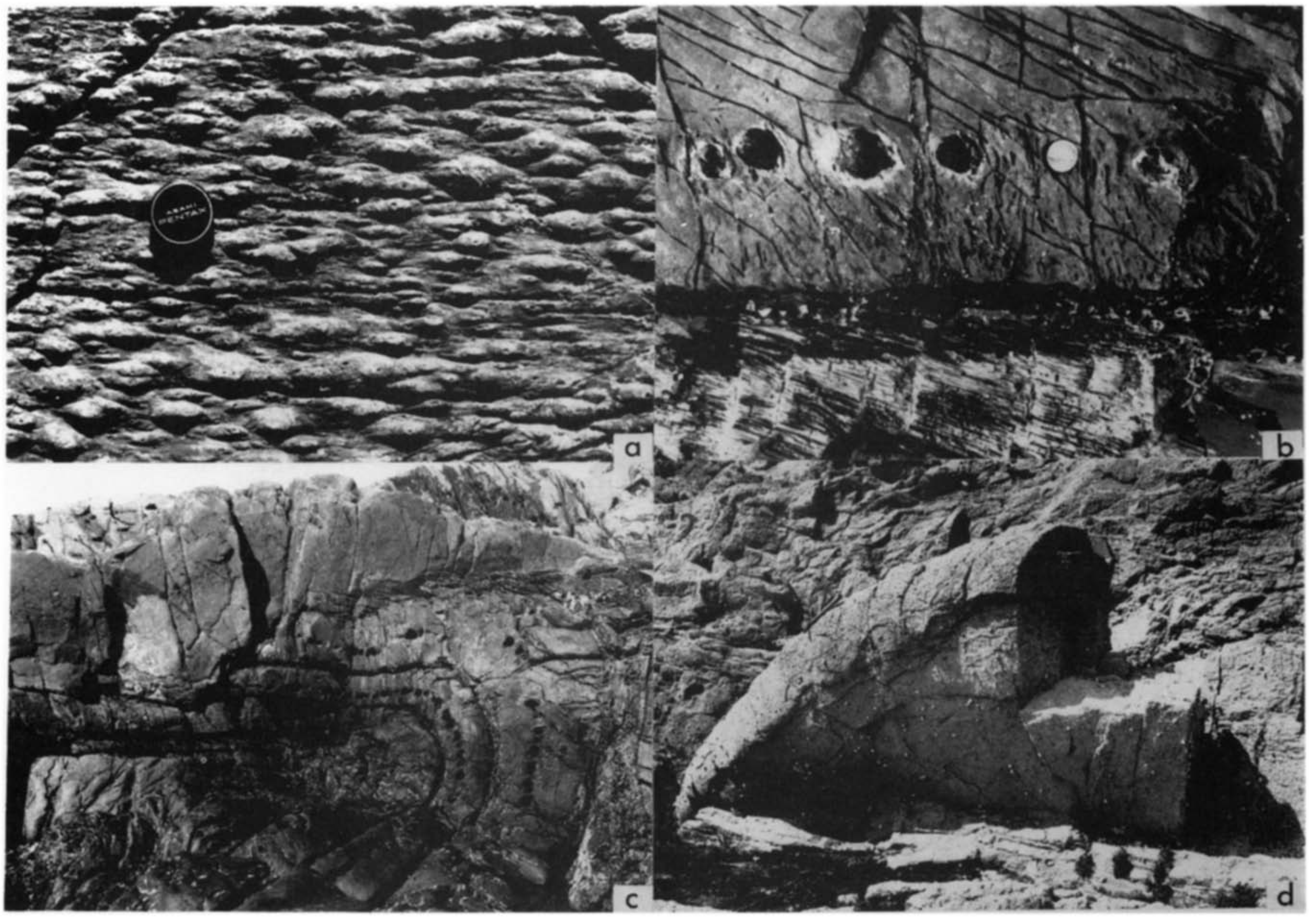

Fig. 4. (a) Sand volcanoes deformed within S_1 cleavage on a gently inclined bedding surface (NX 5376 5188), 50 m southeast of Boatdraught. Diameter of lens cap is 54 mm. (b) Weathered carbonate-rich nodules, Brighouse Bay (NX 6315 4495). Nodules are slightly compressed within the S_1 cleavage striking clockwise of vertical greywacke sandstone beds (plan view). (c) Weathered carbonate-rich nodules parallel to bedding in greywacke sandstone are slightly compressed within S_1 at the hinge of a tight F_1 anticline, Mossyard (NX 5410 5167). The F_1 fold is recumbent due to local F_2 folding. Width of outcrop is 3 m. (d) Tight upright F_1 anticline, north side of Borness Bay (NX 6060 4565). Curvilinear fold hinge plunges southwest (left) at 5° to 42°.

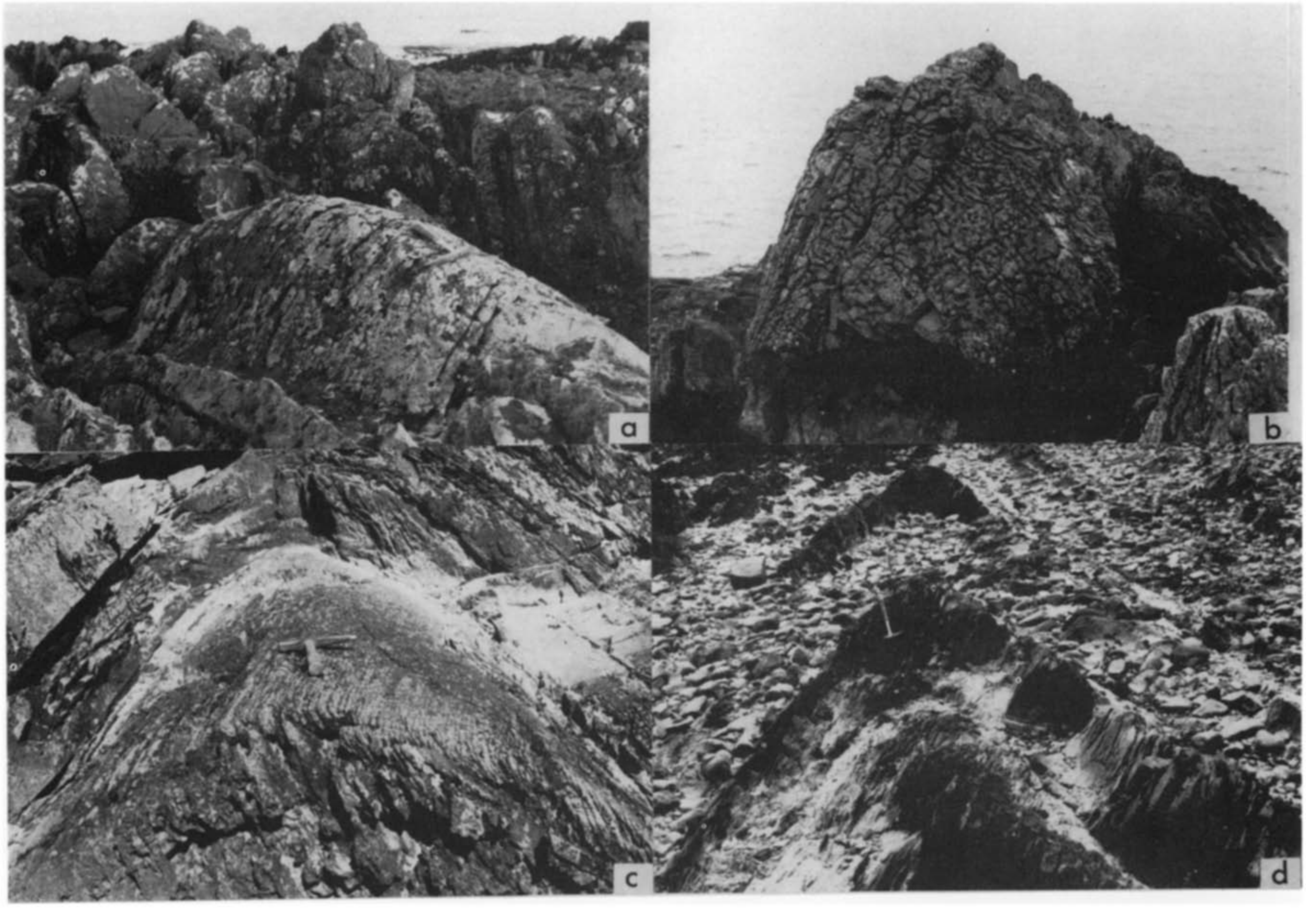

Fig. 5. (a) F_1 pericline, Shaddock Point (NX 4785 3927). Curvilinear fold hinge trends ENE–WSW. (b) Downward-facing F_1 syncline, Point of Green (NX 6233 4445). Fold plunges steeply ENE (toward observer). Load casts on antiform surface are inverted. Width of outcrop is 6 m. (c) F_1 anticline hinge, Garvellan Rocks (NX 5501 5132). Fold plunges gently northeast parallel to hammer handle. Non-axial planar S_1 cleavage dipping steeply SSE (right) strikes clockwise of the axial surface. (d) Upright F_1 anticline, Galloway House (NX 480 448). Fold plunges moderately SW. Non-axial planar S_1 cleavage dipping steeply SSE (left) transects the axial surface and both fold limbs.

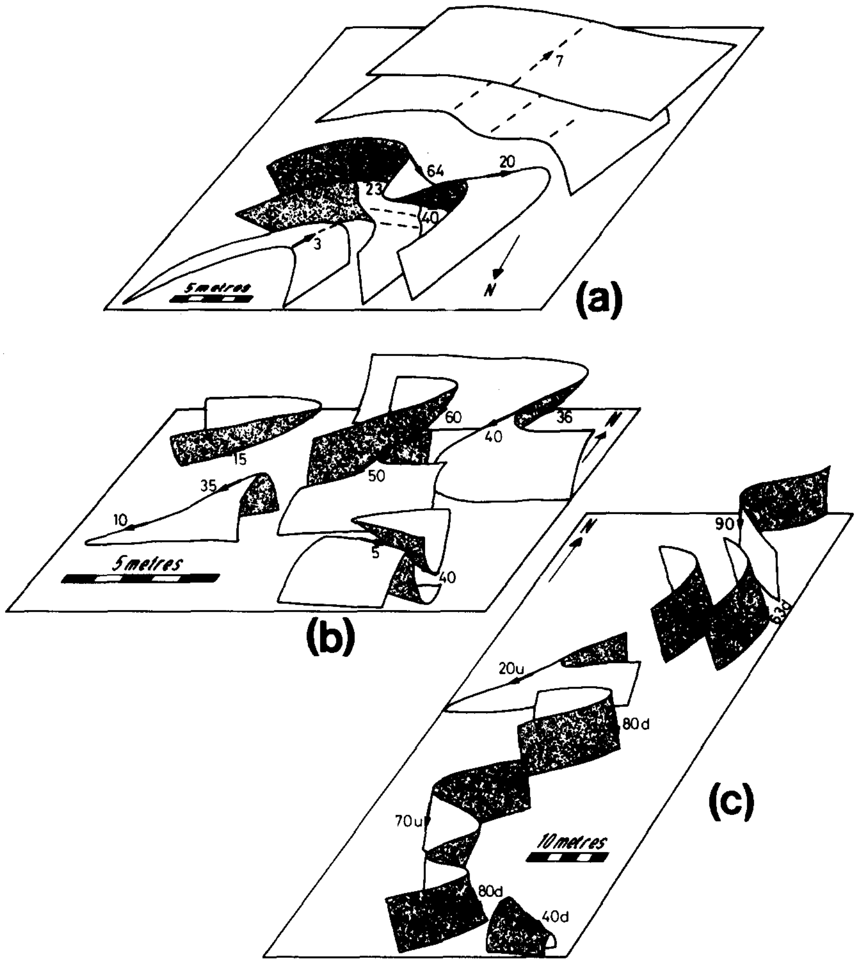

Fig. 6. Variations in plunge and fold-profile. (a) Changes in profile in an F_1 anticline (fold No. 135) near Corseyard Point (NX 5950 4805–5946 4802). (b) Opposing plunge in F_1 folds at Cairn Head (NX 4829 3843). (c) Adjacent upward-facing (u) and downward-facing (d) F_1 folds, west side of Isle of Whithorn harbour (NX 4757 3631–4764 3648).

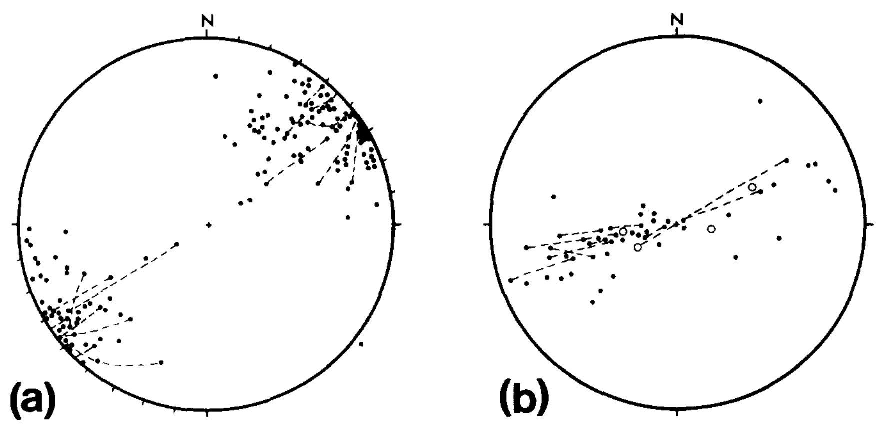

Fig. 7. Stereograms (lower hemisphere, equal-area) of F_1 fold plunge in Hawick rocks of the Galloway area. Solid circles, upward facing folds; open circles, downward facing folds; dashed lines, curvilinear hinges. (a) F_1 folds excluding main zone of steep plunge (135 folds). (b) F_1 folds in main zone of steep plunge (45 folds).

1). The zone is about 1000 m wide on the coast of Luce Bay 2 km northwest of Burrow Head, and about 1500 m wide between Cairn Head and Isle of Whithorn harbour. The steeply plunging F_1 folds are prominent at Cairn Head and Carrickaboys (the zones of F_3 concentration of Rust 1965a, p. 112). On the opposite side of Wigtown Bay, the zone is represented by two strike belts of steeply plunging folds, one 300 m along the northwest side of Brighouse Bay (Craig & Walton 1959) and the other 200 m wide on the north side of Ross Bay.

In the zone of steeply plunging folds, SW plunges are more common than NE (Fig. 7b); gentle to moderate SW and NE plunges are also present. Interlimb angles range from 8 to 76°, but are mostly about 45°. Fold hinges locally display axial curvature, and adjoining hinges may plunge in opposite directions (Fig. 6b). Upward-facing steeply plunging folds in places curve through vertical or reclined attitudes into downward-facing folds with an opposite direction of plunge (Fig. 7b). Opposing plunges include adjoining upward-facing and downward-facing hinges (Fig. 6c). Commonly, hinges are isolated by intense subvertical strike faults and shears. Complete F_1 fold pairs are mostly asymmetrical, with strata in the long limbs younging northwest, hinges plunging steeply SW (or NE, downward-facing), and axial surfaces subvertical, striking close to E–W. In places the folds appear symmetrical, for example at Carrickaboys (Fig. 8), and northwest of Burrow Head an asymmetrical downward-facing F_1 fold pair (NX 4390 3483) plunging 64°/262° has strata in the long limbs younging southeast. F_1 folds with strata in the long limbs younging towards the northwest predominate in the zone of steep plunge, as they do in Silurian and Ordovician rocks elsewhere in the Galloway area.

Steeply plunging F_1 folds occur in a few localities outside the main zone. To the southeast, folds near Isle Head plunge steeply NE, an anticline (fold No. 21) plunges 40–58°/074° near Dykefoot, and near Broom Point an anticline (fold No. 19) plunges SW at 15–75°, changing rapidly to the steep plunge over a distance of 10 m. To the northwest, folds plunge steeply near Port Castle Bay (Fig. 1), and 5 km northwest of Brighouse Bay an anticline (fold No. 135, and Fig. 6a) plunges SW at 3–64°. In the Ordovician rocks, reclined F_1 folds in a shaly

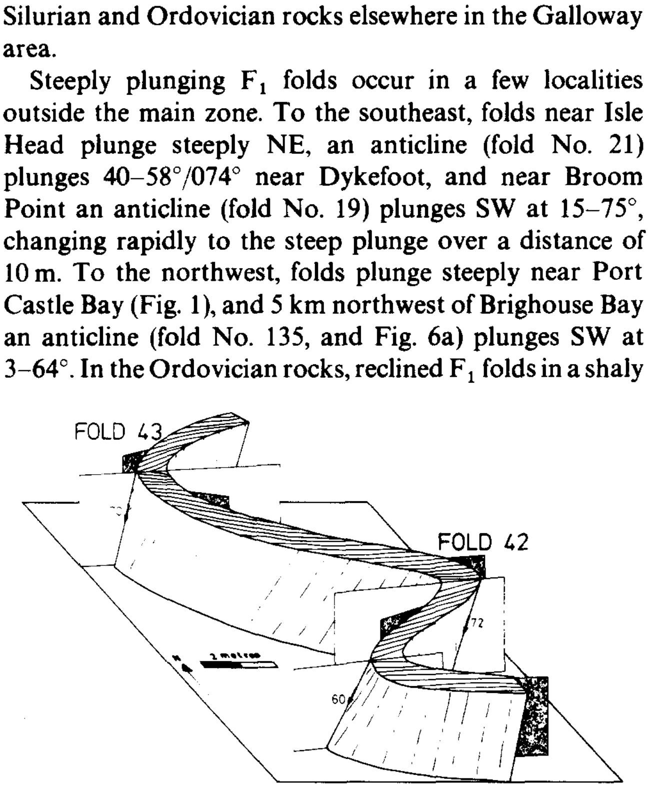

Fig. 8. Folded mudstone bed, Carrickaboys (NX 4877 3773). F_1 folds plunge steeply W and axial surfaces dip steeply S. S_1 cleavage-fans are divergent. S_1 cleavage/bedding intersections are skew of fold axes.

sequence at Salt Pans Bay (NW 9654 6147) plunge steeply S.

GEOMETRICAL RELATIONSHIPS

Throughout the coastal sections of Hawick Rocks, the strike of the steep to vertical S_1 cleavage is predominantly clockwise of the strike of the steeply inclined bedding in both northwestward and southeastward younging strata; both dextral and sinistral F_1 folds are transected in a predominantly clockwise sense by the S_1 cleavage (Figs. 2 and 5c & d). At a few localities the non-axial planar S_1 cleavage strikes anti-clockwise of the axial surface of dextral and sinistral folds. Folds in which the angle between the axial surface and S_1 cleavage is less than 5° are rare (Figs. 9b & c) but the absence of F_1 folds with strictly axial planar S_1 cleavage may, in part, result from the difficulty of accurately constructing axial surfaces to non-cylindroidal folds.

Within S_1 cleavage-fans, individual cleavage planes transect the F_1 fold hinges (Fig. 2). The general relationships (Fig. 10) are best displayed along the hinges of extensively exposed subhorizontal folds. Figure 10 is based upon detailed observations at many localities but particularly those near Corseyard Point (fold Nos. 132–136, Fig. 2) and near Eggerness Point (fold Nos. 79–85). A progressive change in orientation of individual S_1 cleavage planes in sandstone beds may be traced northeastward along the fold hinges from SE dip in the northwest limb of the anticlines, through the vertical where the steeply inclined axial surface is transected, to NW dip in the southeast limb. In mudstone beds the reverse relationship of steep NW cleavage dips traced through vertical to steep SE dips is less obvious, but the transection of fold hinges by the clockwise-striking cleavage is clearly displayed. In profile sections of gently plunging folds, the mean plane to the S_1 cleavage-fan is usually a few degrees oblique to the axial surface, often dipping more steeply.

Steeply plunging F_1 folds are also transected by the S_1 cleavage. In folds of mudstone beds plunging steeply W at Carrickaboys (Fig. 8), the mean plane to the S_1 cleavage-fans dips S at slightly different angles to the axial surfaces and strikes clockwise of the axial surfaces at a small angle. The syncline (fold No. 34) and anticline which form a sinistral fold pair plunging steeply NE at Isle Head are transected by S_1 cleavage in an anti-clockwise sense (Fig. 3), and the S_1 cleavage dips NW more steeply than the axial surface.

The angle between the strike of the axial surface and the strike of the mean plane to S_1 cleavage is independent of the plunge of F_1 folds (Fig. 9a). In F_1 folds plunging gently or steeply to the NE or SW, the strike of clockwise S_1 cleavage differs by about 5–15° from the strike of the axial surface in folded mudstone beds, and by a larger angle in folded sandstone beds. Anti-clockwise S_1 cleavage shows similar differences in strike to the axial surface. The dihedral angle between the axial surface and the mean plane to S_1 cleavage-fans, more meaningful than the strike difference, is also independent of the angle of plunge (Fig.

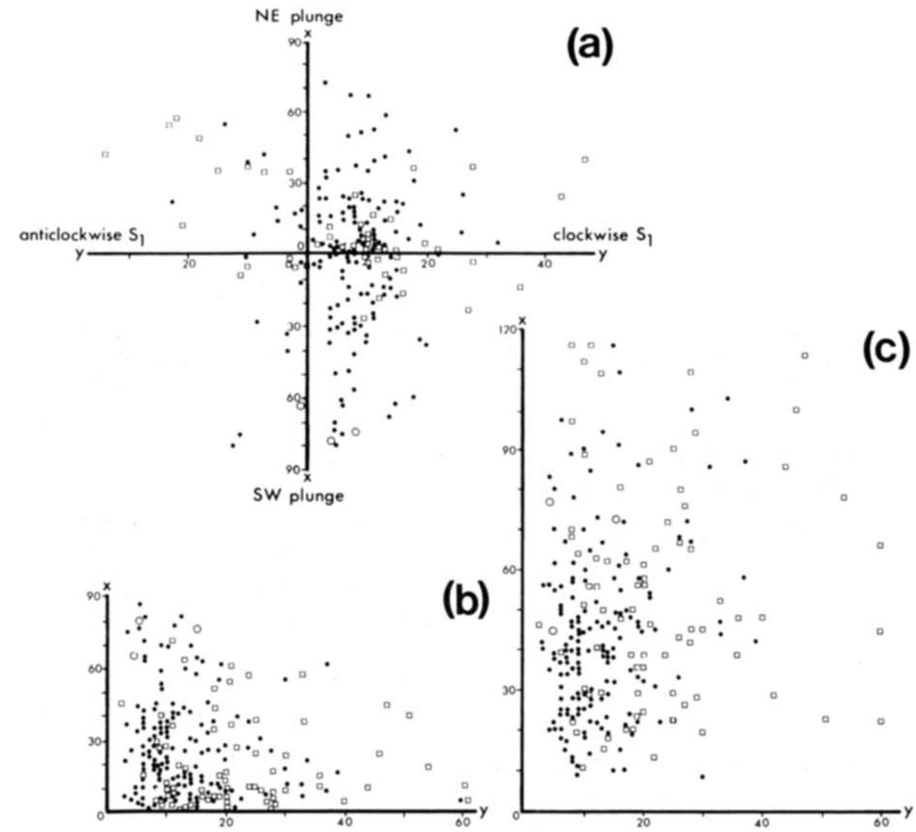

Fig. 9. Angular relationships between S_1 cleavage and axial surface of F_1 folds: solid circles, mudstone beds; open circles, mudstone beds in downward-facing F_1 folds; squares, sandstone beds. (a) Plot of angle of plunge of F_1 folds (x) against the angle between strike of axial surface and strike of the mean plane to S_1 cleavage-fan (y). (b) Plot of angle of plunge of F_1 folds (x) against the dihedral angle between axial surface and the mean plane to S_1 cleavage-fan (y). (c) Plot of interlimb angle of F_1 folds (x) against the dihedral angle between axial surface and the mean plane to S_1 cleavage-fan (y).

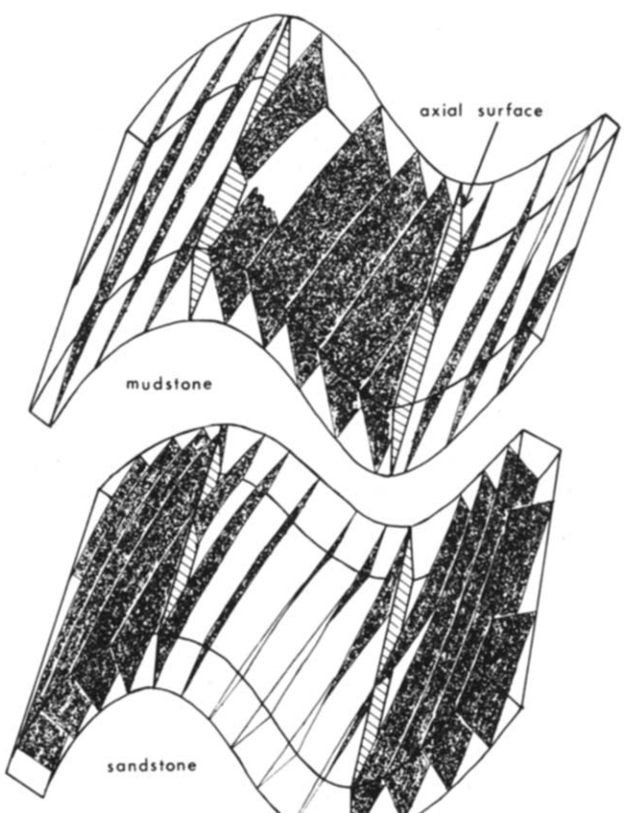

Fig. 10. A schematic representation of the relationship of S_1 cleavage planes to cylindroidal F_1 folds in sandstone and mudstone beds in the Galloway area.

9b), and is independent of the interlimb angle (Fig. 9c).

Poles to bedding and S_1 cleavage measured along a single fold profile in F_1 folds usually show an approximate great circle distribution. In the fold pair at Isle Head (Fig. 3), poles to S_1 cleavage and bedding measured in one mudstone bed along the fold profile plot as great circles (Fig. 11a). A great circle distribution of poles is also shown by S_1 cleavage in another mudstone bed (Fig. 11b) and by bedding in a sandstone bed (Fig. 11c) in the same fold pair. The beds have the same thickness in the short and long limbs. Thus the orientations of the axial surface and of the mean plane to the S_1 cleavage-fans can be determined stereographically for the syncline and anticline in the fold pair, together with other geometrical data (Table 1). Similar data have been determined for over one hundred F_1 folds in the Galloway area and incorporated in Fig. 9 and Table 2. Axial surface attitudes were taken as the bisectors of the bedding attitudes at the inflexion points on opposite limbs of individual folds. The mean planes to the S_1 cleavage-fans were taken as the bisectors of the extreme attitudes of the cleavage within individual folds.

In Silurian rocks north of the Hawick Rocks, at Ardwell Bay and Rocks of Garheugh, S_1 cleavage strikes 5–10° clockwise of, and dips more steeply than, the axial surface of F_1 folds (fold Nos. 153–160). In the Ordovician rocks, F_1 folds transected within a short distance by S_1 cleavage have not been observed, but the calculated strike of the mean plane to the S_1 cleavage-fans is oblique to the strike of the axial surface of F_1 folds, anti-clockwise north of Salt

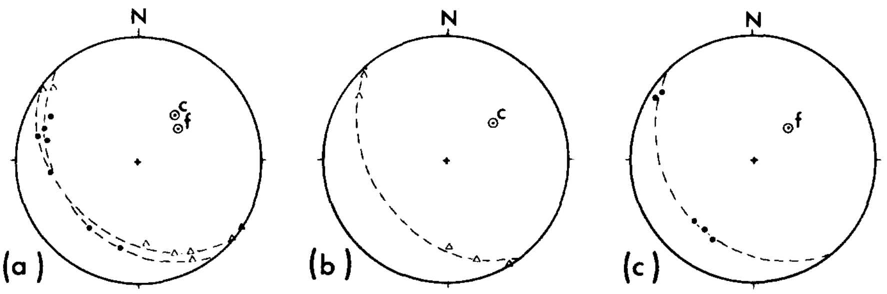

Fig. 11. Stereograms (lower hemisphere, equal-area) of structural data from F_1 fold pair at Isle Head (Fig. 3), showing great circle distributions of poles to S_1 cleavage and poles to bedding in different beds measured along the fold profile; f, fold plunge; c, intersection of fanned cleavage. (a) Mudstone bed, S_1 cleavage and bedding poles. (b) Mudstone bed, S_1 cleavage poles. (c) Sandstone bed, bedding poles.

Pans Bay (fold No. 149), and slightly clockwise at Cranberry Point (fold No. 150), south of Portpatrick (fold No. 151), and on the south side of Port of Spittal Bay (fold No. 152).

Curvature of S_1 cleavage-fans and axial surfaces

In a sinistral F_1 fold pair plunging moderately NE in Port Allen (fold Nos. 61 and 62), the axial surface of the anticline and syncline curve northeastward from 056°/72° NW to 078°/40° NW (Fig. 12) as the interlimb angle increases and the plunge decreases. The curvature of the axial surfaces was an original feature of the F_1 folding concomitant with change in profile. The S_1 cleavage-fans in the folded mudstone and sandstone beds curve in sympathy with, but remain oblique to, the axial surface; the mean plane to the S_1 cleavage-fans changes from 058°/82° NW to 063°/50° NW in the folded mudstone beds and from 044°/86° NW to 069°/46° NW in the folded sandstone beds, maintaining a steeper NW dip than the axial surface and an anti-clockwise strike throughout the curvature.

Table 1. Geometry of F_1 folds and S_1 cleavage, Isle Head

	1	2	3	4	5	6
Sandstone bed						
Syncline	58°/048°	94°	076°/72°NW	6°	049°/83°NW	29°
Anticline	58°/046°	90°	073°/74°NW	20°	050°/85°NW	25°
Mudstone bed						
Syncline	55°/048°	91°	060°/71°NW	44°	048°/82°NW	16°
Anticline	54°/046°	90°	061°/79°NW	58°	052°/74°NW	10°

KEY

1. Plunge of F_1 fold.
2. Interlimb angle.
3. Strike and dip of axial surface.
4. Dihedral angle of S_1 cleavage fan.
5. Strike and dip of the mean plane to S_1 cleavage fan.
6. Angle between axial surface and the mean plane to S_1 cleavage fan.

Modal (vector mean) orientations

Modal (vector mean) orientations of the mean plane to S_1 cleavage-fans (referred to below as modal S_1 cleavage) and modal (vector mean) orientations of axial surfaces have been calculated for individual and combined categories of F_1 fold geometry (Table 2).

Modal S_1 cleavage dips more steeply than the modal axial surface in all categories of F_1 folds of mudstone beds. In F_1 folds of sandstone beds, modal S_1 cleavage is steeper than NW dipping modal axial surfaces and is predominantly less steep than SE dipping modal axial surfaces.

In folds of mudstone beds, the difference in strike between the modal axial surface and modal clockwise S_1 cleavage is about 5–10°, and for modal anti-clockwise S_1 cleavage it is about 5–20°. In folds of sandstone beds, the difference in strike is about 5–25° for clockwise S_1 cleavage and 5–20° for anti-clockwise S_1 cleavage.

The modal S_1 cleavage of 157 cleavage-fans (067°/vertical) strikes clockwise of the modal axial surface (061°/86° NW) and is more steeply inclined. Modal orientations determined for 28 F_1 folds of mudstone beds, in which the cleavage-fans could not readily be measured, are similar to those for cleavage-fans (Table 2); the modal S_1 cleavage is derived from individual S_1 cleavage attitudes measured where the cleavage transects the axial surface.

DISCUSSION

The Hawick Rocks of the Galloway area display two unusual structural features that require discussion; (i) the

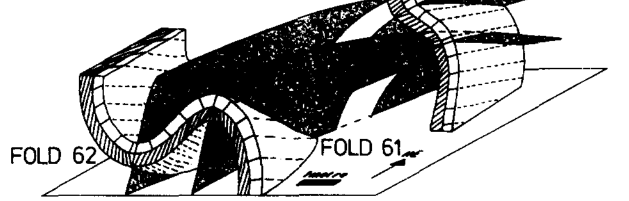

Fig. 12. Relationship of cleavage-fans to changes in F_1 fold profile, Port Allen (NX 4780 4108). The cleavage-fans curve in sympathy with the curviplanar axial surfaces. S_1 cleavage/bedding intersections are skew of the fold axes.

Table 2. Modal (vector mean) orientations

F_1 fold and S_1 cleavage geometry (see key)	Folded mudstone beds: Number of folds	Folded mudstone beds: Modal orientation of F_1 axial surfaces	Folded mudstone beds: Modal orientation of mean plane to S_1 cleavage fans	Folded sandstone beds: Number of folds	Folded sandstone beds: Modal orientation of F_1 axial surfaces	Folded sandstone beds: Modal orientation of mean plane to S_1 cleavage fans
1	19	055°/79°NW	064°/81°NW	12	050°/74°NW	075°/85°NW
2	17	064°/76°SE	072°/78°SE	15	058°/74°SE	068°/70°SE
3	11	061°/82°NW	070°/86°NW	4	055°/74°NW	072°/81°NW
4	7	069°/72°SE	076°/76°SE	0		
5	24	056°/75°NW	064°/78°NW	10	057°/79°NW	071°/85°NW
6	7	060°/77°SE	064°/80°SE	3	068°/74°SE	072°/56°SE
7	3	088°/75NW	075°/76°NW	4	057°/72°NW	048°/79°NW
8	4	077°/69°SE	074°/70°SE	1	077°/66°SE	068°/71°SE
9	5	083°/70°NW	064°/88°NW	3	085°/72°NW	065°/82°NW
10	0			1	032°/64°SE	022°/60°SE
11	5	063°/64°NW	055°/76°NW	2	067°/56°NW	057°/66°NW
12	0			0		
13	86	060°/88°NW	068°/89°NW	44	056°/89°NW	071°/83°SE
14	16	075°/78°NW	064°/86°NW	11	066°/72°NW	053°/79°NW
15	102	062°/86°NW	067°/88°NW	55	058°/86°NW	067°/87°SE
16	10	076°/87°SE	085°/88°SE	0		
17	7	085°/83°NW	070°/90°	4	083°/71°NW	062°/82°NW
	Folded mudstone and sandstone beds					
18	157	061°/86°NW	067°/90°			
	Folded mudstone beds					
	Number of folds	F_1 axial surface	S_1 cleavage at axial surface			
19	28	060°/84°NW	068°/87°NW			

KEY TO F_1 FOLD AND S_1 CLEAVAGE GEOMETRY

(1-6) Mean plane to S_1 cleavage fan striking clockwise of axial surface in F_1 folds; as defined below.

Asymmetrical folds:

1 Strata in long limbs young NW, axial surfaces dip NW.
2 Strata in long limbs young NW, axial surfaces dip SE.
3 Strata in long limbs young SE, axial surfaces dip NW.
4 Strata in long limbs young SE, axial surfaces dip SE.

Symmetrical folds:

5 Axial surfaces dip NW.
6 Axial surfaces dip SE.

(7-12) As 1-6, mean plane to S_1 cleavage fan striking anti-clockwise of axial surface in F_1 folds.

13 F_1 folds with clockwise S_1 cleavage (1-6 combined).

14 F_1 folds with anti-clockwise S_1 cleavage (7-12 combined).

15 F_1 folds with clockwise and anti-clockwise S_1 cleavage (1-12 combined).

(16-17) F_1 folds plunging more steeply than 50°: mean plane to S_1 cleavage fan strikes clockwise of axial surface (16); anti-clockwise of axial surface (17).

18 F_1 folds of mudstone beds and sandstone beds combined.

19 Modal S_1 cleavage orientation based on single S_1 cleavage attitudes measured where the cleavage transects the axial surface of F_1 folds.

non-axial planar cleavage related to the F_1 folds, and (ii) the zone of steep plunging and locally downward-facing F_1 folds.

Non-axial planar cleavage

Interpretations of folds with associated non-axial planar cleavage have usually invoked closely related, but successive, non-coaxial strains (Ramsay 1965, Moseley 1968, Powell 1974, Stringer 1975, Soper & Moseley 1978, Borradaile 1978, Engelder & Geiser 1979, Stringer & Lajtai 1979). An alternative model with coeval formation of folds and non-axial planar cleavage, in which folds are generated on bedding planes non-orthogonal with respect to the axes (X, Y. Z) of the finite strain ellipsoid (Flinn 1962), has been developed by Treagus (1972) and further discussed by Borradaile (1978, pp. 482–486). In this model, cleavage, regarded as parallel to the XY principal plane of the finite strain ellipsoid, would not be parallel to the axial surface.

In Fig. 13 initial bedding has been chosen to strike 10° clockwise of the plane (XY) perpendicular to the bulk shortening direction (Z), and to dip 15° (N or S). The

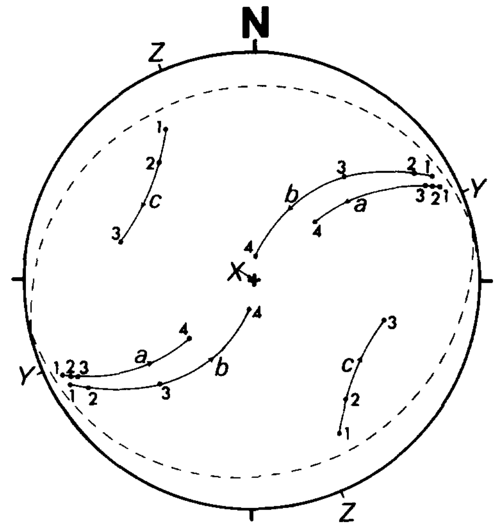

Fig. 13. Stereographic representation of possible fold paths, a, b and c, developed on bedding planes (dashed lines) with an initial non-orthogonal relationship to strain axes (X, Y, Z). Path a is for plane strain, while paths b and c represent the two directions of folding possible with a small amount of shortening in Y. The three incremental stages (points 1, 2 and 3) shown on each path are the following strain ratios ($X:Y:Z$): a^1, 1.3 : 1 : 0.8; a^2, 1.6 : 1 : 0.63; a^3, 2 : 1 : 0.5; b^1 and c^1, 1.3 : 0.95 : 0.8; b^2 and c^2, 1.8 : 0.9 : 0.63; b^3 and c^3, 2.4 : 0.85 : 0.5. Folds a^4 and b^4 are developed with strains of 4 : 1 : 0.25 and 5.27 : 0.73 : 0.25 respectively.

attitude of X, Y and Z has been chosen to match the general attitude of cleavage (XY) in the Hawick Rocks. It is assumed that folds initiate perpendicular to the direction of principal shortening in the bedding plane. This direction will not lie in the XY plane. It is further assumed that as the bedding plane, or the fold envelope of the initial buckles, rotates during deformation, the fold axes will migrate in order to remain perpendicular to the changing direction of principal shortening. At geologically realistic values, folds will generally migrate away from the XY plane with increasing strain (a^1–a^3, b^1–b^3, Fig. 13). All folds will increase in plunge during deformation. The orientation of axial surfaces are difficult to predict, but as deformation progresses, the folds would become increasingly asymmetrical (Treagus 1972, 1973, Anthony & Wickham 1978) with axial surfaces nearer in dip to the XY plane.

The attitude and development of folds developed on planes non-orthogonal to X, Y and Z depends on the initial strike and dip of the plane and the magnitude, ratio and orientations of the incremental stains. In Fig. 13 the path a^1 to a^3 represents the migration of fold axes in plane strain with 50% shortening, at chosen strain increments. In this example, assuming a vertical axial surface, the dihedral angle with cleavage ($=XY$) would be no more than 8° and the plunge 14°. Larger dihedral angles can be achieved by assuming higher initial dips.

Another fold progression is shown in Fig. 13 (b^1–b^3), in which a slight shortening component parallel to Y has been introduced; in this strain regime, folds generated on the initially tilted bedding are transected by the XY plane at angles up to 20°, somewhat larger than the average angle (about 15°) between S_1 cleavage and axial surface in F_1 folds of the Galloway area (Figs. 9b & c). This model also provides for plunge variation, because weak cross folds (c^1–c^3, Fig. 13) would develop concomitantly with b^1–b^3 as a result of a second, weaker, direction of shortening developing in the plane perpendicular to the dominant direction. This might be expected to cause culminations and depressions in the *b* fold axes during the early stages of folding. This model would account for the development of F_1 folds in the Galloway area which plunge gently to moderately (up to 50°) into either the NE or the SW quadrants (Fig. 7a) and are transected in a clockwise sense by the S_1 cleavage. The relatively small number of folds with axial surfaces clockwise of the cleavage would have been initiated on bedding planes which had a strike originally anti-clockwise of the *XY* plane.

The above models invoke plane strain, or a slight constrictional departure, whereas the scant data we have from the Galloway area indicate oblate strains. We emphasize, however, that our data are only from competent sandstones and tuffs and are unlikely to be representative of the strains for the rock mass as a whole. Moreover, Ramsay & Wood (1973) have shown that tectonic plane strain following initial compaction may give rise to finite strains in the flattening field. Similarly, it can be shown that finite flattening strains can arise from tectonic strains of a slightly constrictional nature.

The non-axial planar S_1 cleavage in the Galloway area shows detailed geometrical relationships to F_1 folds that are typical of axial planar cleavage: (a) fans in both competent and incompetent folded layers are centred on the axial surface (Fig. 10); (b) the intensity of cleavage varies according to position in the fold (S_1 cleavage changes from crenulation cleavage in mudstone beds at fold hinges to incipient S_1 fabric in fold limbs, and S_1 cleavage in folded sandstone beds is often more intense at fold hinges); (c) finite neutral points are present locally in folded mudstone beds; and (d) cleavage orientation changes in sympathy with original curvature of the axial surface in F_1 folds (Fig. 12). These relationships strongly support the proposition that the non-axial planar cleavage developed synchronously with the F_1 folding.

Zone of steep plunge

The model proposed above, however, does not account for the relatively small number of F_1 folds that plunge in the range 50–90° or that face downwards to the northeast or southwest (Fig. 7b). These folds occur principally in a single zone (Fig. 1) but, apart from their unusual plunge (Figs. 3 and 8), have the same geometry (interlimb angle, fold class, axial curvature) and relationship to cleavage (fans, refraction, transection) as the more usual gently plunging folds. Although folds within this zone cannot be shown individually to have abnormal angles of axial curvature, when compared with adjacent folds across strike, the range and rapidity of change in plunge is certainly unusual for the area (cf. Fig. 2). That dislocations occur within the zone is strongly suggested by the difficulty in tracing beds in one fold to another across strike, and by occasional narrow belts of intense folding with isolated hinges and sheared limbs.

The steep plunges may be explained by; (a) inhomogeneous F_1 strain, both of the zone with respect to the area as a whole and within the zone, or (b) bodily rotation, either syn- or post-F_1, of 'packets' of folds between dislocations. A development of the model proposed above could produce nearly vertical plunging folds but it is necessary to invoke higher strains than we consider realistic for the zone of steep plunges. For example, fold a^4 in Fig. 13 requires strains typical of rocks with a good slaty cleavage, and fold b^4 would certainly be associated with a strong extension fabric. The more realistic strain models used for folds a^3 and b^3 would, however, still apply if larger angles of pre-F_1 tilting were invoked. The variation in plunge direction in successive folds across the strike would require a complex pattern of pre-F_1 domes and basins, and the existence of downward-facing folds towards both the NE and SW quadrants would require the extension direction during F_1 to have changed rapidly in attitude through the zone.

This first model (a) gains some support from the observations of Dewey & McManus (1964) in rocks of similar age and analogous structural position in the West Connaught area, western Ireland. A plunge depression with axial curvature of 30° was there found to be associated with oblate deformation of conglomerate pebbles and calcareous nodules and was attributed to a pre-F_1 cross-fold. Along strike, however, the rapid steepening of the plunge (into 45° downward-facing attitudes) was attributed to the increasing importance of differential stretching in a progression from oblate to nearly plane strain F_1 deformation. Sliding in the area was attributed to differences in the degree of stretching on either side of the slide-plane. In contrast to the Hawick Rocks, the Irish area has isoclinal folds in a dominantly pelitic lithology and shortening strains of 60% (Dewey 1969) in competent units (cf. 30% in the Hawick sandstones). However, the association of oblate strain with gentle plunges and the rapid transition into steep and downward-facing plunges with increasing stretching are attractive similarities between the two areas. Although we have no positive evidence for the increasing importance of stretching in the belt of steep plunges, a plane strain regime in the pelitic rocks with 50% shortening may not be unrealistic for the Hawick Rocks. Other models and examples of transition from gentle to steep plunges (e.g. Roberts & Sanderson 1974, Ramsay 1979) require extension strains and fold geometry which are inappropriate for the present area. Brenchley & Treagus (1970) and Stringer (1975) have recorded downward-facing F_1 folds in structurally analogous Ordovician and Silurian rocks elsewhere; in both instances deformed objects were only available in competent lithologies and indicate oblate strain, while in incompetent lithologies a slaty cleavage exhibited no obvious stretching lineation.

The second model (b) for the zone of steep plunge is that 'packets' of folds with gentle plunge have been rotated with respect to one other by movement on strike dislocations. This model is attractive for a number of reasons: (a) the steeply plunging folds have the same interlimb angle and the same fold class as those outside the zone; (b) in profile view the cleavage refracts and fans with respect to the axial plane trace as outside the zone; (c) in longitudinal view the cleavage transects the fold hinges in the same sense and by the same angle as outside the zone; (d) the strain data, although very limited and restricted to competent lithologies, show no differences to those outside the zone; and (e) there is evidence of strike dislocation within the zone and Rust (1965a) has proposed on stratigraphic grounds that a major dislocation lies close to the southeast margin of the zone. Major reverse faults have long been invoked in the Southern Uplands on stratigraphic and structural grounds (Craig & Walton 1959) and have more recently been linked with décollement on basal shales (Fyfe & Weir 1976). It is possible that relatively high extensional F_1 strains in the vicinity of these thrusts gave rise to a zone of folds where the plunge variation was higher than normal in the manner envisaged in the first model (a). These folds were segmented and rotated by smaller imbricate dislocations resulting from local strain inhomogeneities where adjacent fold hinges were rotating in opposite directions.

CONCLUSIONS

The composite S_1 cleavage is a low metamorphic grade fabric, comprising pressure solution planes, crenulated bedding, and incipient mineral orientation. Objects deformed within the S_1 cleavage indicate varying degrees of oblate strain. The F_1 folds are concentric to flattened concentric, and hinges are curvilinear varying in plunge from NE to SW. Original plunge variation includes steeply plunging and locally downward-facing F_1 folds in which the non-axial planar cleavage relationships persist. Steeply plunging F_1 folds are abundant in a zone along the southeast margin of the Hawick Rocks (Fig. 1), and are sporadically developed elsewhere in the Galloway area. F_1 folds are intermediate in scale, asymmetrical with mainly SE vergence, and in the Hawick Rocks have a regionally uniform distribution. The S_1 cleavage is persistently non-axial planar to F_1 folds. The dihedral angle between S_1 cleavage and the axial surface, about 5–15° in folded mudstones and larger in folded sandstones, is independent of the plunge, vergence and interlimb angle of F_1 folds. The S_1 cleavage forms moderate to strong fans in F_1 folds. Individual cleavage planes within the S_1 cleavage-fans strike clockwise, or locally anti-clockwise, of axial surfaces, and the mean plane to the S_1 cleavage-fans dips predominantly more steeply than the associated F_1 fold axial surface. The regional (vector mean) orientation is 067°/90° for the mean plane to S_1 cleavage-fans and is 061°/86° NW for the axial surface of F_1 folds. Finite neutral points are present locally in folded mudstone beds, and S_1 cleavage orientation changes in sympathy with original curvature of F_1 fold axial surfaces.

It is concluded that the non-axial planar cleavage can be attributed to the development of the F_1 folds on planes non-orthogonal with respect to the bulk strain axes. The exceptional steep plunge of some F_1 folds may be explained by local variations in the strain regime but it seems likely that rotation of some folds between dislocations is necessary to explain at least those folds that are downward-facing.

Steeply plunging F_1 folds and marked plunge spread within the mean F_1 axial surface are locally significant features of the deformation in the Silurian rocks. Steeply plunging F_1 folds similar to those in the Hawick Rocks have been recorded in three zones several kilometres apart in the Silurian rocks of the Ards (Anderson 1962). Dewey (1969, p. 314) reinterpreted polyphase deformation in the Silurian rocks of Berwickshire (Shiels & Dearman 1963) as fold-plunge variation within a uniform axial surface. Folds with original plunge variation have also been described in Ordovician strata north of the Southern Uplands Fault (Ramsay & Sturt 1973, p. 100, Ramsay 1976, Williams & Spray 1979).

S_1 cleavage non-axial planar to F_1 folds may be widespread in the Southern Uplands and the equivalent zone in Ireland. Near Hawick, scattered S_1 cleavage in the Hawick Rocks recorded by Warren (1964, plate 9) strikes close to E–W, clockwise of the regional 060° strike of bedding. In Wenlock rocks south of the Hawick Rocks, the mean orientation of the S_1 cleavage coincides with that of F_1 axial surfaces (Warren 1964, pp. 213–214), but at some localities S_1 also strikes close to E–W, oblique to the regional strike. In Silurian and Ordovician rocks north of the Hawick Rocks, S_1 cleavage has been described as axial planar in the Glenluce area (Gordon 1962) and in the Rhinns of Galloway (Kelling 1961, p. 65), but in the F_1 folds that we have investigated from these areas the S_1 cleavage shows non-axial planar relationships similar to those in the Hawick Rocks. Observations of downward-facing on S_1 cleavage have recently been made by Leggett *et al.* (1979, fig. 4) in Silurian rocks near Moffat; it is not clear whether this is the result of non-axial planar cleavage or of downward-facing F_1 folds. In the Ards Peninsula, Ireland, Anderson (1978) described restricted zones where the normally axial planar S_1 cleavage transects the F_1 axial traces and produces relationships very similar to those described in this paper.

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APPENDIX

F_1 FOLD NUMBER	NATIONAL GRID REFERENCE NX 100 km square	F_1 FOLD NUMBER	NATIONAL GRID REFERENCE NX 100 km square	F_1 FOLD NUMBER	NATIONAL GRID REFERENCE NX 100 km square	F_1 FOLD NUMBER	NATIONAL GRID REFERENCE NX 100 km square
1	3639 4031	43	4877 3773	87	4942 4678	131	5797 4968
2	3640 4010	<u>44</u>	4877 3778	<u>88</u>	4945 4680	132	5824 4871
3	3690 3938	<u>45</u>	4867 3800	89	4945 4691	133	5835 4865
<u>4</u>	3690 3935	46	4867 3829	90	4950 4698	134	5935 4808
<u>5</u>	3745 3900	<u>47</u>	4868 3829	91	4955 4720	135	5950 4805
6	4196 3612	48	4868 3830	92	4955 4745	136	5979 4807
7	4230 3590	49	4800 3840	93	4950 4752	137	5990 4670
<u>8</u>	4245 3590	<u>50</u>	4789 3857	94	4948 4765	138	6031 4610
9	4265 3568	<u>51</u>	4795 4069	95	4943 4791	<u>139</u>	6037 4604
<u>10</u>	4265 3568	<u>52</u>	4794 4072	<u>96</u>	4930 4850	140	6085 4585
11	4265 3565	53	4794 4073	97	4896 4880	141	6104 4566
<u>12</u>	4265 3565	<u>54</u>	4793 4074	98	4890 4897	142	6105 4565
13	4280 3560	55	4793 4075	99	4848 4914	143	6119 4541
14	4284 3556	56	4792 4080	100	4848 4915	<u>144</u>	6119 4541
<u>15</u>	4390 3483	57	4792 4084	<u>101</u>	4848 4918	145	6120 4540
<u>16</u>	4615 3415	<u>58</u>	4786 4090	102	4847 4920	146	6224 4451
17	4685 3482	<u>59</u>	4780 4100	103	4765 4957	<u>147</u>	6231 4449
<u>18</u>	4695 3492	60	4778 4102	104	4766 4958	<u>148</u>	6443 4400
19	4696 3490	61	4780 4108	105	4765 4965		
20	4705 3495	<u>62</u>	4781 4109	106	5375 5189		NW
	- 4704 3494	63	4780 4114	<u>107</u>	5376 5188		100 km square
21	4740 3520	<u>64</u>	4799 4140	108	5407 5165		
22	4754 3538	65	4840 4220	<u>109</u>	5418 5150	<u>149</u>	9607 6217
	- 4765 3545	66	4825 4241	<u>110</u>	5430 5140	150	9671 6083
<u>23</u>	4766 3558	<u>67</u>	4852 4295	111	5480 5040	151	9990 5380
24	4775 3570	68	4850 4296	<u>112</u>	5502 5153		
<u>25</u>	4775 3577	69	4841 4320	113	5520 5160		NX
<u>26</u>	4773 3596	70	4842 4327	114	5489 5126		100 km square
<u>27</u>	4765 3605	71	4842 4336	115	5514 5141		
28	4759 3634	<u>72</u>	4842 4337	116	5563 5220	152	0196 5207
29	4763 3647	73	4842 4338	117	5600 5270	153	0709 4531
<u>30</u>	4764 3648	<u>74</u>	4843 4344	118	5606 5280	154	0710 4530
31	4794 3607	75	4843 4344	<u>119</u>	5607 5280	<u>155</u>	0709 4529
<u>32</u>	4796 3601	76	4858 4385	<u>120</u>	5607 5282	156	0709 4529
33	4798 3600	<u>77</u>	4840 4490	121	5606 5283	<u>157</u>	2615 5100
<u>34</u>	4813 3594	78	4800 4480	122	5740 5280	158	2615 5098
35	4808 3626	79	4845 4683	<u>123</u>	5735 5263		- 2613 5097
<u>36</u>	4805 3650	80	4850 4680	124	5736 5260	159	2676 5020
37	4800 3652	<u>81</u>	4888 4650	125	5740 5258	<u>160</u>	2680 5016
<u>38</u>	4795 3657	82	4888 4650	<u>126</u>	5748 5204		
39	4795 3658	83	4892 4643	127	5725 5165		
40	4800 3655	84	4890 4642	<u>128</u>	5779 5103		
<u>41</u>	4865 3743	85	4922 4645	129	5765 5080		
<u>42</u>	4877 3772	86	4945 4674	130	5765 4990		

National Grid Reference of F_1 fold Nos. 1–160. Synclines are underlined.