The kinematic linkage of the Dent, Craven and related faults of Northern England

C W Thomas[1] & N H Woodcock[2]

[1]British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, United Kingdom

[2]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, Cambridgeshire, CB2 3EQ, United Kingdom

SUMMARY:

New mapping of the southern part of the Dent Fault reveals three 5 to 6 km long segments overlapping at two left-stepping zones 1 to 2 km wide. The main fault strands probably dip steeply WNW. A faulted footwall syncline in Carboniferous strata indicates reverse dip-slip, with a stratigraphic throw of at least 750 metres. Locally-developed plunging folds and imbricate fault duplexes developed at fault bends reveal a strike-slip component, indicated to be sinistral from limited slickenline data. Silurian strata in the hanging wall lack the Variscan folds observed further north. The northern overstep is problematic in hosting upfaulted slivers of older Silurian and Ordovician rocks. The southern overstep zone hosts a younger faulted block compatible with releasing kinematics in sinistral strike-slip.

The Dent Fault converges at its southern end with the Barbon Fault, with an upfaulted wedge between them near the branch point. The two faults swing southeastward, joining the Craven fault system via splays and linkages. Regionally, the Dent and Barbon faults form the innermost pair of a fan of ~N-S trending faults splaying off the northwest end of the South Craven – Morley Campsall Fault System around the southwestern corner of the Askrigg Block.

The kinematics of the Dent, Barbon and Craven faults fit NNW-SSE orientated shortening during late Carboniferous Variscan deformation. The rigid Askrigg Block forced

displacements around its west and south margins where fault and fold orientations were influenced by pre-existing structures, at least Acadian in age to the west and early Carboniferous to the south.

Zones of transpression in the Earth's crust result in complex coupled fault and fold architectures in which displacements are typically partitioned into domains dominated either by strike- or dip–slip (Fossen & Tikoff 1993; Holdsworth *et al* 2002; Jones and Tanner 1995; Sanderson and Marchini 1984; Woodcock & Rickards 2003a). Structures developed in such zones vary along their length, particular complexities arising at restraining and releasing bends and offsets and at the tips of major faults, where strain is often accommodated by fanning arrays and duplexes of subsidiary faults (Woodcock & Fischer 1986).

Previous studies have demonstrated such complexity arising from Variscan sinistral transpression along the northern sector of the Dent Fault of Northern England (Fig. 1). The fault is of particular interest because it provides an easily accessible and *locally* well-exposed example of a transpressive structure (Underhill *et al* 1988; Woodcock & Rickards 2003a) and hosts informative fault breccias (Mort & Woodcock 2008; Tarasewicz *et al* 2005; Woodcock & Mort 2008; Woodcock *et al* 2008).

The dominant architecture comprises a forced, east-facing monocline breached by the reverse Dent Fault, the latter interpreted to be a reactivated basement fracture that propagated up through the fold as deformation progressed. Weak clockwise-transecting cleavages in the footwall syncline, clockwise *en echelon* arrangement of faults and fault-bounded folds, and oblique slickenlines indicate a component of sinistral strike-slip. An assemblage of Variscan folds and their bounding fault duplex forms positive flower structures developed within a NNW-SSE transpressional regime (Woodcock & Rickards 2003a, fig. 7).

In this study, we extend the work of Underhill *et al* (1988) and Woodcock & Rickards (2003a), presenting new field evidence for transpressional deformation along the southern sector of the Dent Fault, from Dentdale to its southerly termination against the Barbon and Craven faults (Fig. 2). We demonstrate a broadly similar kinematic development, but highlight several key structural differences in the Dent Fault zone in the south. We interpret the available evidence to show that the Dent Fault represents the innermost component of a 10-kilometre-scale fault fan that extends off the northwest tip of the Craven Fault Zone, particularly the South Craven Fault. We thereby reassess the geometrical and kinematic relationship between the Dent, Craven and Barbon faults. Critically, several of these faults, developed in the Silurian rocks of the Southern Lake District, have significant, pre-Carboniferous histories (Barnes *et al* 2006; Soper 1999; Soper & Woodcock 2003; Woodcock & Rickards 2003a; Woodcock & Rickards 2003b), supporting interpretation of the Dent Fault as a surface manifestation of a re-activated, pre-Carboniferous basement fracture (Soper 1999; Woodcock & Rickards 2003a). Finally, we suggest that the wider system of major faults that dominates the geology of Northern England reflects a structural template developed during pre-Variscan deformation events.

1. REGIONAL SETTING

One of the earliest major faults to be identified in Britain (Dakyns *et al* 1890; Sedgwick 1835), the Dent Fault forms the western margin of the Askrigg Block (Dunham & Wilson 1985). This buoyant region is cored by the Wensleydale Granite (Dunham 1974). Although this granite currently has an Emsian Rb/Sr age, it is considered more likely on various grounds to be late Ordovician in age (Millward 2002, 2006; Pharaoh *et al* 1997). The granite is covered by a thin succession of cyclic sedimentary rocks of dominantly lower Carboniferous (Visean – Bashkirian) age. To the west of the fault lie rocks largely of Silurian age, belonging to the Windermere Supergroup of the Southern Lake District (Figs 1, 2) (Barnes *et al* 2006). At its southern termination, the Dent Fault links with the Craven Fault system that bounds the southern margin of the Askrigg Block, separating the block 'high' from the deep Craven Basin to the south. To the north of the Stockdale Disturbance ('SD', Fig. 1), the Dent Fault passes into a linear zone of more complex and diffuse deformation known as the Dent Line (Underhill *et al* 1988, figs. 1,2), ultimately linking to the Pennine Fault that forms the western margin of the Alston Block (Fig. 1). Thus, the Dent Fault forms a regionally SSW-trending structure linking two major northwesterly trending fault systems, the Pennine Fault and the South Craven – Morley-Campsall Fault (Fig. 1). These three fault systems are components of the fundamental structural framework defining the block and basin architecture of the geology of northern England (e.g. Corfield *et al* 1996).

The relationship between the Dent and adjacent faults at its southern termination has been a source of conjecture since first identified. Various interpretations have been proposed (Fig. 3). Broadly, the Dent Fault has been interpreted to be a continuation of the Craven fault system (Fig. 3b) (Aveline *et al* 1872; British Geological Survey 2007; Stone *et al* 2010) or to be separate, possibly linked to NNE-trending monoclinal structures, such as the Hutton Monocline, that lie to the SW (Fig. 3a,c,d) (Aitkenhead *et al* 2002; Phillips 1836; Turner 1935).

In N England, pre-Carboniferous strata were strongly deformed and weakly metamorphosed during late Early Devonian Acadian deformation at around 400 Ma (Woodcock & Soper 2006). Late Carboniferous Variscan deformation resulted in inversion of Carboniferous basins and the development of fault-fold belts (Arthurton 1984; Corfield *et al* 1996; Gawthorpe 1987). The influence of existing basement structures resulted in variable orientation in Variscan fold and fault patterns, but an overall regional NNW-SSE shortening direction is indicated from the kinematics (Corfield *et al* 1996; Underhill *et al* 1988;

Woodcock & Rickards 2003a). As discussed by Underhill *et al* (1988) and Woodcock & Rickards (2003a), this shortening vector results in sinistral transpression across the Dent Fault. However, several other studies have presented evidence for geographically widespread E-W shortening early on during Variscan deformation, including an analysis of fracture patterns in the adjacent Alston Block (Critchley 1984).

2. STRUCTURAL GEOMETRY ALONG THE DENT FAULT

2.1 Overview

The entire southern sector of the Dent Fault and adjacent Carboniferous strata have been mapped by CWT at 1:10 000-scale from Dentdale southwards to its junction with the Craven Fault system (Fig. 2), as part of the revision of British Geological Survey 1:50 000 Sheet 49 (Kirkby Lonsdale). The Silurian strata west of the fault and north of gridline 85 were mapped by NHW, with data from R.B. Rickards, on contract to the British Geological Survey. Stereographic analysis was undertaken using StereoStat 1.6.1 (Rockware (R) © 1997-2012) and Stereonet 8 (Allmendinger *et al* 2013; Cardozo & Allmendinger 2013).

In the study area, the Dent Fault comprises three gently concave-east segments, roughly 5 to 6 km long (Fig. 2). The segments meet at two overstep zones, 2 to 3 km long and about 1 km wide. Overall, the fault trace becomes more southerly trending towards the south. Although exposure is poor over the southernmost segment because of increasing superficial cover, the evidence suggests that it is structurally simpler than the two northern segments.

The geometry of the main structures is described below from north to south.

2.2 Faults

2.2.1 North of the Dentdale overstep zone

The complex deformation described by Woodcock & Rickards (2003a) to the northeast of Sedbergh [SD 66 92] and Dentdale (Fig. 2), and bounded on the southeast by the Dent Fault, is transferred across an overstep zone in Dentdale by a series of south-striking faults within Silurian strata (**A**, Fig. 2). In their interpretation, dominantly strike slip displacement on the Rawthey and the Branthwaite faults is transferred back on to the Dent Fault by two N-S faults, the Helm Gill and Underwood faults (HGS, UF respectively; Figs 2, 4). The northern end of the Underwood Fault branches from a strand designated as the Dent Fault in the sense that it separates Silurian from Carboniferous rocks. The Helm Gill and Underwood faults bound an inlier of late Ordovician Cautley Mudstone (Dent Group, CMU, **C**, Fig. 2; Figs 2, 4, 5a), discussed in section 3.2. A splay off the Helm Gill Fault trends SSW before losing definition via a fan of minor faults in Silurian strata on Middleton Low Fell (Fig. 4). Offsets in strata at the root of the fan around [SD 680 878] indicate sinistral displacement along this splay.

2.2.2 Barbondale segment

Two main fault strands are developed through Barbondale (Figs 2, 4). These parallel structures are roughly 200m apart, near vertical, and bound an elongate domain of very steeply dipping or overturned Carboniferous strata (Figs 4, 5a). The easternmost of the two strands separates very thick bedded massive limestones of the Great Scar Limestone Group from those of the overlying heterolithic, thin- to thick-bedded Alston Formation (Yoredale Group). East of this strand, the bedding dip changes rapidly to sub-horizontal in Alston Formation strata and it is clear that this fault cuts through the hinge of a fault-parallel footwall syncline analogous to the Fell End Syncline of Woodcock & Rickards (2003a) (Fig. 5b).

At the northeastern end of the Barbondale segment, the two main strands converge closely where the fault passes over the watershed into Dentdale, between Crag Wood [SD 687 872] and Gawthrop [SD 694 875] (Fig. 4). They diverge to the southwest of Crag Wood due to a marked southerly swing in the trace of the easternmost fault over c. 200m at Stone Rigg [SD 684 867], (Fig. 4). This fault is coupled with another just a few tens of metres east; between them is a sliver of very steeply easterly dipping Alston Formation strata. In map view, this fault-bound sliver has an open ‘S’ shape. Within the sliver, a prominent joint set dips at c. 55° to the SW.

To the southeast of Crag Wood, and immediately south of the northwards bend in the Dent Fault, a NW-divergent fan of normal faults with small NE-down displacements drops Carboniferous strata progressively down into Dentdale, resulting in a broad dip-slope (Figs 4, 5b).

The development of these extensional structures in the footwall of the Dent Fault and at a sharp bend in the fault is consistent with a sinistral component of displacement on the Dent Fault; under sinistral displacement, this would be a releasing bend. The narrowness of the Dent Fault zone in this area suggests that brittle fracture dominated over ductile forced folding more than on other segments of the Dent Fault.

In the central part of the Barbondale segment, around Rowell Gill [Figs 2, 4; SD 67 85], there is a marked swing in the trend of the Dent Fault from SW to SSW over just a few tens of metres. Notably, the parallel eastern fault swings SSW some 500m NE of the swing in the Dent Fault (Fig. 4). Between the two bends, two SW trending faults form a duplex within which lie strata of the Great Scar Limestone Group deformed by strongly oblique folds (Figs 4, 5c). Immediately east of this duplex, two faults splay ENE off the Dent Fault zone. These faults lose definition eastwards along their length in the more ductile shales and thin sandstones of the Alston Formation (Fig. 4). However, between them, adjacent to the Dent

Fault zone, there lies a complex set of folds; fold axial plane traces are parallel to the Dent Fault, but axes have variable plunge. The fault duplex developed at Rowell Gill is inferred to have developed at a restraining bend as the strike in the Dent Fault swings abruptly to the SSW.

The parallel faults continue to the SSW into southern Barbondale (**B**, Figs 2; 6). Here they are inferred to merge into a single structure that swings WSW along the northern side of Barkin Beck, continuing westward through a narrow valley separating Barbon Low Fell from Middleton Fell. Although the fault trace is imprecisely defined because of the similarities in Silurian strata on either side, linear zones of brecciation and cataclasis broadly locate the fault plane.

2.2.3. The Blindbeck overstep zone

The Barbondale fault strands lose displacement westwards into the Silurian, whilst the Dent Fault itself is well located again about 1 km southeast of Blindbeck Bridge, crossing Great Aygill and Hazel Sike (**B**, Fig. 2). The intervening area is an overstep zone analogous to that in Dentdale. Underhill *et al* (1988) used VLF surveying to locate the trace of the Dent Fault through this ground (their fig. 4a-c), contrasting their interpretation with an existing Geological Survey interpretation that showed an easterly offset in the fault across an E-W trending fault (their fig. 4c). Careful bedrock mapping across this ground has refined the trace inferred by the VLF data, revealing a somewhat more complex arrangement of faults striking both nearly N-S and E-W (Fig. 6), and confirming the easterly offset.

Within the transfer zone lies a small, fault-bound and folded outlying block of Alston Formation strata (Fig. 6, at [SD 663 832]). The trace of the fault bounding the southern side of this block is tightly constrained by adjacent outcrops of Silurian and Carboniferous strata. Although surface exposure of Carboniferous strata is limited, underground evidence from large potholes immediately adjacent to the trace of the NNW-trending fault reveals extremely broken ground (Hugh St. Lawrence, personal communication, 2009).

2.2.4. South of the Blindbeck overstep zone

South of the confluence of Hazel Sike with Great Aygill (Fig. 6; [SD 662 819]), the Dent Fault strikes just W of S. Subsidiary sub-parallel faults account for displacements in Alston Formation strata; sharp changes in dip and steep faulting parallel to the Dent Fault is observed underground in Bull Pot of the Witches (Figs 6, 5d; [SD 662 813]).

South of Leck Beck Head (Fig. 2; [SD 662 801]), the Dent Fault strikes just E of S. Although exposure is poor, available evidence suggests that the fault develops splays as it converges with the North Craven and Barbon faults. The crop of Silurian strata at the southern end of Barbon Low Fell narrows between the acutely convergent Dent and Barbon faults (Fig. 2). The strata increase in age towards this tip and dip northwards. We interpret and discuss the implications of this structure below.

Throughout the southern sector of the Dent Fault, the fault plane itself is not exposed; indeed, unambiguously identifiable fault planes are very difficult to find. However, in Hazel Sike, just a few tens of metres east of the confluence with Great Aygill, the plane of the Dent Fault can be located to <5m in the stream section [Fig. 6; [SD 662 819]). Silurian strata become increasingly brecciated eastwards until bedding is completely obscured and a coarse, anastomosing, very steeply west-dipping fracture fabric is developed in brecciated rock. This fabric is inferred to parallel the fault plane. Immediately east, Carboniferous strata are near vertical (Fig. 6).

2.3 Folds

In the sector of the Dent Fault north of our study area, *en echelon* fault/fold duplexes characteristic of strike-slip deformation at constraining fault bends, are developed in Silurian strata between the Rawthey and Dent faults (Woodcock & Rickards 2003a, figs. 3, 4). East of the Dent Fault, a relatively simple footwall syncline (the Fell End Syncline) is developed. Together, the duplexes and the Fell End Syncline are interpreted as a large-scale east-facing monocline that developed above a reactivated basement fracture system. Ultimately, faults propagating off this basement fracture pierced the monocline in an upwardly divergent fan or flower. The Dent Fault is the most continuous strand, cutting the steep limb of the monocline.

The structural style is somewhat different south of Dentdale. Although the footwall syncline persists along the southern sector of the Dent Fault, locally complex fault/fold duplexes are developed in Carboniferous strata in the footwall but *not* observed in Silurian strata in the hanging wall (Fig. 5), in contrast to the situation further north.

The contrast in response to deformation either side of the fault along the southern sector of the Dent Fault is apparent from stereonet analysis of bedding orientation (Fig. 7). To the west, Silurian strata are gently folded about Acadian hinges plunging gently between west and northwest (Fig. 7a, b, c). They are little affected by Variscan deformation and *en echelon* fault duplexes of the type that host the Taythes Anticline (Woodcock & Rickards 2003a, fig 3) are notably absent. In Carboniferous strata, poles to bedding reflect folds orientated broadly parallel to the fault (Fig. 7d, e, f), particularly the persistent, fault-disrupted footwall syncline (Fig. 5). Broader scatter indicated in stereonet 7d reflects the effects of the NW-trending fan of faults that intersects the southwesterly bend in the Dent Fault (Figs 2, 4). Stereonet 7f reflects folds in line with the North Craven Fault, mostly within the fault duplex at Tow Scar.

In general, the same Carboniferous stratigraphical level persists along the footwall of the Dent Fault, indicating that the footwall syncline is *grossly* cylindrical and sub-horizontal (Fig.

5). However, plunging structures are developed locally. The most evident of these is an anticline hinge exposed over some 30m in Hazel Sike (Fig. 4, [SD 663 819]). This fold plunges at about 25° towards the SW and is asymmetric, having a steeply-dipping NW limb and shallow-dipping SE limb. This fold geometry is consistent with sinistral transpressional deformation.

2.4 Estimates of displacement across the Dent Fault

The dip-slip component of Variscan displacement across the Dent Fault and its associated monocline has been estimated by comparing the height of the base of the Carboniferous at about two-kilometre intervals along the length of the fault, as shown in Fig. 8. The base Carboniferous itself is infrequently exposed. Where higher Carboniferous units crop out in the eastern footwall and between northing grid lines 90 to 95 and 01 to 15 in the hangingwall, the base has been estimated using the nearest available stratigraphic thickness of underlying units, as shown on the cross-sections here (Fig. 5) and in Woodcock & Rickards (2003a, Fig. 4). In the remaining areas, between grid lines 77 to 90 and 95 to 01 in the western hangingwall, the height of the topography in Silurian rocks provides only a minimum constraint on the height of the now-eroded base Carboniferous. In the sector opposite Taythes Gill and the River Rawthey (grid lines 95-01) the Silurian rocks on topographic summits commonly preserve the secondary reddening characteristic below the Carboniferous unconformity, and are unlikely to be more than about 100 metres below the base-Carboniferous. Despite the uncertainties, the total throw across the Dent Fault zone must exceed 1km down to the east along most of its length, with the majority of the displacement accommodated on the Dent Fault itself. The displacement could decrease to about half its maximum value at the south end of the fault as it joins the Barbon and Craven faults.

Down-east displacement declines at the northern end of the fault until it switches to down-west throw of up to 700 m on the linked Argill Fault. There is an apparent decrease in the throw where thick alluvial fan sediments of the Sedbergh Conglomerate Formation form the base of the Carboniferous sequence in the hangingwall near the Clough River (grid 90-95). However, these sediments may fill a deep palaeovalley into the sub-Carboniferous rocks, questioning throw estimates that assume an originally sub-horizontal base to the Carboniferous (Fig. 8).

3. KINEMATIC INTERPRETATION ALONG THE DENT FAULT

3.1 General kinematic model

Transpressional Variscan displacement on the Dent Fault due to NNW-SSE shortening is well-established (Underhill *et al* 1988; Woodcock & Rickards 2003a) mostly from evidence along the sector of the fault north of the study area. The new mapping along the southern sector corroborates this gross kinematic model (Fig. 9) whilst revealing local contrasts. The key differences include less complex Variscan deformation in Silurian strata in the hanging wall, 1 – 2 km wide stepover zones in the Dent Fault (Fig. 2), and more structural complexity within Carboniferous footwall rocks at fault bends (Figs 4, 5).

The few slickenline data for the Dent Fault (Fig. 10) come from central Barbondale southwards (Fig. 2). Of these, three lineations plunge at between 60° and 70° on their respective fault planes and indicate sinistral-oblique displacement on reverse faults. The fourth, measured on a shallow west-dipping bedding plane, is consistent with sinistral strike slip. Assuming that the host faults are all reverse, a kinematic analysis of these data using FaultKin (based on Allmendinger *et al* 2013) yields a dominantly thrust solution with a component of sinistral strike-slip on west or northwest dipping faults such as the Dent Fault. The local shortening vector is predicted to be about 113° (Fig. 10). If this vector was proved to be correct by further data, much of the strike-slip component evidenced on the northern segment of the Dent Fault would have to be partitioned on to the Barbon Fault in the study area. However, locally-developed southwest-plunging folds and transverse structures, including faults and joints, at fault bends along the Dent Fault indicate a component of strike-slip (Fig. 4).

3.2 Local kinematics along the Dent Fault

3.2.1 The Dentdale overstep zone

There are three zones in the study area that deserve further analysis, because they are both problematic but instructive. The first such area is the overstep zone in Dentdale (Figs 2, 4). This is interpreted as a left-stepping zone which should act, in sinistral strike slip, as a releasing overstep. The faults that link across the overstep – the Helm Gill, Underwood and Dent faults – would be expected to bound young Silurian rocks dropped down along normal faults. Instead the faults bound slivers of older rocks; Cautley Mudstone Formation (upper Ordovician) and Brathay Formation (mid-Silurian).

There are three possible explanations of this anomalous geometry. First, the slivers could have been excised from the Dent Fault hangingwall further north, moved southwards and obliquely upwards, and parked at the releasing overstep. Secondly, the old slivers could have been thrust up by dominantly dip-slip displacements in the hangingwall, consistent with the shortening vector from slickenline analysis (Fig. 6). In both these possibilities, under NNW-SSE compression, thrusting is possible at the southern ends of the inlying slivers where they abut the Dent Fault (Fig. 11a). Thirdly, the old slivers could record deformation in a restraining bend from a previous dextral phase on the Dent Fault. There is no evidence for this third possibility, and we regard one of the first two explanations as more plausible.

3.2.2. The Blindbeck overstep zone

The Blindbeck overstep zone (Fig. 5) is also left-stepping, and therefore also predicted to be a releasing zone in sinistral strike-slip. Here the new mapping is more compatible with releasing kinematics than in the Dentdale overstep. The overlapping strands of the Dent Fault are linked mainly by NNW-striking and ENE dipping faults. They act as normal faults, with net downthrow to the ENE, in sympathy with the releasing bend model. In contrast to the fault-bounded slivers of older strata in the Dentdale overstep, these normal faults let down a block of folded younger Alston Formation strata north of Fell House, surrounded by older rocks. The fault planes are not exposed, but we assume them to be very steep.

3.2.3 The Barbon Low Fell fault wedge horst

At the southern end of Barbon Low Fell, the Dent Fault converges acutely with the Barbon/South Craven fault system and is interpreted to link with the North Craven Fault via a system of splays (Fig. 2, **D**). This linkage is likely to be more complex than shown as field evidence is limited by poor exposure. The crop of the Wenlock (mid-Silurian) Brathay Formation (Tranearth Group) is progressively narrowed between the Dent and Barbon faults. The Silurian strata between the two faults increase in age southwards, dipping north. This fault wedge contrasts with the Silurian strata west of the Barbon Fault, which young southwards, and have a cover of basal Carboniferous conglomerates (Fig. 2). We attribute the southwards increase in age in the faulted wedge to its uplift by transpression between the two bounding faults, with dip-slip concentrated on the Dent Fault and strike-slip on the Barbon Fault (Fig. 11b). The two faults must meet at depth as well as southwards, squeezing the Silurian sliver upwards (Fig. 11b).

3.2.4 Linkage of the Barbon and Craven faults

Sinistral strike–slip displacement is apparent in the northern sector of the Barbon Fault (Soper 1999; Woodcock & Rickards 2003b) and, based on wider mapping evidence, the fault is interpreted to be continuous southward with the South Craven Fault (Figs 2, 12). However, this continuity is geometric rather than kinematic, since it requires a switch from the sinistral shear sense on the Barbon Fault to dextral shear recorded on the Craven Fault System (Arthurton 1984; Gawthorpe 1987; Woodcock & Rickards 2003a) Local evidence for dextral shear along the Craven Fault System is found at Tow Scar (Fig 2). Here, a fault duplex is developed within the North Craven Fault zone, bounding an anticline-sycline pair. The *en echelon* arrangement of the bounding faults and fold axial traces strongly suggests dextral transpression.

The Craven Fault System and the fault and fold deformation developed in the Craven Basin comprise a regional SE to ESE-striking dextral shear zone. The faults show a conjugate strike-slip pattern facing a northwesterly maximum principal stress (Figs 9, 13), with the North, Mid and South Craven faults as part of the dextral set. The folds in the Craven Basin indicate NNW-directed shortening and have en echelon minor folds and faults indicating a component of dextral strike-slip (Arthurton 1984).(cf. Woodcock & Fischer 1986, fig. 1) The switch in shear sense from sinistral to dextral along the linked Barbon – Craven faults requires a neutral shear point along their conjugate trace. This lies at about the tip of the Barbon Low Fell fault wedge, as shown schematically on Figure 12.

3.4 Regional fault patterns: implications for fault history, kinematics and structural architecture in NW England

When set in the wider context of Northwest England (Fig. 13), the Dent, Craven and Barbon faults form part of a coherent system of faults that extends across the region. Readily apparent is the swing in fault orientations from N-S in the Southern Lake District to WNW-

ESE in the Craven Basin. The first-order reason for this swing is the structural rigidity of the Askrigg Block. The more plastic rocks beneath the Silurian Windermere Supergroup to the west of the block and the Carboniferous Craven Basin to the south had preferentially to take up the NNW-directed Variscan shortening. However, the width of the western and southern deformation zones suggests other controls that require explanation. These controls are most likely the influence on Variscan structures of Acadian basement structures (e.g. Moseley 1972; Turner 1949).

A number of the N-S faults in the Southern Lake District are known to have a pre-Carboniferous history and to partition strain during Acadian deformation in the late Silurian (Moseley 1972; Soper 1999; Woodcock & Rickards 2003a; Woodcock & Rickards 2003b). At least two of these faults, the Firbank and Kensgriff faults, are unconformably overlain by Carboniferous strata (Fig. 13; (British Geological Survey 2007)). Fault breccia in the Wray Castle Formation is hornfelsed (Soper, 1999) by the Shap Granite (397 ± 7 Ma; Millward 2002, and references therein), and two faults are cut by the pluton (British Geological Survey, 2007; Soper, 1999) (Fig. 13). An earlier history is further implied by apparent fault control on Silurian sedimentation (Barnes *et al* 2006; Soper 1999, page 15) indicating that these faults themselves likely represent older basement structures which were reactivated and propagated up through the Silurian cover during Acadian deformation (Soper 1999). We pursue the implications of such an older history with regard to the structural development of the Caledonides of England and Wales more fully in a separate paper.

In the Craven (or Bowland) Basin, Gawthorpe (1987) used stratigraphic and gravity data to identify major Dinantian (early Carboniferous) ENE-striking basin-bounding faults offset by SE-striking strike-slip transfer faults. The ENE-striking structures parallel the Acadian cleavage in the southern Lake District, suggesting an earlier control. The Variscan (late Carboniferous) folds of the Craven Basin (Arthurton 1984) parallel the earlier basin-bounding faults and the Craven fault zone and other SE-striking faults in the basin parallel the earlier transfer faults.

By at least 400 Ma (mid-Emsian, Early Devonian), and possibly much earlier, the Askrigg Block had been structurally stabilised by the Wensleydale pluton. Although the upper margin of the pluton in the Raydale borehole is cleaved, comparison with analogous exposed plutons at Skiddaw and Shap suggests that the Acadian deformation (about 400-390 Ma; Woodcock & Soper 2006) would not have pervaded the Wensleydale pluton and that earlier faults would be sealed. The block therefore resisted both early Carboniferous extension and late Carboniferous (Variscan) shortening.

The pattern of major faulting around the southwest corner of the Askrigg Block is reminiscent of a leading extensional fan splaying off a dextral strike-slip fault, as shown schematically by Woodcock & Fischer (1986, fig. 1). A subordinate but regular set of NNE-SSW trending conjugate faults is also developed, consistent with extensional displacement. Given that the N-S faults in the Southern Lake District reflect basement fault patterns, and given that the South Craven – Morley Campsall Fault is known to separate geophysically different crust at depth in the sub-Carboniferous basement (Kirby *et al* 2000), we suggest that, together, they reflect a structural architecture in the basement that is at least Acadian in age. Indeed, this architecture may be considerably older, given that the Lake District *is* and the Askrigg Block *could be* underlain by plutons of late Ordovician age. These plutonic components are interpreted by some workers to be part of the supra-subduction arc established in northern and eastern England during convergence of Avalonia with Baltica and closure of the Tornquist Sea (e.g. Noble *et al* 1993; Pharaoh *et al* 1997; Pharaoh *et al* 1993). Variscan deformation has resulted in the exploitation and reactivation of this basement structural architecture, in response to the regional NNW-SSE shortening direction. The Dent, Barbon and Craven faults and related fold and fracture patterns are readily explained as a consistent, collective response to this tectonic event (Fig. 13).

In summary, the Variscan kinematic history of the region can be explained in terms of three basement sectors of contrasting rheology. The Askrigg Block with its granite core acts as a rigid body, with limited internal deformation. The Lower Palaeozoic rocks of the Southern Lake District form a relatively rigid block, consolidated by ~E-W-trending Acadian structures. The Craven Basin, with its thick fill of heterolithic Carboniferous strata, rich in mudstones and siltstones, is more deformable than the Askrigg and Lower Palaeozoic blocks. During Variscan deformation, the Lower Palaeozoic block moved southwards (sinistrally) relative to the Askrigg Block, which moved dextrally relative to the Craven Basin. The convergence of the Lower Palaeozoic block with the Craven Basin was accommodated by shortening and reverse faulting in the basin (Fig. 12).

4. CONCLUSIONS

Along its southern extent, south of Sedbergh, the Dent Fault comprises three gently east-concave strands, meeting at two 1-2 km wide overstep zones.

Structures developed along the fault demonstrate transpressional deformation. A persistent faulted footwall syncline indicates strongly reverse dip-slip deformation, but locally developed plunging folds and imbricate fault duplexes developed in the footwall at fault bends indicate a strike-slip component along favourably orientated segments.

Silurian strata in the hanging wall lack the Variscan folds observed further north by Underhill et al (1988) and Woodcock & Rickards (Woodcock & Rickards 2003a). However, horsts of older Silurian and Ordovician strata at the Dentdale overstep and at the southern tip of the Dent Fault are analogous to the excision up out of the hanging wall of the wedge of Silurian strata in the Taythes Anticline (Woodcock & Rickards 2003a, fig. 3). The difference in style probably reflects significant partitioning of sinistral strike-slip on to the Barbon Fault to the west.

The Barbon Fault is considered to be contiguous with the Craven Fault system, particularly the South Craven Fault. The Dent Fault merges with these two structures via splays and linkages with the North Craven Fault. Regionally, the Dent and Barbon faults form the inner-most pair of an assemblage of ~N-S trending faults developed across the Southern Lake District extending off the South Craven – Morley Campsall Fault System around the southwestern margins of the Askrigg Block.

The kinematics of the Dent, Barbon and Craven faults, are consistent with NNW-SSE orientated shortening during late Carboniferous Variscan deformation. The rigid Askrigg Block partitioned Variscan displacements to its west and south margins. Here, Variscan fault and fold orientations were strongly influenced by pre-existing structures, at least as old as Acadian to the west and early Carboniferous to the south.

Acknowledgements. We wish to acknowledge the contributions of Jack Soper and the late Barrie Rickards to our understanding of the geology of the Dent Fault and adjacent ground, particularly of the adjacent Lower Palaeozoic rocks. Dave Millward is thanked for numerous discussions about the Dent and related faults, and Northern England geology in general during the course of this work, and for his encouragement. Dave Schofield and Tim Pharaoh, Bob Holdsworth and Doug Holliday are thanked for their reviews of an original manuscript that ultimately led to this significantly different paper. CWT wishes to acknowledge the help given by Marion Dunn, Ray Duffy, Michael Hale, Andy Hall, Hugh St Lawrence and other members of the Red Rose Cave & Pothole Club. CWT publishes with the permission of the Executive Director, British Geological Survey (NERC). This paper is an output of the former BGS Northern England Project.

References

AITKENHEAD, N., BARCLAY, W.J., BRANDON, A., CHADWICK, R.A., CHISHOLM, J.I., COOPER, A.H. & JOHNSON, E.W. 2002. British regional geology: the Pennines and adjacent areas (4th edition). British Geological Survey, Nottingham.

ALLMENDINGER, R.W., CARDOZO, N.C. & FISHER, D. 2013. Structural Geology Algorithms: Vectors & Tensors. Cambridge University Press, Cambridge, England.

ARTHURTON, R.S. 1984. The Ribblesdale fold belt, NW England - a Dinantian-early Namurian shear zone. *In*: HUTTON, D.H.W. & SANDERSON, D.J. (eds.) *Variscan tectonics of the North Atlantic region*. The Geological Society of London, Special Publication of the Geological Society of London, **14**, 131-138.

AVELINE, W.T., HUGHES, T.M. & TIDDEMAN, R.H. 1872. *The geology of the neighbourhood of Kirkby Lonsdale and Kendal*.

BARNES, R.P., BRANNEY, M.J., STONE, P. & WOODCOCK, N.H. 2006. The Lakesman Terrane: the Lower Palaeozoic record of the deep marine Lakesman Basin, a volcanic arc and foreland basin. *In*: BRENCHLEY, P.J. & RAWSON, P.F. (eds.) *The geology of England and Wales*. Geological Society of London, 105-129.

BRITISH GEOLOGICAL SURVEY. 2007. *Kendal. England and Wales Sheet 39. Solid Geology. 1:50 000 Series*.

CARDOZO, N. & ALLMENDINGER, R.W. 2013. Spherical projections with OSXStereonet. *Computers & Geosciences*, **51**, 193-205, doi: http://dx.doi.org/10.1016/j.cageo.2012.07.021.

CORFIELD, S.M., GAWTHORPE, R.L., GAGE, M., FRASER, A.J. & BESLY, B.M. 1996. Inversion tectonics of the Variscan foreland of the British Isles. *Journal of the Geological Society,* **153**, 17-32.

CRITCHLEY, M.F. 1984. Variscan tectonics of the Alston block, northern England. *Geological Society, London, Special Publications*, **14**, 139-146, doi: 10.1144/gsl.sp.1984.014.01.14.

DAKYNS, J.R., TIDDEMAN, R.H., GUNN, W. & STRAHAN, A. 1890. The Geology of the Country around Ingleborough, with parts of Wnesleydale and Wharfedale. Memoir of the Geological Survey, England and Wales.

DUNHAM, K.C. 1974. Granite beneath the Pennines in North Yorkshire. *Proceedings of the Yorkshire Geological and Polytechnic Society*, **40**, 191-194, doi: 10.1144/pygs.40.2.191.

DUNHAM, K.C. & WILSON, A.A. 1985. Geology of the Northern Pennine Orefield, Vol. 2: Stainmore to Craven. HMSO.

FOSSEN, H. & TIKOFF, B. 1993. The deformation matrix for simultaneous simple shearing, pure shearing and volume change, and its application to transpression-transtension tectonics. *Journal of Structural Geology*, **15**, 413-422.

GAWTHORPE, R.L. 1987. Tectono-sedimentary evolution of the Bowland Basin, N England, during the Dinantian. *Journal of the Geological Society*, **144**, 59-71.

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*, **159**, 401-415, doi: 10.1144/0016-764901-123.

JONES, R.R. & TANNER, G.P.W. 1995. Strain partitioning in transpression zones. *Journal of Structural Geology*, **17**, 793-802, doi: http://dx.doi.org/10.1016/0191-8141(94)00102-6.

KIRBY, G.A., BAILY, H.E., CHADWICK, R.A., EVANS, D.J., HOLLIDAY, D.W., HOLLOWAY, S., HULBERT, A.G., PHAROAH, T.C., SMITH, N.J., AITKENHEAD, N. & BIRCH, B. 2000. The structure and evolution of the Craven Basin and adjacent areas. Stationery Office.

MCCLAY, K.R. 2013. The mapping of geological structures. John Wiley & Sons.

MILLWARD, D. 2002. Early Palaeozoic magmatism in the English Lake District. *Proceedings of the Yorkshire Geological and Polytechnic Society*, **54**, 65-93, doi: 10.1144/pygs.54.2.65.

MILLWARD, D. 2006. Caledonian intrusive rocks of northern England and the Midlands. *In*: BRENCHLEY, P.J. & RAWNSLEY, K. (eds.) *The Geology of England and Wales*. The Geological Society, London, 147-154.

MORT, K. & WOODCOCK, N.H. 2008. Quantifying fault breccia geometry: Dent Fault, NW England. *Journal of Structural Geology*, **30**, 701-709, doi: doi:10.1016/j.jsg.2008.02.005.

MOSELEY, F. 1972. A tectonic history of northwest England. *Journal of the Geological Society*, **128**, 561-594, doi: 10.1144/gsjgs.128.6.0561.

NOBLE, S.R., TUCKER, R.D. & PHARAOH, T.C. 1993. Lower Palaeozoic and Precambrian igneous rocks from eastern England, and their bearing on late Ordovician closure of the Tornquist Sea: constraints from U-Pb and Nd isotopes. *Geological Magazine*, **130**, 835-846.

PHARAOH, T.C., ALLSOP, J.M., HOLLIDAY, D.W., MERRIMAN, R.J., KIMBELL, G.S., RUNDLE, C., BREWER, T.S., NOBLE, S.R. & EVANS, C.J. 1997. The Moorby Microgranite: a deformed high level intrusion of Ordovician age in the concealed Caledonian basement of Lincolnshire. *Proceedings of the Yorkshire Geological Society*, **51**, 329-342.

PHARAOH, T.C., BREWER, T.S. & WEBB, B.C. 1993. Subduction-related magmatism of late Ordovician age in eastern England. *Geological Magazine*, **130**, 647-656.

PHILLIPS, J. 1836. Illustrations of the geology of Yorkshire, Part 2: The Mountain Limestone District. John Murray, London.

SANDERSON, D.J. & MARCHINI, W.R.D. 1984. Transpression. *Journal of Structural Geology*, **6**, 449-458, doi: http://dx.doi.org/10.1016/0191-8141(84)90058-0.

SEDGWICK, A. 1835. Introduction to the general structure of the Cumbrian Mountains; with a description of the great dislocations by which they have been separated from the neighbouring Carboniferous chains. *Transactions of the Geological Society, London*, **(2) 4**, 47-68.

SOPER, N.J. 1999. The Windermere Supergroup of 1:25 000 sheets NY50 and NY60, Southern Shap Fells and Northern Howgill Fells, Cumbria. *British Geological Survey Technical Report*, **WA/99/35**, 40pp.

SOPER, N.J. & WOODCOCK, N.H. 2003. The lost Lower Old Red Sandstone of England and Wales: A record of post-Iapetan flexure or Early Devonian transtension? *Geological Magazine*, **140**, 627-647.

STONE, P., MILLWARD, D. & YOUNG, B. 2010. British Regional Geology: Northern England. British Geological Survey.

TARASEWICZ, J.P.T., WOODCOCK, N.H. & DICKSON, J.A.D. 2005. Carbonate dilation breccias: examples from the damage zone to the Dent Fault, northwest England. *Geological Society of America Bulletin*, **117**, 736–745.

TURNER, J.S. 1935. Structural geology of Stainmore, Westmorland, and notes on late-Palaeozoic (late-Variscan) tectonics on the north of England. *Proceedings of the Geologists' Association*, **44**, 121-151.

TURNER, J.S. 1949. The Deeper Structure of Central and Northern England. *Proceedings of the Yorkshire Geological and Polytechnic Society*, **27**, 280-297, doi: 10.1144/pygs.27.4.280.

UNDERHILL, J.R., GAYER, R.A., WOODCOCK, N.H., DONNELLY, R., JOLLEY, E.J. & STIMPSON, I.G. 1988. The Dent Fault System, northern England - reinterpreted as a major oblique-slip fault zone. *Journal of the Geological Society, London*, **145**, 303-316.

WOODCOCK, N. & SOPER, N. 2006. The Acadian Orogeny. *In*: BRENCHLEY, P.J. & RAWSON, P.F. (eds.) *The Geology of England and Wales*. Geological Society of London, 131-146.

WOODCOCK, N.H. & FISCHER, M. 1986. Strike-slip duplexes. *Journal of Structural Geology*, **8**, 725-735.

WOODCOCK, N.H. & MORT, K. 2008. Classification of fault breccias and related fault rocks. *Geological Magazine*, **145**, 435-440.

WOODCOCK, N.H. & RICKARDS, B. 2003a. Transpressive duplex and flower structure: Dent Fault System, NW England. *Journal of Structural Geology*, **25**, 1981-1992.

WOODCOCK, N.H. & RICKARDS, R.B. 2003b. Geological notes and local details for 1:10 000 sheet SD69NE (Westerdale) and parts of sheets SD69NW (Howgill), SD69SW (Firbank) and SD69SE (Sedbergh). Part of 1: 50 000 sheets 39 (Kendal) and 40 (Kirkby Stephen). *British Geological Survey Internal Report*, **IR/03/090**, 61pp.

WOODCOCK, N.H., SAYERS, N.J. & DICKSON, J.A.D. 2008. Fluid flow history from damage zone cements near the Dent and Rawthey faults, NW England. *Journal of the Geological Society*, **165**, 829-837, doi: 10.1144/0016-76492007-133.

Captions

Figure 1. Summary of the regional geology of northern England, showing the major stratigraphical subdivisions, the known or inferred extent of key plutonic rocks and the distribution of the main fault systems, including the location of the Dent Fault and its relationship to the regional geology.

Figure 2. The geology of the southern sector of the Dent Fault. Three NNE-striking segments meet at two overstep zones in Dentdale and lower Barbondale. The southwestern limit of the study of the northern sector of the Dent Fault by Woodcock & Rickards (2003a) is outlined, together with the extent of figures 4 and 6.

Figure 3. Previously published models of the relationship between the Dent and adjacent faults. NCF: North Craven Fault; MCF: Middle Craven Fault; SCF: South Craven Fault; SD: Stockdale Disturbance.

Figure 4. The geology of the Dent Fault in upper Barbondale and Dentdale.

Figure 5. Simplified cross-sections across the Dent and adjacent faults, revealing the reverse displacement and the moderate development of upward-divergent fault fans.

Figure 6. The geology of the Dent Fault in lower Barbondale.

Figure 7. Lower hemisphere equal area projections of poles to bedding from the Silurian strata west of the Dent Fault (stereonets a to c) and Carboniferous strata (stereonets d to f) to the east.

Figure 8. Estimated stratigraphic throw (vertical displacement) across the Dent Fault and its associated monoclinal fold, using the base-Carboniferous as a datum. Data are plotted along the whole length of the fault from its branch points with the Argill and Augill faults in the north and the Barbon and Craven faults in the south.

Figure 9. Rose diagram of nominally straight-line segments of the Dent, Craven and Barbon faults with respect to the inferred NNW-SSE shortening direction and the corresponding strain fields that result. The Dent Fault lies dominantly in the sinistral displacement field, the North Craven Fault wholly within the dextral field.

Figure 10. Lower hemisphere equal area projection of slickenline data and the surfaces on which they were recorded, with results of kinematic analysis to yield best-fit shortening axis using FaultKin (Allmendinger *et al* 2013).

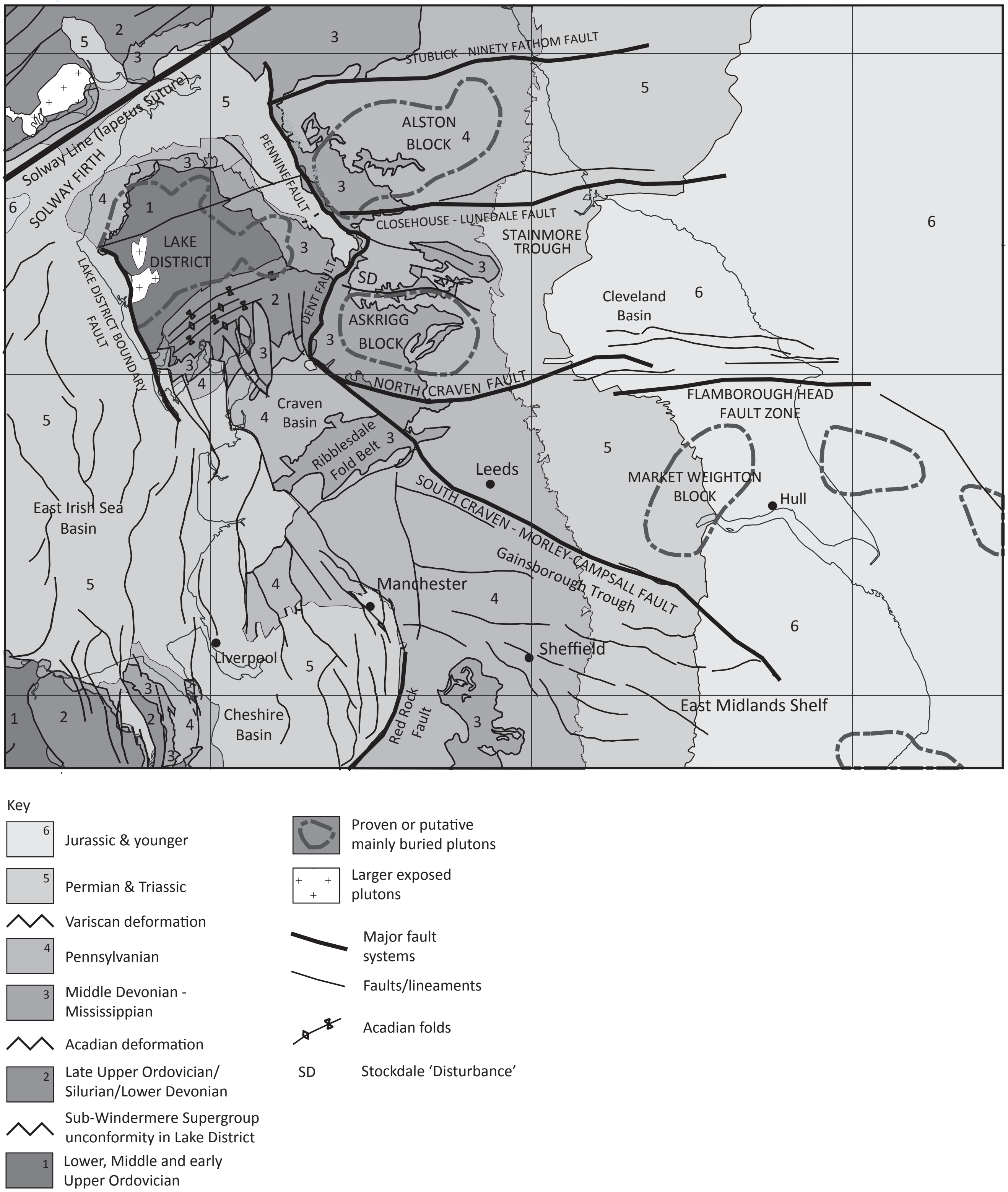
Figure 11.

a) Kinematic interpretation of the horst of Ordovician Cautley Mudstone between the Helm Gill (HGF) and Underwood UF) faults.

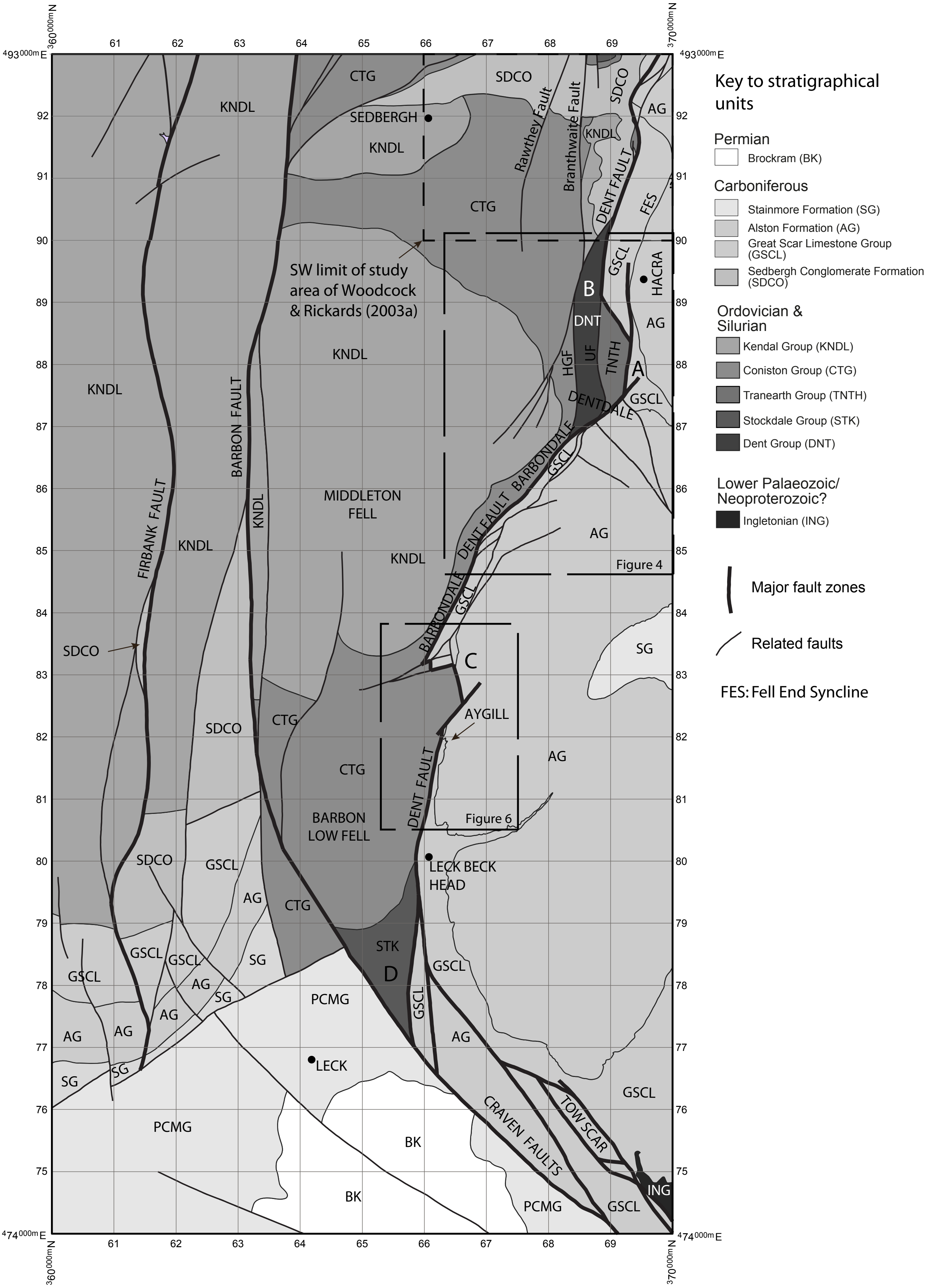
b) Block-diagram model for the uplifted wedge of older Silurian strata at the junction of the Dent and the Barbon – South Craven faults. Dip-slip is partitioned increasingly on the Dent fault as strike-slip continues on the Barbon Fault. The wedge of Silurian strata is pinched up between these two converging faults (inferred also to connect at depth).

Figure 12. Summary of the kinematics around the junction of the Dent, Barbon and Craven faults, highlighting the switch from sinistral to dextral shear around the southwest corner of the Askrigg Block, and the partitioning of deformation around this rigid block.

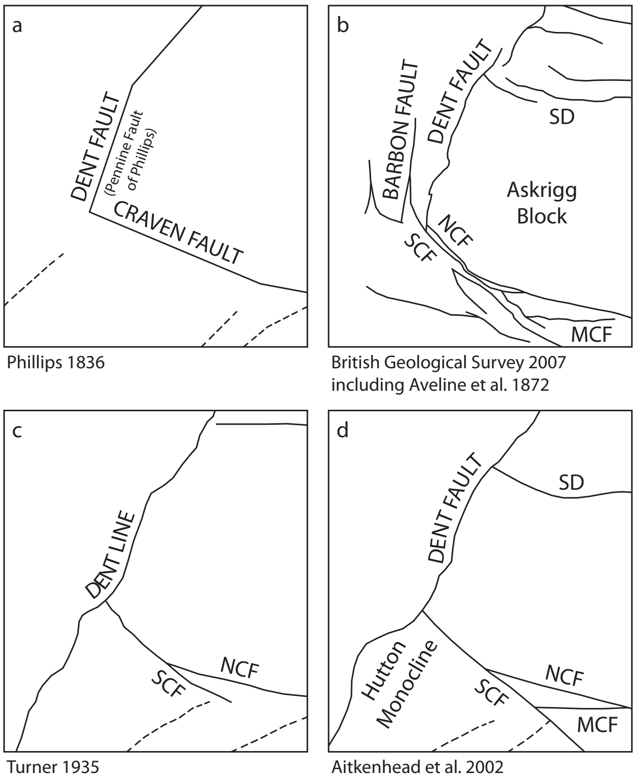
Figure 13. Simplified map of fault arrays in N England to the west and south of the Askrigg Block. Fault data are from British Geological Survey 1:50 000 Geological Sheets 39, 40, 41,49, 50, 51, 59, 60 & 61. Inset A: Location in the United Kingdom. Inset B: the resolved best-fit shortening direction for Variscan deformation from Woodcock & Rickards (2003, fig. 7). Schematic strain ellipsoids, adapted from McClay (1987, fig. 6.16a), show correspondence of observed fault and fold orientations to theoretical geometry of structures developed in dextral and sinistral shear.



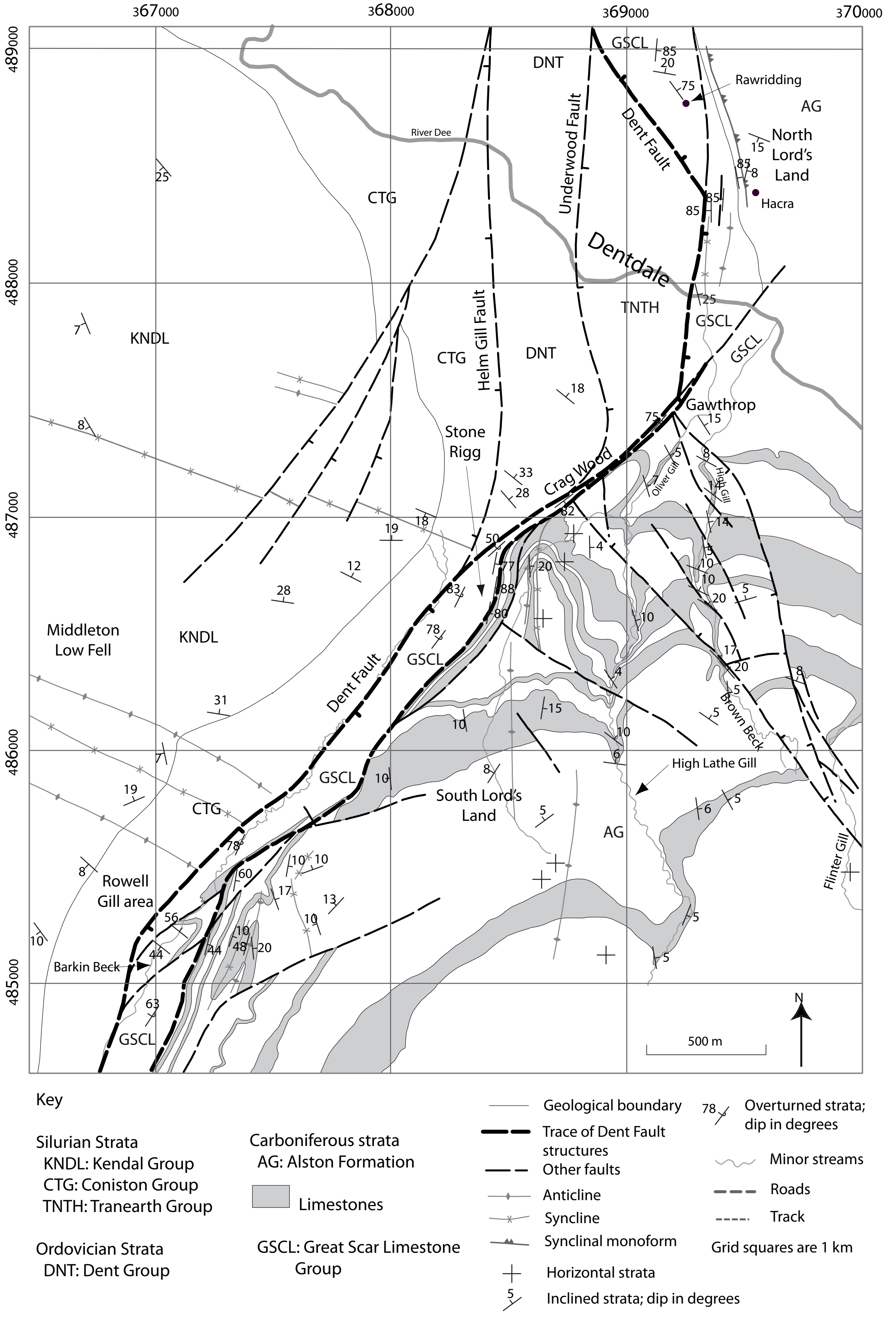
Thomas & Woodcock. Figure 1



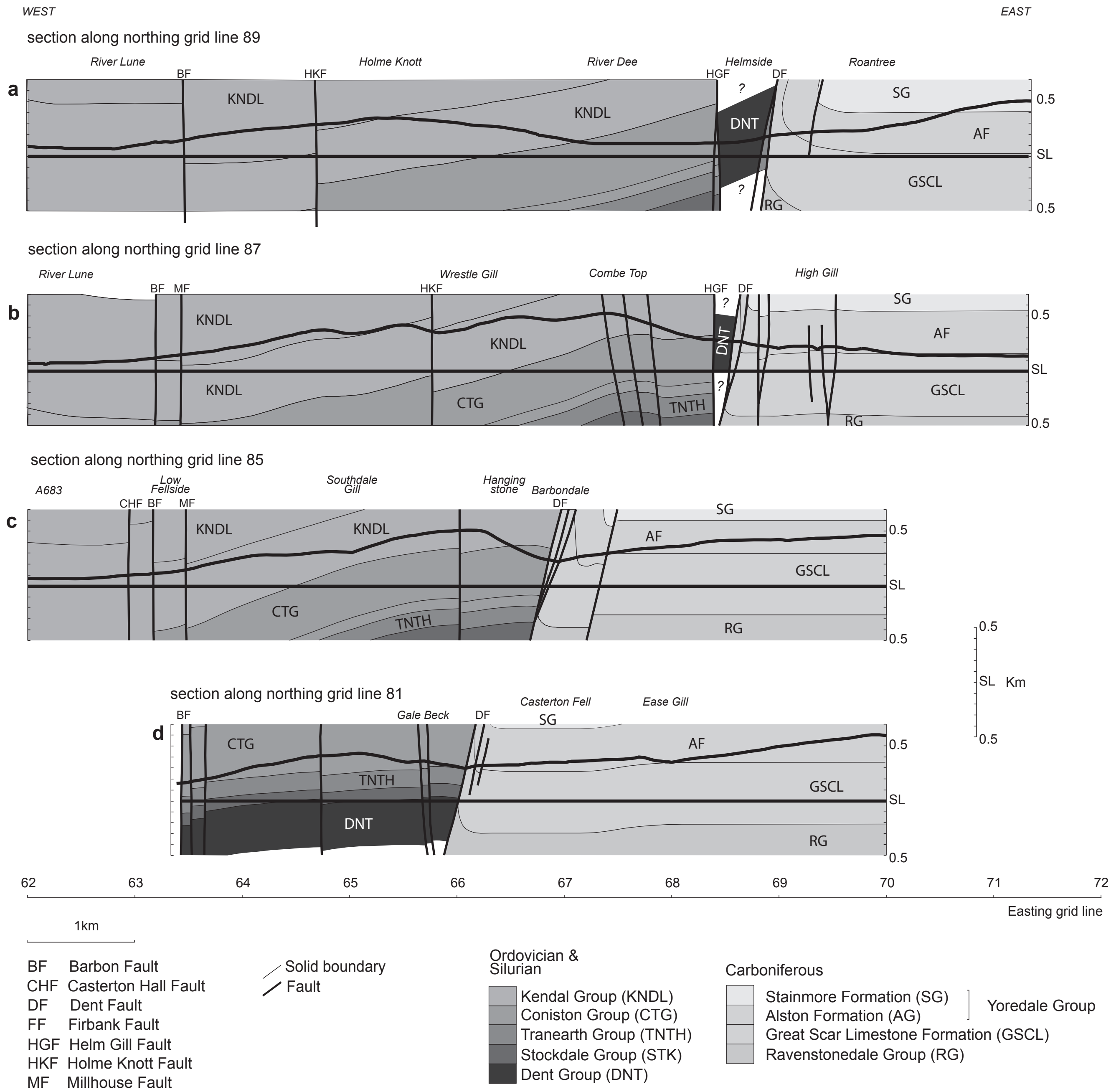
Thomas & Woodcock. Figure 2



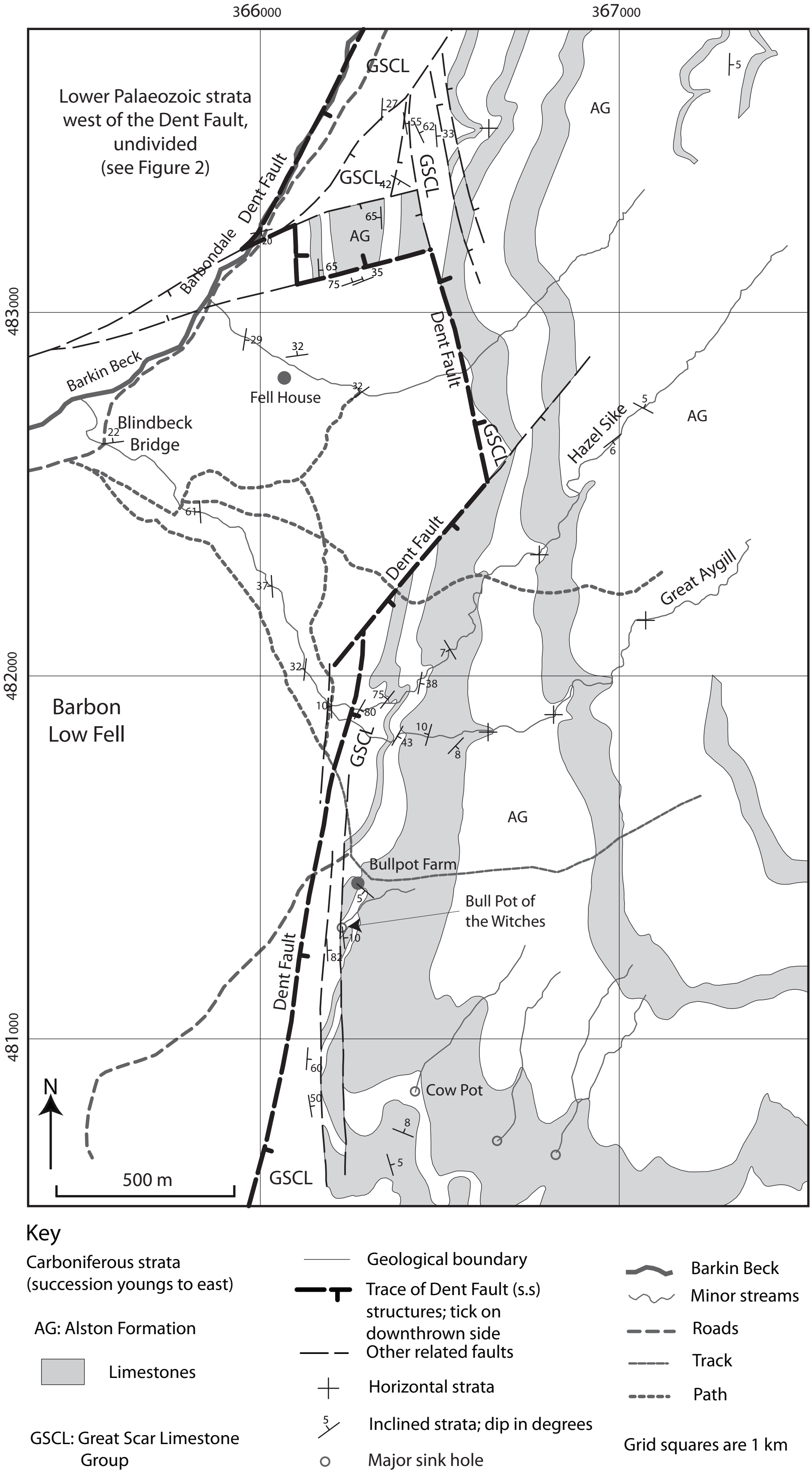
Thomas & Woodcock. Figure 3



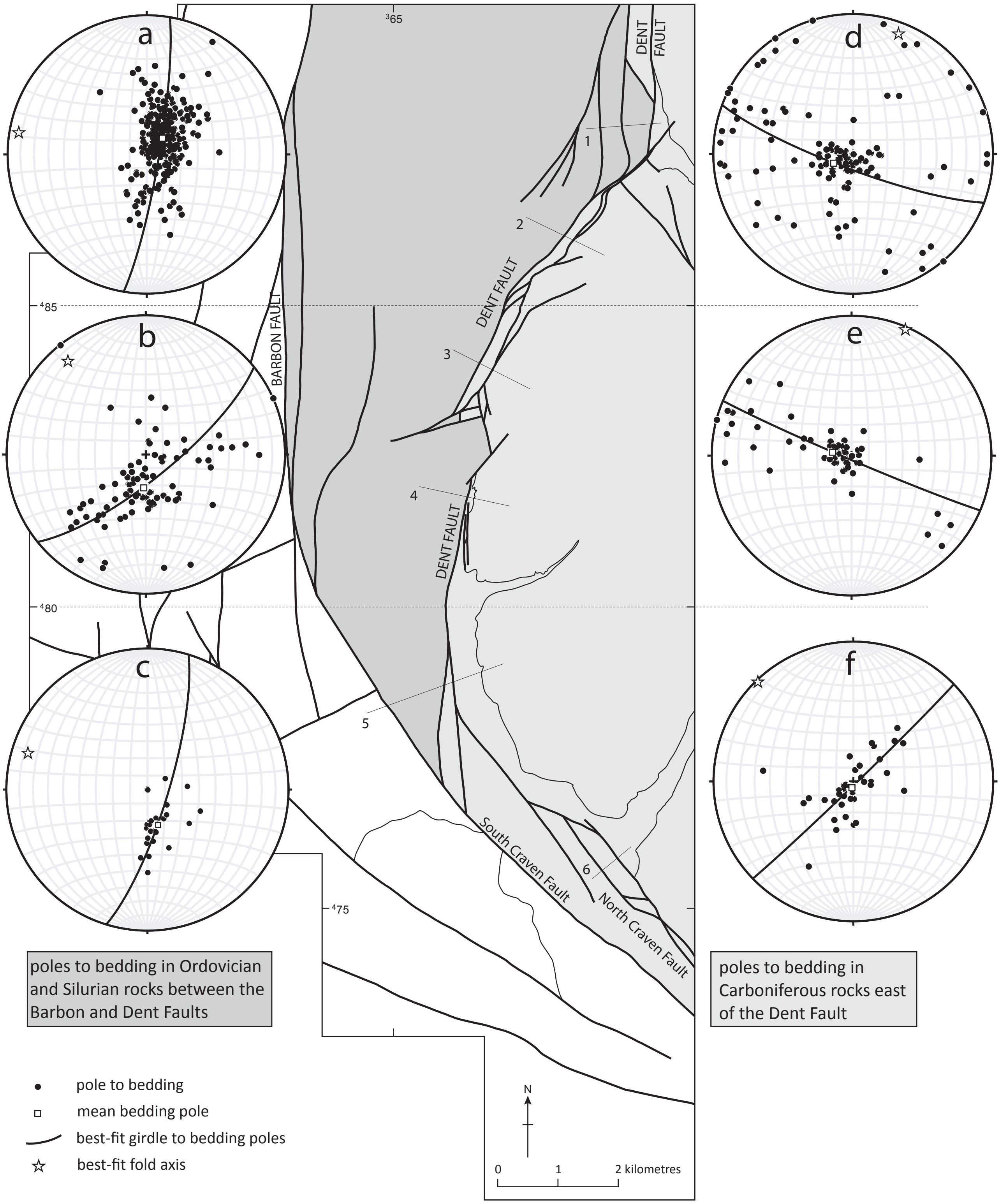
Thomas & Woodcock. Figure 4



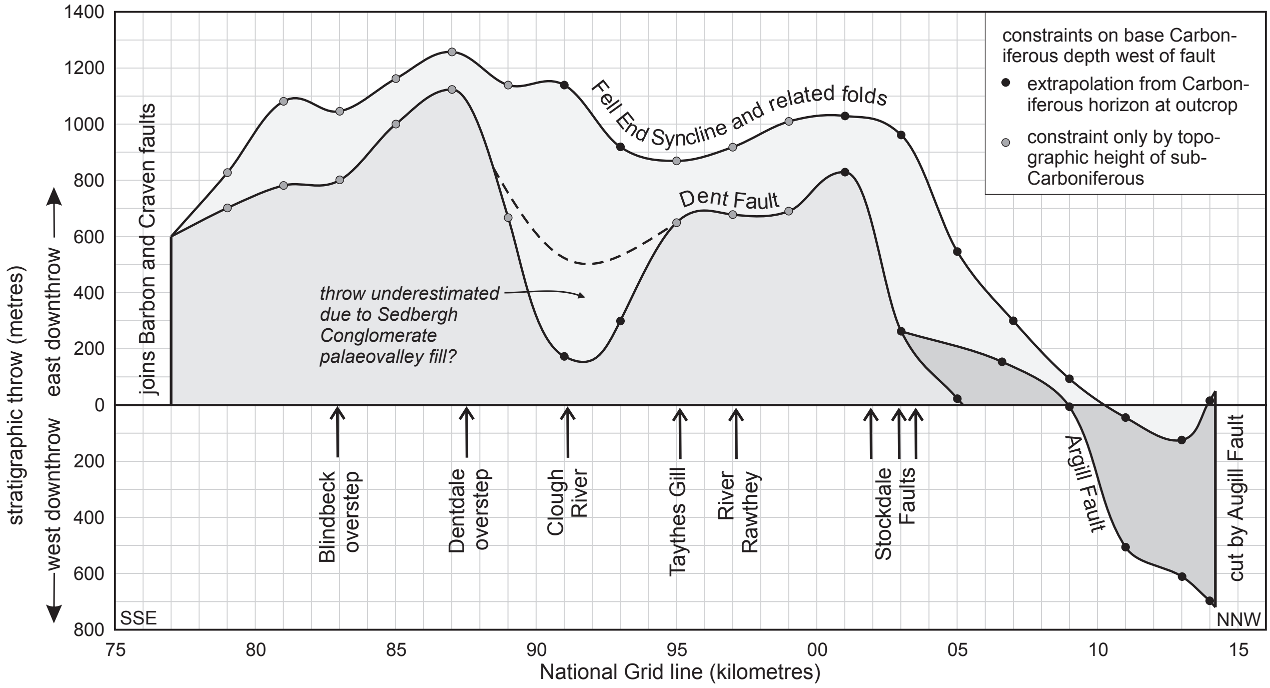
Thomas & Woodcock Figure 5



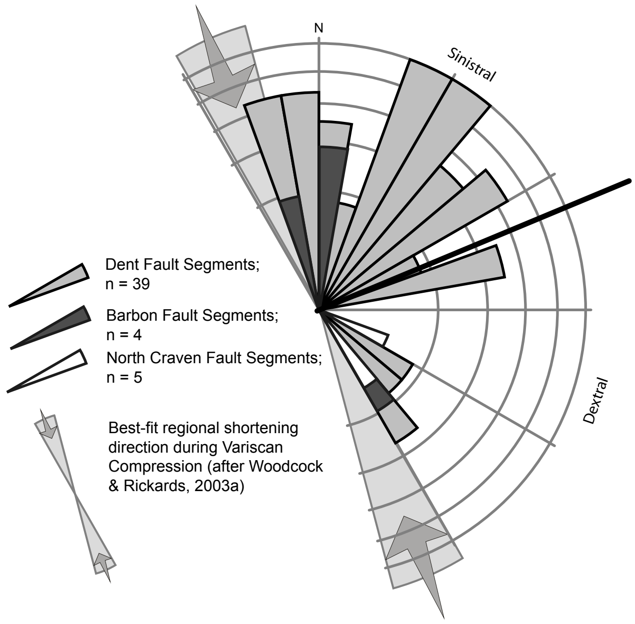
Thomas & Woodcock. Figure 6



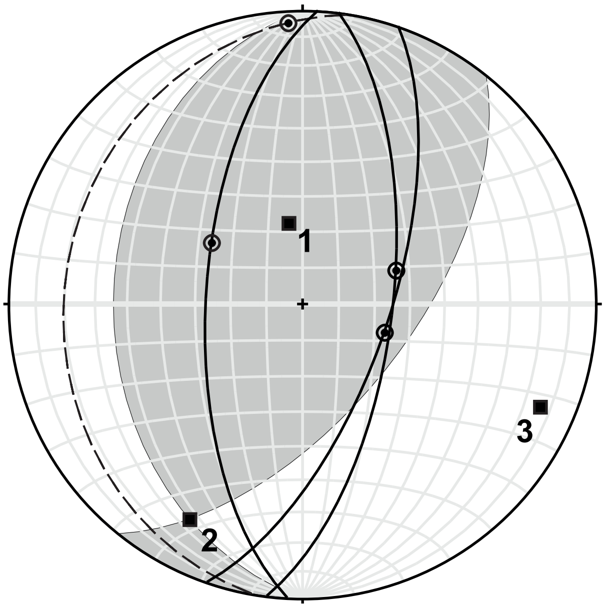
Thomas & Woodcock. Figure 7



Thomas & Woodcock Figure 8



Thomas & Woodcock. Figure 9



⊙ Slickenline orientation

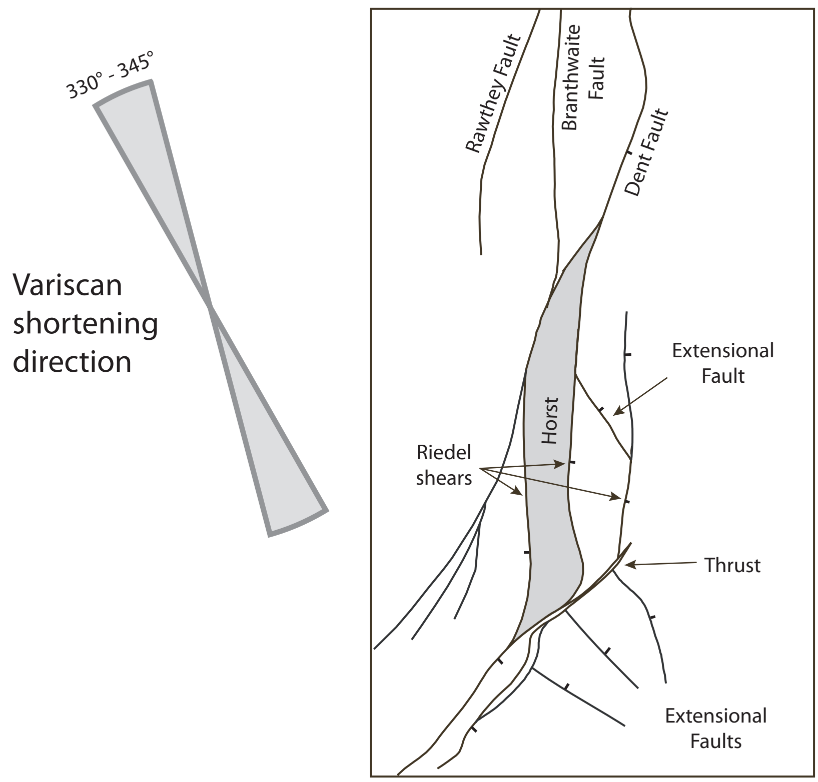
■ **1** Orientation of principal axes
Best estimate shortening direction:
13/113 (axis 3)

Bedding plane

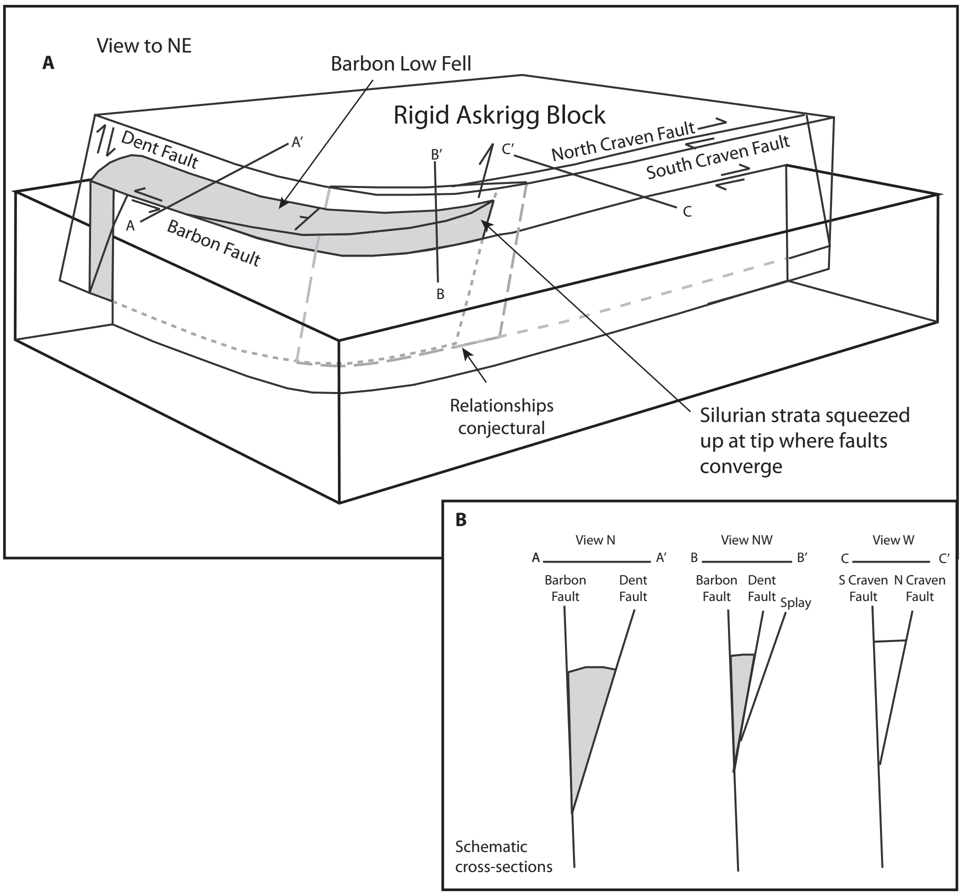
Fault plane

Thomas & Woodcock. Figure 10

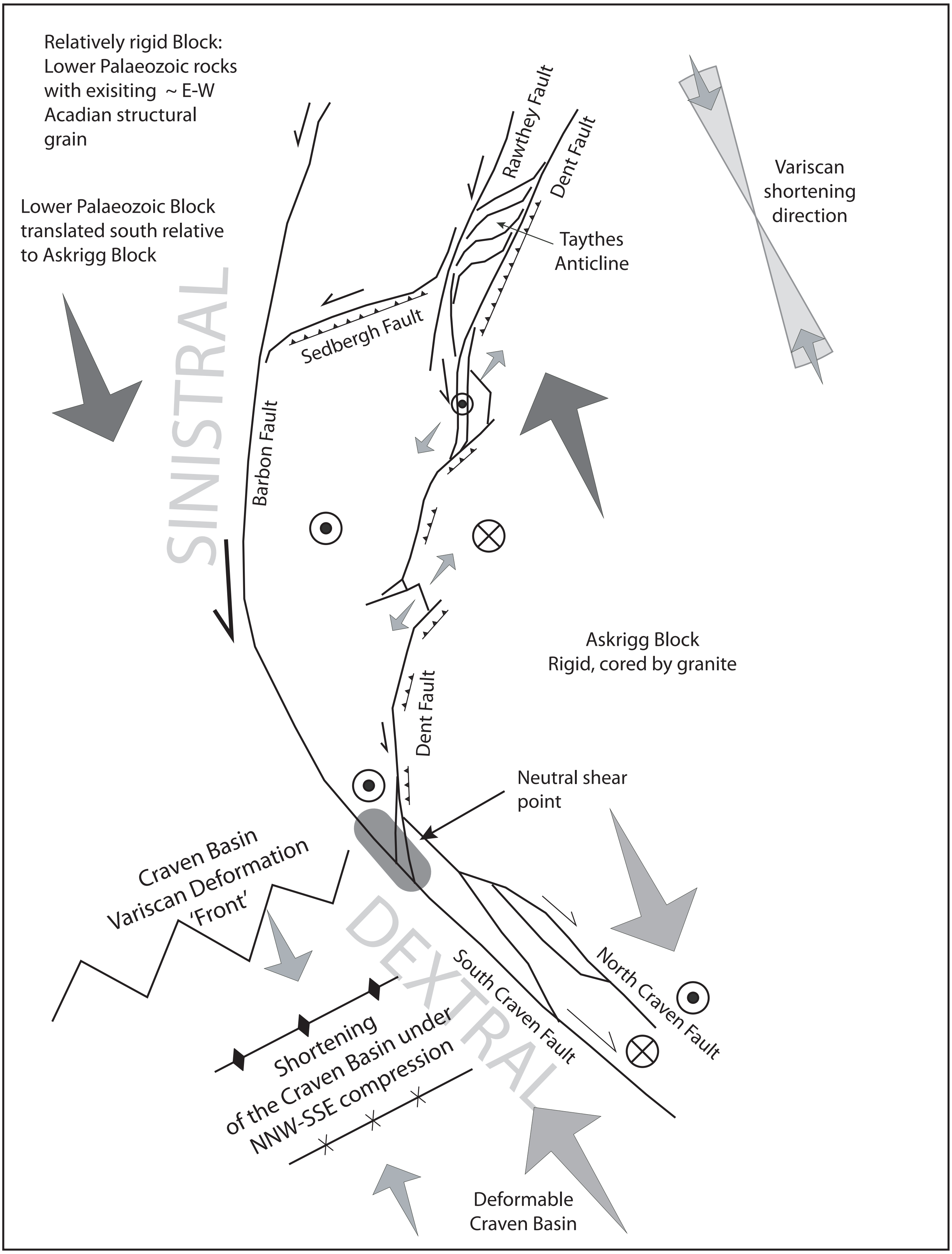
11a



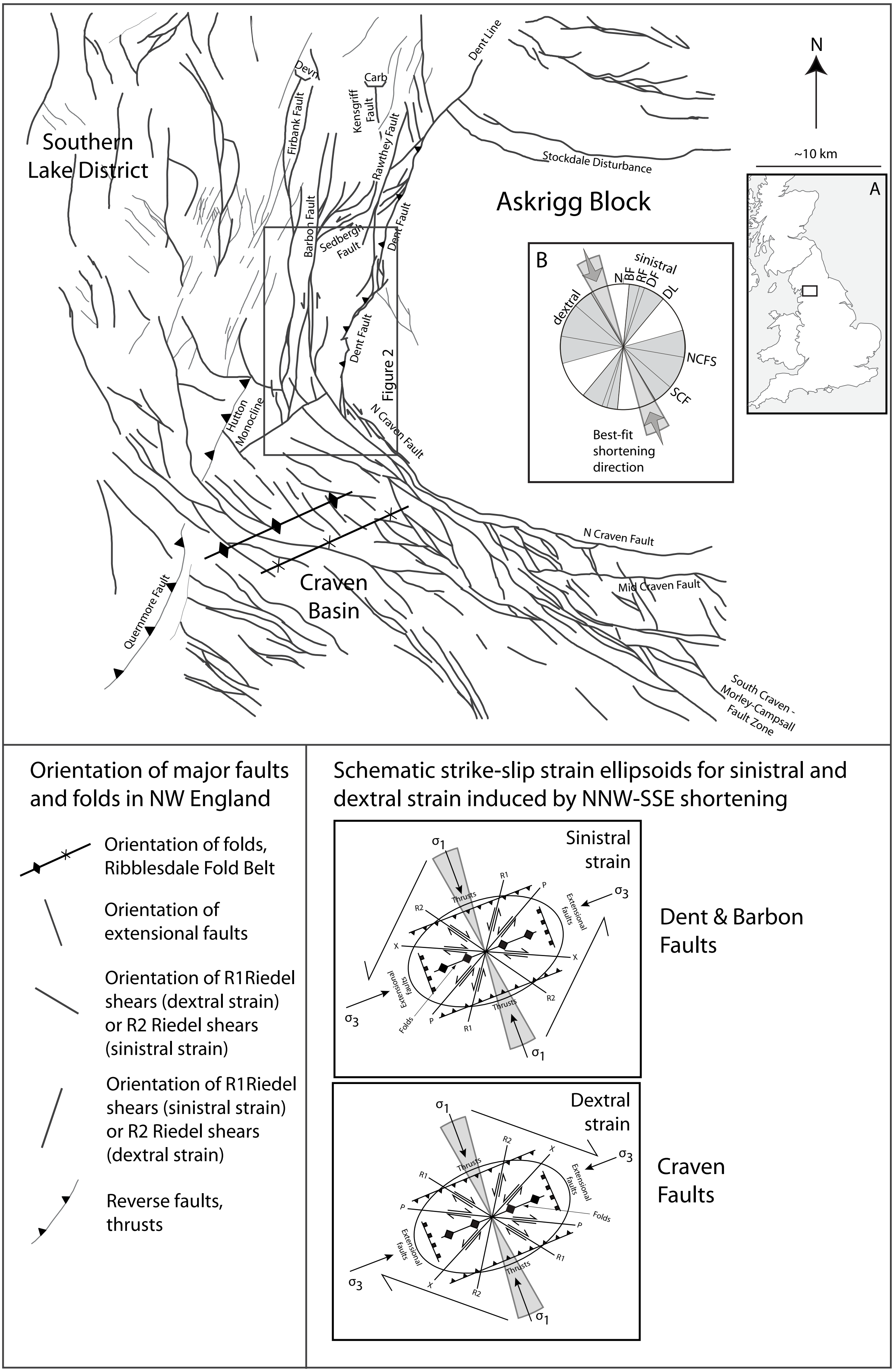
11b



Thomas & Woodcock. Figure 11



Thomas & Woodcock. Figure 12



Thomas & Woodcock. Figure 13