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Transpressive duplex and flower structure: Dent Fault System, NW England

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Abstract

Revised mapping along the Dent Fault (northwest England) has improved the resolution of folds and faults formed during Variscan (late Carboniferous) sinistral transpression. A NNE-trending east-down monocline, comprising the Fell End Syncline and Taythes Anticline, was forced in Carboniferous cover above a reactivated precursor to the Dent Fault within the Lower Palaeozoic basement. The Taythes Anticline is periclinal due to interference with earlier Acadian folds. The steep limb of the monocline was eventually cut by the west-dipping Dent Fault. The hangingwall of the Dent Fault was dissected by sub-vertical or east dipping faults, together forming a positive flower structure in cross-section and a contractional duplex in plan view. The footwall to the Dent Fault preserves evidence of mostly dip-slip displacements, whereas strike-slip was preferentially partitioned into the hangingwall faults. This pattern of displacement partitioning may be typical of transpressive structures in general. The faults of the Taythes duplex formed in a restraining overlap zone between the Dent Fault and the Rawthey Fault to the west. The orientations of the duplex faults were a response to kinematic boundary conditions rather than to the regional stress field directly. Kinematic constraints provided by the Dent and neighbouring Variscan faults yield a NNW–SSE regional shortening direction in this part of the Variscan foreland.

Keywords: Flower structure; Duplex; Transpression; Dent Fault

1. Transpression zone architecture

The range of structural geometries in strike-slip deformation zones is well known (e.g. Christie-Blick and Biddle, 1985; Sylvester, 1988; Woodcock and Schubert, 1994), typically allowing ancient examples of such zones to be distinguished from zones of extension or shortening. However, most real strike-slip zones have an additional component of either extension or shortening across the zone. Such zones of transtension or transpression have been analysed theoretically (e.g. Sanderson and Marchini, 1984; Fossen and Tikoff, 1993; Dewey et al., 1998), but their more complex architecture is less well documented than for pure strike-slip belts. An important complication is the tendency for oblique displacements to be partitioned into spatially discrete strike-slip and dip-slip zones (e.g. Tikoff and Teyssier, 1994; Jones and Tanner, 1995; Holdsworth et al., 2002).

Perhaps the most reliable fingerprint of strike-slip deformation is the map-view en échelon arrangement of component structures such as faults (Riedel, 1929) and folds (Moody and Hill, 1956). Particularly diagnostic are the map-view imbricate fault patterns that define open *fans* or closed *duplexes* (Woodcock and Fischer, 1986) (Fig. 1). More problematic is the diagnosis of a strike-slip component in vertical cross-sections and on seismic profiles. *Flower structures* (Wilcox et al., 1973) have become the main candidate geometry. These structures comprise upward-diverging faults, typically cutting an antiformal *push-up* or a synformal *pull-apart* (Fig. 1). However, closely similar geometries can be formed along dip-slip, reverse or normal, faults, and the resulting ambiguity presents a significant problem in structural interpretation (e.g. Coward, 1996; Corbett, 1999).

One important route to a better understanding of structural styles in strike-slip zones is the description of well-constrained field examples. Accordingly, this paper

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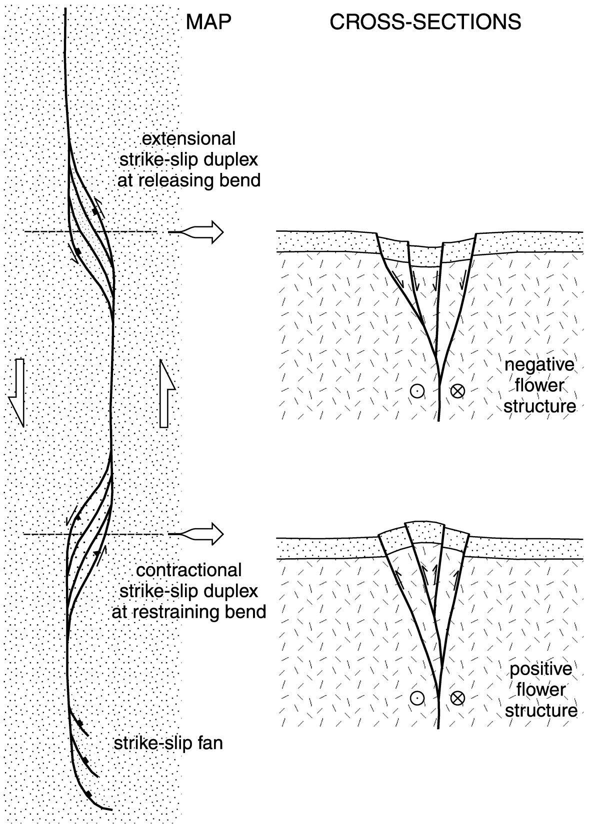


Fig. 1. Map and cross-sections of a generic strike-slip fault system, showing flower structures and duplexes developed at bends.

details flower structures and a strike-slip duplex along the Dent Fault Zone of northwest England. These structures are interpreted as having formed through sinistral transpression during the Variscan Orogeny, probably between about 310 and 290 Ma.

2. Variscan setting of Northwest England

Northwest England lies in the foreland to the Variscan Orogen, about 300 km north of the front of strong Variscan folding (Fig. 2 inset). Here, Carboniferous and later sedimentary rocks unconformably overlie inliers of Ordovician and Silurian sedimentary and volcanic rocks (Fig. 2). These Lower Palaeozoic rocks had been strongly deformed and weakly metamorphosed during the Acadian (late Caledonian) event at around 400 Ma. Variscan deformation in the foreland was thick-skinned, typically involving reactivation of pre-existing basement structures. Three Acadian and older batholiths beneath NW England provided the basement template both for Carboniferous sedimentation and for Variscan tectonics (Fig. 2). The Lake District batholith underpins the Lake District Massif, whilst the Weardale and Wensleydale granites underlie the Carboniferous rocks to the east, beneath the Alston and Askrigg blocks respectively.

The Dent Fault forms the NNE-striking, 30-km-long boundary between the Lake District Massif and the Askrigg Block (Fig. 2). At its southern end, the Dent Fault joins the Craven Fault System, which strikes first southeastward, then eastward along the south edge of the Askrigg Block. The Dent Fault is continued to the northeast by a more complex deformation zone, the Dent Line (Underhill et al., 1988). This zone links, in turn, with the NW–SE and E–W striking faults that bound the Alston Block (Fig. 2a).

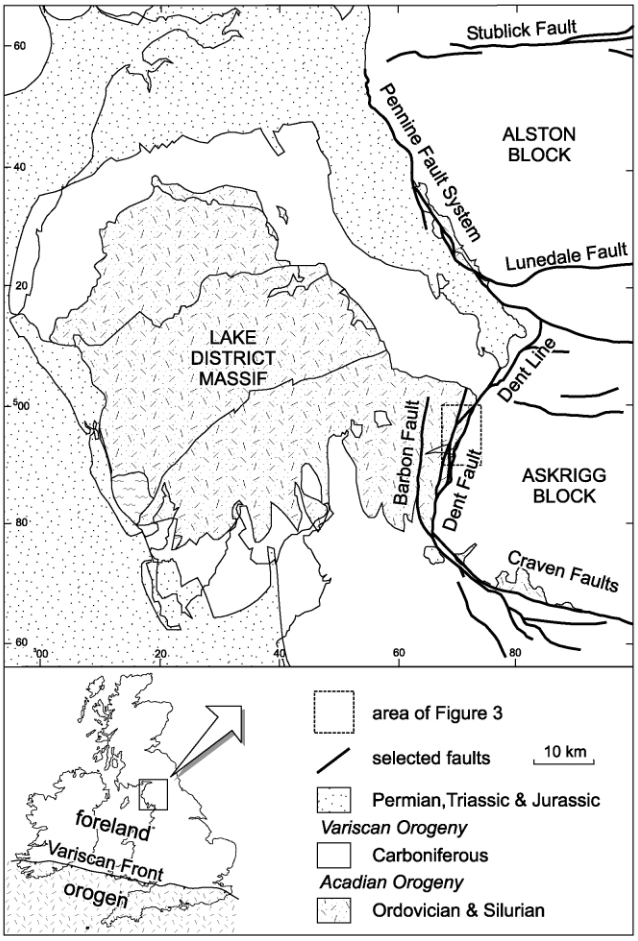


Fig. 2. Regional setting of the Dent Fault and selected related faults in northwest England. Inset is the location of northwest England in the foreland to the Variscan Orogen.

The Variscan Front and its hinterland folds and thrusts (Fig. 2 inset) generally strike E–W or ESE–WSW. However kinematic evidence from south of the Variscan Front strongly favours a regional NW–SE shortening direction (e.g. Gayer and Nemcock, 1994; Gayer et al., 1998), with the more oblique-trending folds having been rotated clockwise in the resulting dextrally transpressive stress field. In the foreland to the north of the Variscan Front, Variscan structures are more variably oriented (e.g. Fig. 2), reflecting the control by basement grain (e.g. Corfield et al., 1996; Warr, 2000). The generally northwesterly Variscan shortening direction is evident in the foreland from the degree of inversion of Carboniferous basins and the sense of transpression in relation to the reactivated structural trends (Corfield et al., 1996). A NW–SE shortening resolves into sinistral transpression across the Dent Fault, the kinematic pattern deduced from local evidence by Underhill et al. (1988) and from new evidence cited in this paper.

A number of studies have documented evidence for a significant E–W shortening event in the Variscan foreland, predating the main NW–SE shortening. Critchley (1984) used brittle fractures on the Alston Block, Bénard et al. (1990) minor structures, including folds, in selected areas across the foreland, and Peace and Besly (1997) seismic data across N–S-trending monoclines in the English Midlands. An E–W shortening event must therefore also be considered for structures along the Dent Fault, whilst accepting the view of Corfield et al. (1996) that partitioning of the NW–SE shortening into pre-existing structures could explain much of the cited evidence.

3. Data collection and analysis

Mapping of the study area by one of us (Rickards, 1967) was incorporated on the Geological Survey's 1:63,360 and 1:50,000 sheets of Kirkby Stephen (Institute of Geological Sciences, 1972; British Geological Survey, 1997). Preliminary results of structural mapping by the other (NHW) were reported by Underhill et al. (1988). The new results in the present paper derive from both authors' revised mapping, mostly at 1:10,000 scale, as part of the resurvey of topographic sheet SD 69 for the British Geological Survey's Kendal geological sheet. Details of sheet SD 69 are available in open-file reports and associated 1:10,000 maps (Woodcock and Rickards, 1999, 2002). The area east of grid line 90 across the Dent Fault (sheet SD 79) has also been resurveyed. Mapping accuracy has been enhanced by new biostratigraphic collecting in Lower Palaeozoic sections (e.g. Rickards, 2002) and by an extensive structural database (NHW), partly reported by Soper et al. (1987). New data have been analysed using structural analysis software: both Quickplot (written by David van Everdingen) and Stereonett (by Johannes Duyster). Throughout this paper, localities are specified by grid references to the UK National Grid, shown in Fig. 3.

4. Folds bordering the Dent Fault

A structural map (Fig. 3) and cross-sections (Fig. 4) of the study area reveal two major Variscan folds: the Fell End Syncline and the Taythes Anticline. Although described separately below, these folds were probably mechanically related as two halves of a large east-facing monocline, later cut by the west-dipping Dent Fault.

4.1. Fell End Syncline

The Fell End Syncline—a new name after the region of Fell End (SD 72 99, Fig. 4a)—is the simpler of the two structures, being displayed only in Carboniferous rocks post-dating the Acadian (~400 Ma) deformation. The syncline is developed in the footwall of the Dent Fault. The syncline axial trace maps out some 200–600 m east of the fault zone (Fig. 3), and typically separates flat or gently-dipping strata to the east from steeply dipping or overturned rocks to the west. The width of the upturned limb on the monocline is related to the 400–500 m thickness of the limestone-dominated Great Scar Limestone Group (Fig. 4). This mechanically competent packet of strata, with underlying lenticular clastic units, has controlled the fold wavelength between the shale and sandstone-dominated Wensleydale and Stainmore groups above and the heterogeneous, but mainly fine-grained, Windermere Supergroup rocks below.

The typical geometry of the Fell End Syncline is shown in the central part of the study area (Fig. 4b–d) where a horizontal eastern limb turns up abruptly into a vertical to overturned western limb. Minor folds and an out-of-syncline thrust accommodate space problems in the core, and more such structures may well exist above and below the present erosion level. The steep limb is dissected by the numerous strands of the Dent Fault, almost always with a reverse component. In the south of the area, the Fell End Syncline becomes more open as its western limb dips more gently. Carboniferous rocks crop out also in the hanging wall of the Dent Fault here, and the diffuse anticlinal component of the proposed monocline structure can be deduced (Fig. 4d and e). In the north of the area, the Fell End Syncline is flanked about 500 m further east by the gentle Clouds Anticline.

The axial trace of the Fell End Syncline maps out sub-parallel to the Dent Fault (Fig. 3b). A stereoplot of poles to bedding (Fig. 5c) shows a mean fold axis of 02/023, also sub-parallel to the fault. In detail, a 4° south-southwestward plunge in the north of the area passes into a 16° north-northwestward plunge in the south. A weak pressure-solution cleavage sporadically affects limestones in the steep limb of the syncline and its intersection with bedding gives a prominent lineation. Both the mean cleavage (Fig. 5f) and mean lineation (Fig. 5i) are oriented significantly clockwise of the fold axis derived from bedding poles. This apparent cleavage transection of the Fell End Syncline is enhanced by the shallow dip (12°) of the mean cleavage. However, the transection survives a test where cleavage/bedding pairs are rotated about the local fold axis so that bedding is horizontal: mean cleavage is then about 6° clockwise of the syncline hinge.

4.2. Taythes Anticline

The Taythes Anticline (Underhill et al., 1988) is evident

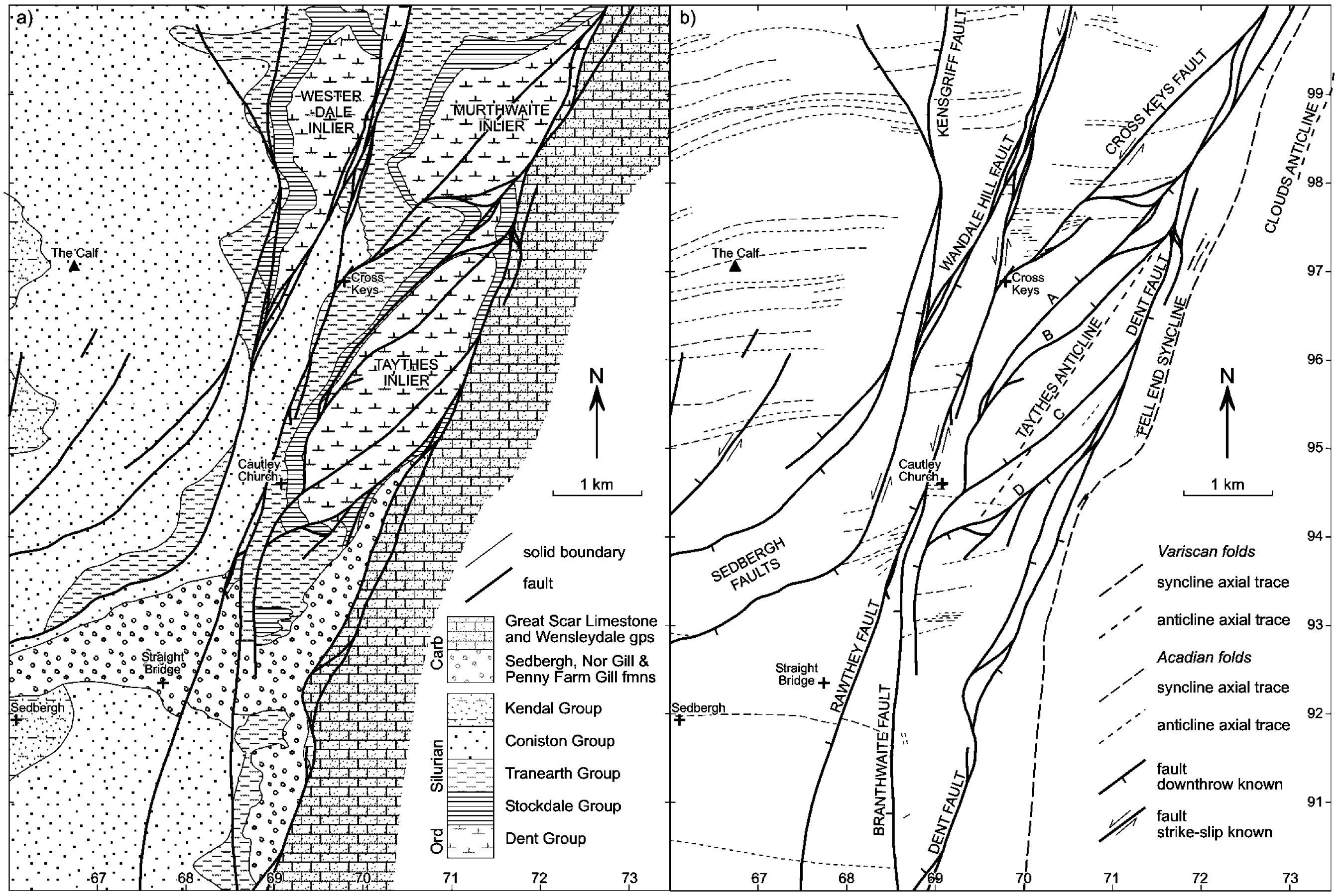


Fig. 3. Maps of the study area across the Dent Fault emphasising: (a) the general geology, and (b) the dominant faults and folds. Marginal grid is the UK National Grid in 100 km square SD.

in Lower Palaeozoic rocks to the west of the Dent Fault in the central part of the study area and, traced southwards, can be seen to affect the overlying Carboniferous strata. Its axial trace is about 800 m west of the main fault in the southwest, but converges with the fault northeastwards along the 4 km trace length. The fullest profile across the fold (Fig. 4c) shows an upright to steeply west dipping fold with a steep to overturned eastern limb and a moderately dipping western limb. The preserved amplitude of the fold lessens both northwards (Fig. 4b) and southwards (Fig. 4d), imparting a periclinal, doubly-plunging geometry to the whole fold. In the south (Fig. 4d) the east-facing monocline formed by the Taythes Anticline and Fell End Syncline is very clear.

Structural data from the Taythes Anticline show more complex patterns than those from the Fell End Syncline, because the anticline affects Windermere Supergroup rocks already deformed by the Acadian event. The relict Acadian fold pattern can best be seen west of the Rawthey Fault (Fig. 3), where bedding poles define a clear E–W fold axis, though plunging gently westwards due to Variscan tilting (Fig. 5a). The Acadian cleavage here strikes consistently clockwise of the fold hinges (Fig. 5d) (Soper et al., 1987), and produces a gently west plunging intersection with bedding (Fig. 5g). In the Taythes Anticline, these Acadian structures are refolded about the Variscan hinge, which is poorly constrained to a NE–SW trend by the dispersed bedding poles (Fig. 5b). The Acadian cleavage is nearly normal to the Variscan fold, and therefore only weakly dispersed by it (Fig. 5e). By contrast, Acadian cleavage-bedding intersections are folded around the Taythes Anticline (Fig. 5h) defining a NNE–SSW axis. A Variscan cleavage has not been observed in the Lower Palaeozoic rocks.

4.3. Interpretation of Variscan folds

Viewed in cross-sections (Fig. 4), the Taythes Anticline and Fell End Syncline together form an east-facing monocline cut by the reverse strands of the Dent Fault. This structure has long been ascribed to E–W shortening (e.g. Dakyns et al., 1891; Moseley, 1972; Underhill et al., 1988). More specifically, the localisation of pervasive Variscan strain close to the fault zone suggests a forced fold above an east-down reverse fault in the basement (e.g. Cosgrove and Ameen, 2000). The progressive temporal growth of the monocline suggested by successive along-strike sections (Fig. 4c–e) matches closely the results from theoretical and analogue experiments of forced folds (e.g.

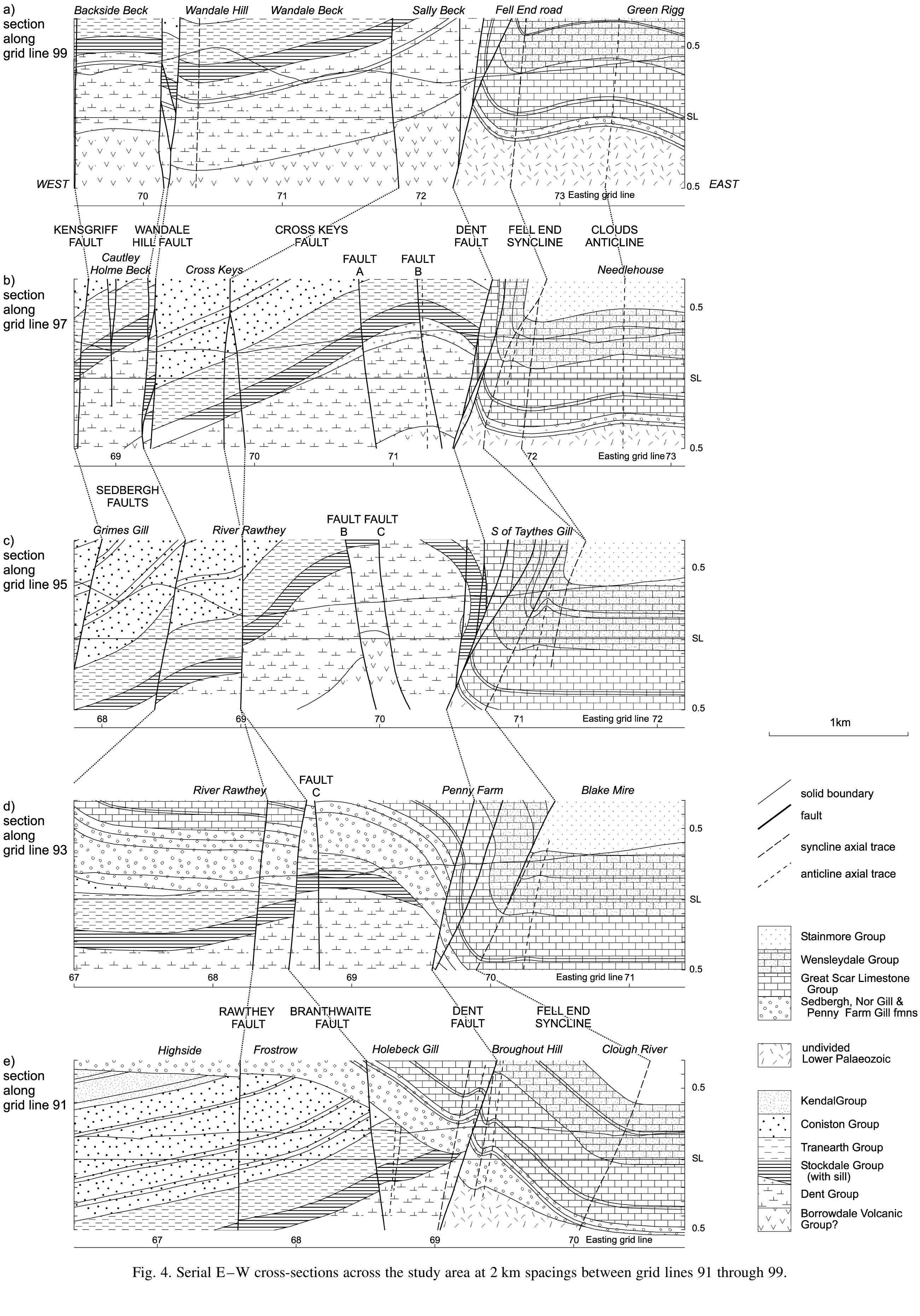
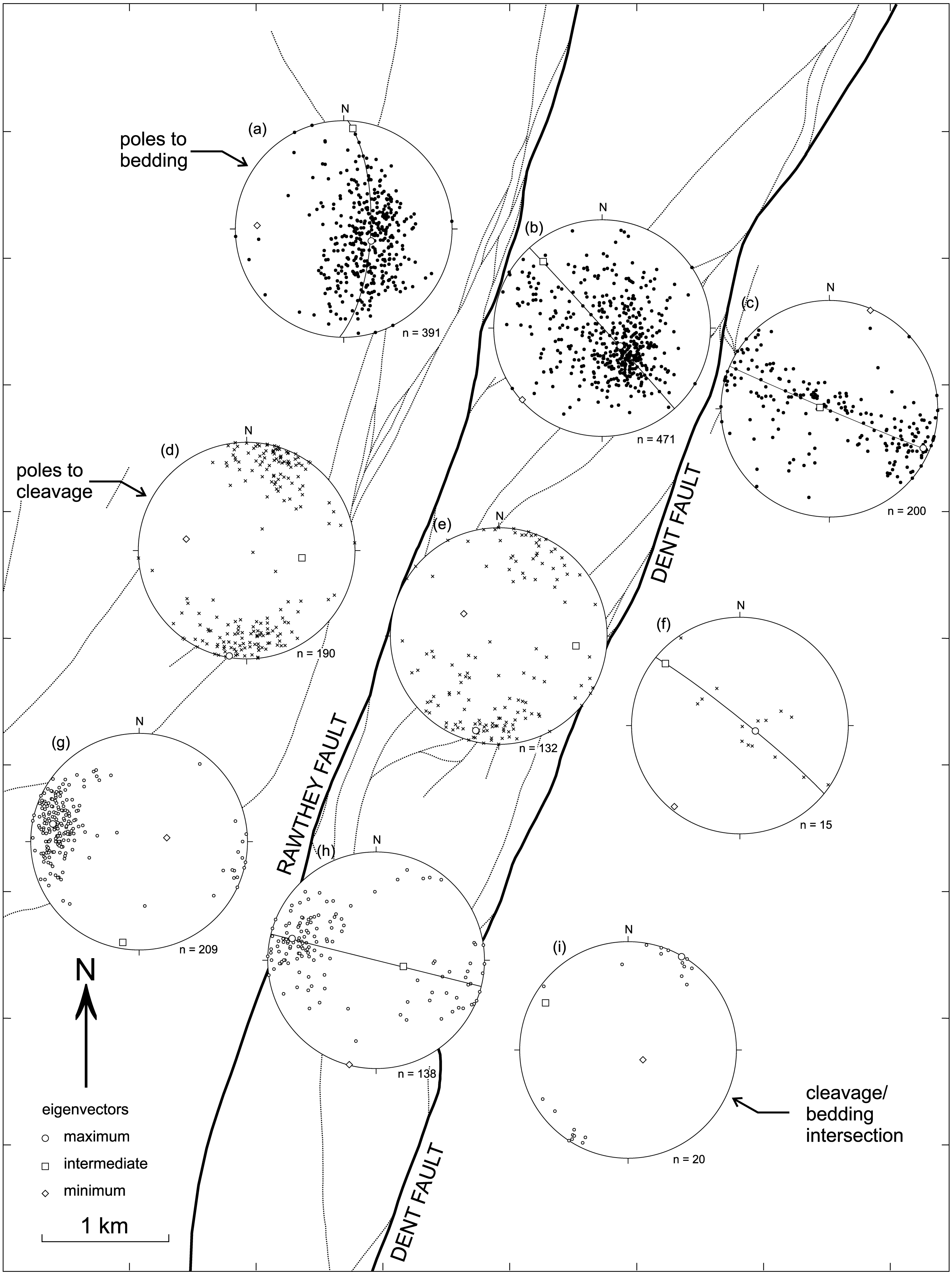


Fig. 4. Serial E–W cross-sections across the study area at 2 km spacings between grid lines 91 through 99.


poles to bedding
(a)
N
n = 391
(b)
N
n = 471
(c)
N
n = 200
poles to cleavage
(d)
N
n = 190
(e)
N
n = 132
DENT FAULT
(f)
N
n = 15
(g)
N
n = 209
RAWTHEY FAULT
(h)
N
n = 138
(i)
N
n = 20
cleavage/ bedding intersection
N
eigenvectors
maximum
intermediate
minimum
1 km
DENT FAULT

Cosgrove and Ameen, 2000; Johnson and Johnson, 2002). Shortening at an early stage in monocline development in Carboniferous rocks is implied by the weak bed-normal pressure-solution cleavage (Fig. 5f) and by minor east-verging folds and thrusts (Underhill et al., 1988; Fig. 7), all now rotated within steeply-dipping fold limbs.

The forced-fold interpretation of the monocline requires a pre-Variscan basement structure along the line of the Dent Fault. Support for this hypothesis comes from early Carboniferous sedimentation patterns (Underhill et al., 1988), from Acadian transection data (Soper et al., 1987; Woodcock and Rickards, 2002), and from Silurian depositional thicknesses (Woodcock and Rickards, 2002). In the study area, the re-activated basement fault has subsequently cut up through the steep limb of the monocline as the mapped strands of the Dent Fault Zone.

Whilst pure dip-slip displacements could alone produce the monoclinal fold, a number of map-view relations suggest an additional component of sinistral strike-slip. The weak clockwise transection of the Fell End Syncline by the Variscan cleavage is compatible with sinistral transpression in most models of transected folds (Sanderson et al., 1980; Soper, 1986; Woodcock and Schubert, 1994). The clockwise obliquity of the Taythes Anticline hinge to the Dent Fault suggests the well-established en-échelon relations in a sinistral transpressive zone (Wilcox et al., 1973; Underhill et al., 1988). An abrupt sinistral strike swing within the Carboniferous in the south of the study area—discussed by Underhill et al. (1988)—may also relate to the transpressive kinematics.

It is also tempting to equate the periclinal geometry of the Taythes Anticline with the typical en-échelon folds in strike-slip zones (e.g. Wilcox et al., 1973). However, there are two contributory local explanations for the domal pattern. One is the influence of lenticular dolerite and felsite sills in the Windermere Supergroup section. A second is the superimposition of the Variscan anticline on an earlier Acadian anticline trending at a high angle to the later fold: that is, a Type 1 fold interference pattern (Ramsay, 1962). Multi-hinged Acadian anticlines and synclines on the appropriate scale occur to the west (Sedgwick, 1846; Woodcock and Rickards, 2002), although they cannot be matched directly with the Taythes Anticline, presumably due to strike-slip offsets on intervening faults (Fig. 2). Moreover, two other fault-truncated domes in the study area—the Westerdale and Murthwaite inliers (Fig. 3)—support the interference hypothesis. By contrast, the Fell End Syncline, developed in formerly unfolded rocks, maintains a conspicuous continuity along strike with only gentle plunge variations.

5. The Dent Fault and related faults

In most cases, the faults in the study area crosscut folded or tilted bedding and presumably post-date folding or accompany its later stages. The faults have mostly been field-mapped directly from observed fault planes or fault rocks. Faults have been extrapolated from directional data, with guidance from mismatch of stratigraphy, which is finely biozoned throughout most of the study area (e.g. Burgess, 1986; Woodcock and Rickards, 2002). Most exposure is in the dense network of stream valleys, but till cover limits the use of feature mapping across the interfluves. Consequently, a cautious approach to joining up fault strands has been used (Fig. 3), and in some areas fault connectivity could be even greater than shown.

5.1. The Dent Fault

The Dent Fault is the easternmost major fault in the study area (Fig. 2), recognised by Sedgwick (1831) and named by the Geological Survey (Dakyns et al., 1891). It comprises one, two or three principal strands, though separated by panels of brecciated and typically minor-faulted rock. The mean strike of the fault zone is about 022°. However, the strike of individual strands varies by ±20° about this azimuth, giving a braided array. One major bend in the fault zone—to about 342°, in the Dovecote Gills (SD 694 919, Fig. 3)—is tracked to the east by a similar swing of bedding in the fault footwall.

Wherever direct evidence is available—particularly in the River Rawthey (SD 718 974), Taythes Gill (SD 709 952), Whinny Gill (SD 703 945), Penny Farm Gill (SD 698 932) and the Clough River (SD 614 914)—the Dent Fault dips steeply westwards or is sub-vertical (Fig. 4). Evidence of westward dip is more common on the more easterly strands, so that reconstructed cross-sections through the fault zone typically show an upward diverging fan (Fig. 5a–c). Displacements on these faults are mostly east-down, with the maximum throw on the westernmost fault of the fan. Sections are difficult to balance, and some require significant strike-slip displacements. The most conspicuous example is in the River Rawthey (SD 718 974) where a sliver of Windermere Supergroup lithology is isolated within Carboniferous rocks (Figs. 3 and 4b). Slip-direction indicators on these faults are rare, but a conjugate set of dextral en échelon vein arrays striking about 130° in the flat-lying strata east of the monocline imply sinistral displacement components on the main Dent zone (Underhill et al., 1988).

Fig. 5. Stereoplots (lower hemisphere, equal area) of bedding, cleavage and bedding/cleavage intersection in three sub-areas separated by the Rawthey and Dent faults.

5.2. The Rawthey Fault

Considerable progress has been made compared with previous work (Underhill et al., 1988; British Geological Survey, 1997) in detailing the faults to the west of the Dent Fault (Fig. 3). The most continuous fault here is the Rawthey Fault, striking about 018°, sub-parallel to the Dent Fault and about 1.5–2 km further west. Displacements of basal Carboniferous rocks, and similar calcite- and dolomite-hosting fault rocks to the Dent Fault seem to confirm its Variscan activity.

The Rawthey Fault is sub-vertical or steeply east-dipping and, in contrast to the Dent Fault, throws down to the west. More significant, in the context of this paper, is the consistent record of sinistral strike-slip displacements along this fault. Evidence includes offset bedding truncations (SD 6926 9542), fold hinges (SD 7004 9710) and nodule bands (SD 6913 9536), and Riedel fracture patterns (SD 6965 9647). At its northern end, the Rawthey Fault joins the Wandale Hill Fault, an east-down sub-vertical fault array (Fig. 3), also with sinistral strike-slip deduced from slickencrysts and displaced vein arrays (e.g. SD 6787 9776). At its southern end the Rawthey Fault itself runs into poorly exposed ground but probably swings southward to join west-down faults mapped by Furness (1965) across the east side of the Middleton Fells. Much of the displacement on the Rawthey Fault, however, may be transferred on to a N–S-striking splay, the Branthwaite Fault (Fig. 3b; new name after the settlement at SD 684 912), which joins the Dent Fault just south of the study area.

5.3. Faults between the Dent and Rawthey faults

A set of five mapped faults (the Cross Keys Fault and faults A–D; Figs. 3 and 4) strike about 045° between, and about 25° clockwise of, the Dent and Rawthey faults, in the north and central parts of the study area. The Cross Keys Fault, links the Dent and Rawthey zones across the Murthwaite inlier, or half-dome. It throws down to the west, but hosts clear evidence of an additional sinistral strike-slip component from Riedel shear patterns (e.g. SD 6982 9695) and steeply-plunging asymmetric folds (SD 7007 9712). Where direct evidence is available, the Cross Keys and A–D faults are sub-vertical to steeply east dipping, implying that they probably converge with the west-dipping Dent Fault at depth (Fig. 4) as well as northeastward. Faults A–D, however, do not link directly to the Rawthey Fault but to the N-striking splay zone of the Branthwaite Fault. To the south, both the Branthwaite and Rawthey faults re-attach to the Dent Fault, as eventually does the Rawthey Fault (Fig. 2).

Faults A–D coincide with the Taythes Anticline, although they transect its hinge by 10–15° in a clockwise sense. The throws on the faults are in sympathy with the displacements due to folding, being NW-down on the northwest-dipping limb (faults A, B and at least the southwest end of C) and SE-down on the southeast-dipping limb (fault D).

5.4. Interpretation of the Dent and related faults

The map-view imbricate pattern of the Cross Keys and A–D faults between the Dent and Rawthey faults (Fig. 3) is that of a strike-slip duplex (Woodcock and Fischer, 1986). Evidence for a sinistral strike-slip component on the Rawthey Fault, the Cross Keys Fault and, less conclusively, the Dent Fault, confirms the overall transcurrent kinematics implied by this geometry. The predominantly reverse sense of dip-slip on non-vertical faults in the duplex suggests transpression rather than transtension, and that the duplex is contractional. The location of the duplex on a straight section rather than a local bend on the Dent Fault implies that this sinistral transpression was on a scale larger than that of the study area, in conformity with previous diagnoses of regional tectonics (Underhill et al., 1988).

In cross-section (Fig. 4) the upward-divergent strands of the Dent Fault and its bordering faults to the west define a flower structure. It is important that the flower faults in section are precisely those that form the duplex in map view, providing a valuable example of this much-illustrated but more sparsely documented three-dimensional relationship. The sub-vertical attitude of the Rawthey Fault makes it probable that it too converges at depth with the Dent Fault, and that it complements the Branthwaite Fault in its kinematic role bounding the west edge of the duplex.

It is tempting to equate the fault architecture between the Dent and Rawthey faults with the helicoidal Riedel shears observed in sand-box experiments of strike-slip deformation (Figs. 1 and 6) (Naylor et al., 1986). However, although there may be geometrical similarities, the field and experimental faults do not match dynamically. Faults A–E splay off the Dent Fault in the wrong sense for Riedel shears in sinistral strike-slip. Because the independent evidence for sinistral displacement is strong, the northeast-striking splays probably owe their origin to kinematic constraints rather than a simple dynamic response. This theme will be developed in Section 6.

5.5. Faults west of the Rawthey Fault

Whether or not the Rawthey Fault is regarded as part of the transpressive duplex or not, it marks the westward transition to a contrasting style of strike-slip deformation, to be detailed elsewhere. No duplex geometries have been recognised in this western ground, but rather a fanning array of steeply-dipping N- to NNE-striking strike-slip faults tending to link into SE-directed reverse faults. The pattern of steep northerly striking faults is typical of the Windermere Supergroup across the southern Lake District, that is for some 60 km to the west (e.g. Soper, 1999; Millward et al., 2000). Moseley (1968) first demonstrated that many of these faults separate tracts with different Acadian fold and cleavage patterns, accommodate

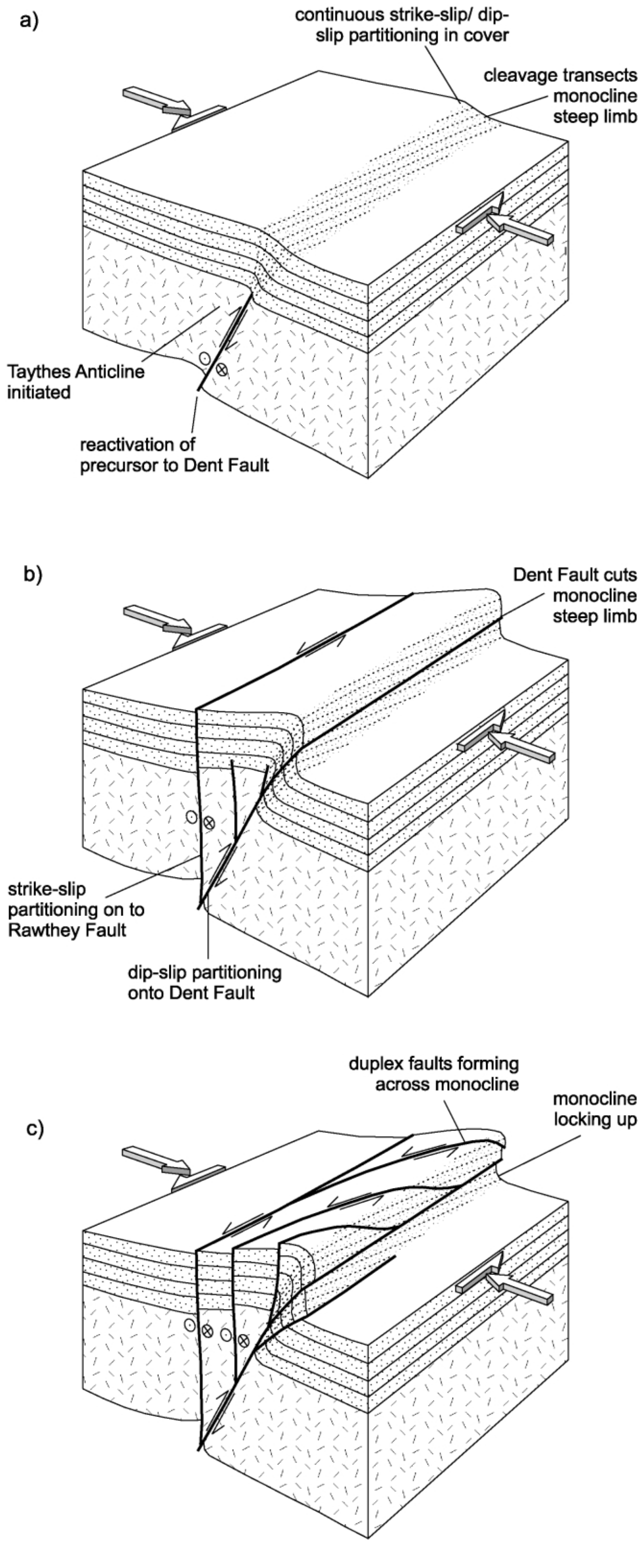


Fig. 6. Schematic interpretation of the formation of the positive flower structure and contractional duplex by transpression across the Dent Fault. The periclinal nature of the Taythes Anticline, due to interference with pre-existing folds, is ignored.

different strains and therefore have variable displacements along their length. They probably had a pre-Acadian inheritance, as well as being reactivated during the Variscan transpression described here.

6. Synthesis: sinistral transpressive kinematics

6.1. Linked duplex, flower, and push-up anticline and horst

The new evidence presented in this paper confirms previous views (Underhill et al., 1988) that both the folds and faults bordering the Dent Fault result from sinistral transpression. Comparing the fold and fault patterns reveals two further geometric relationships. First, that the central part of the strike-slip duplex—comprising faults A–D—is closely superimposed on the periclinal Taythes Anticline. Second, that cross-sections through this part of the duplex show a flower-structure whose faults have displacements in broad kinematic harmony with the anticline that they cut: they throw down northwest on the northwest dipping limb and southeast on the opposing steep limb. These fold/fault relationships are unlikely to be coincidental, but probably record sequential ductile and brittle responses to the same transpressive regime (Fig. 6). Early folding (Fig. 6a) was partly forced by bending above the reactivated precursor Dent Fault but enhanced by buckling in response to layer-parallel transmission of the regional transpression. Later faults propagated up through the resultant monocline (Fig. 6b and c) but their reverse displacements continued to take up shortening as well as a component of strike-slip. The Taythes Anticline, and then the larger duplex within which it is nested, was therefore transformed into a fault-bounded push-up horst in the transpressive zone.

6.2. Displacement partitioning

It is significant that the duplex, and indeed most of the evidence for strike-slip displacement, lies on the western, hangingwall side of this segment of the Dent Fault. The footwall Fell End Syncline is relatively cylindroidal, is not cut by any duplex fault patterns, and preserves only a weak signature of strike-slip deformation as transecting cleavage. The contrasts across the Dent Fault point to strain partitioning; the strike-slip components were concentrated in the hangingwall, and the dip-slip components in the footwall and possibly along the Dent Fault itself (Fig. 6). The degree of strain partitioning probably increased through time, with more continuous accommodation of variable strains during early folding (Fig. 6a) and later concentration of strike-slip in the duplex faults as they propagated through the hangingwall block (Fig. 6b and c).

6.3. Duplex as an overlap transfer zone

It has been noted that the duplex faults splay off the Dent

Fault in the wrong sense for Riedel shears in sinistral transpression (cf. Riedel, 1929; Naylor et al., 1986). These faults are probably a response to kinematic boundary conditions in the study area rather than to the regional stress system. Specifically, it is suggested that the duplex lies in a right-stepping overlap zone between the Rawthey and Dent Faults (Fig. 7). On this model, a significant component of strike-slip displacement in the south of the study area was accommodated on the Rawthey and Branthwaite faults. By contrast, in the north of the area, a higher component of strike-slip was accommodated on the Dent Fault itself. The intervening strike-slip duplex is seen as a transfer zone, progressively transmitting strike-slip northeastward across the duplex faults, particularly the Cross Keys Fault. In support of this model is that the Rawthey/Wandale Hill fault zone seems to lose Variscan displacement northwards and to cut the sub-Carboniferous unconformity only weakly (Fig. 2). By contrast, the Dent Fault steps northeastwards into the Dent Line (Underhill et al., 1988), which transfers significant strike-slip displacement to the faults at the southwest corner of the Alston Block. Beyond the south of the study area, the Rawthey and Branthwaite faults rejoin the Dent Fault, emphasising that the Taythes duplex formed within a discrete fault-bounded wedge chopped out of the hangingwall of the Dent Fault. This wedge was squeezed upwards in the restraining overlap zone as a push-up horst.

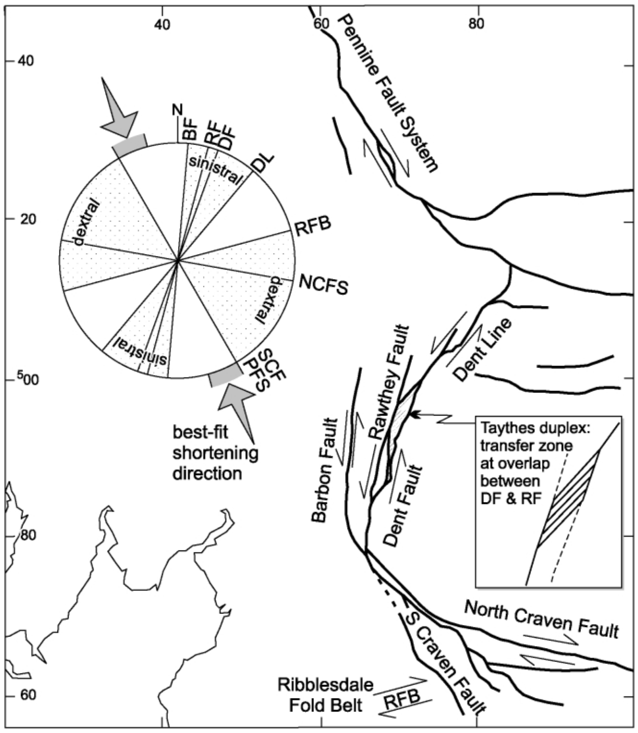


Fig. 7. Regional map of selected Variscan faults in northwest England (cf. Fig. 2), showing the location of the Taythes duplex at a restraining overlap, and (inset) the kinematic constraints on the best-fit regional shortening direction.

6.4. Regional transpressive kinematics

An examination of the regional tectonic map south of the study area (Fig. 2; simplified in Fig. 7) suggests that the kinematic relationship of the Rawthey and Branthwaite faults to the Dent Fault may be replicated on a larger though weaker scale. The Barbon Fault also seems to transmit sinistral strike slip northwards from the northwest end of the Craven Fault System. The sinistral slip on the Barbon Fault, like the Rawthey Fault, also diminishes northward (Soper, 1999; Woodcock and Rickards, 2002). It is probable that its strike-slip displacement is transferred northeastward from the Barbon Fault to the Rawthey and Dent zones. The intervening transfer zone contains a number of kinematically suitable northeast striking faults, including the Sedbergh and Wandale Hill faults (Fig. 3b), which are currently the subject of further investigation.

The strengthened evidence for sinistral transpression on the Dent Fault allows a more quantitative estimate of the regional Variscan shortening direction (Fig. 7). Key additional constraints are provided by structures around the Bowland Basin, to the south of the Askrigg Block. Here, the Ribblesdale fold belt comprises en échelon fold trains and faults indicating dextral shear trending about 075°, once interpreted as syn-depositional (Arthurton, 1983, 1984), but re-interpreted as Variscan (Gawthorpe, 1987). The North and Middle Craven fault systems have conjugate normal faults implying dextral shear along 100° (Arthurton, 1984), but the shear sense on the South Craven fault is less clear. Combining all this regional evidence (Fig. 7 inset) constrains the regional shortening vector to between 310° and 345°, or to between 330° and 345° if tentative evidence for a dextral component on the Pennine fault system is accepted. This NNW bulk shortening direction across this part of the Variscan foreland is therefore consistent with estimates from wider areas of the foreland (Corfield et al., 1996) and from the orogen as a whole (Gayer and Nemcock, 1994; Gayer et al., 1998).

7. General conclusions

Although the regional tectonic setting is reassuringly consistent with the local kinematic relationships in the study area, the general conclusions of the study relate to features on this local scale.

1. Field mapping has detailed an intimate geometric relationship between a strike-slip fault duplex in map view, a positive flower structure geometry of the same faults in cross-section, and an anticline on which the faults were superimposed. The structures are all isolated within a push-up horst in the hangingwall of the Dent Fault. The geometric inter-relationship of this suite of structures is often postulated as a feature of strike-slip influenced deformation (see reviews by Sylvester, 1988;

Woodcock and Schubert, 1994), and is observed in analogue experiments (e.g. Naylor et al., 1986). However, it is infrequently documented from natural examples in the detail possible in this study.
2. Data on the displacement senses of faults combined with accurate cross-sections show that the duplex, flower and anticline structures are related kinematically and not just geometrically. Ductile strains, taken up by forced folding early in transpressive deformation, were later replaced by brittle faults that took up the same bulk shape change. So, duplex faults with northwest downthrow are superimposed on the northwest-dipping limb of the precursor anticline and vice versa.
3. The duplex faults are oblique to the main Dent Fault in the wrong sense to have formed as Riedel shears with respect to inferred regional stresses. The faults are interpreted as kinematically induced linkage faults, progressively transferring strike-slip displacement eastward in the overlap zone between the Dent Fault and the Rawthey/Branthwaite faults further west. This kinematic explanation is in harmony with growing realisation (Molnar, 1992; Tikoff and Teyssier, 1994; Dewey et al., 1998) that many structures in transpression zones are more influenced by kinematic boundary conditions than by regional stress orientations.
4. Strike-slip deformation is preferentially partitioned into the hangingwall faults to the Dent Fault, particularly those bounding the duplex, whereas the footwall preserves predominantly dip-slip displacements. This partitioning mimics closely that seen in larger-scale tectonic settings, for instance at subduction zones (Fitch, 1972; Molnar, 1992) and in continental collision belts (e.g. Avouac and Tapponnier, 1993). Partitioning on the small scale of the study area can be ascribed to its greater energy-efficiency compared with oblique-slip faults (Michael, 1990) and to the influence of a pre-existing basement weakness suitably oriented to take up one component of deformation (Jones and Tanner, 1995).

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