# Thrust-related folding in the Windermere Supergroup, Gawthwaite Moor

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**Abstract**

This contribution documents folds spatially, and probably genetically, related to a thrust fault in the Windermere Supergroup on Gawthwaite Moor. An open/close anticline south of the thrust is the major fold and immediately south of this is a gentle anticline. Both folds show transection geometries; the major fold has a clockwise sense and the gentle fold anticlockwise. A possible explanation for these differences is that the tighter major fold evolved further than the gentle fold through the progression of layer-parallel-shortening, fold amplification to fold flattening during a rotational strain history. As such the transection pattern in the gentle fold may support the inference that sinistral transpression operated during the Acadian Orogeny in South Lakeland

**Introduction**

Acadian deformation in Cumbria produced the dominant tectonic planar fabric in all the pre-Devonian stratigraphic units but the expression of this orogenic event is very variable. In the Windermere Supergroup the result is a paratectonic slate-belt with a classic folded multilayer-sedimentary sequence which is the subject of this account. To date only a handful of accounts provide detailed documentation of these structures (e.g. Webb & Lawrence 1986, Millward et al. 2000) despite their potential for providing constraints on plate tectonic scale displacements (Soper et al. 1987). Gawthwaite Moor (Figure 1) is well exposed and the greywacke/slate alternations of the Silurian Gawthwaite Formation allow structural data to be collected around a series of folds related to a thrust fault (Soper 1991).

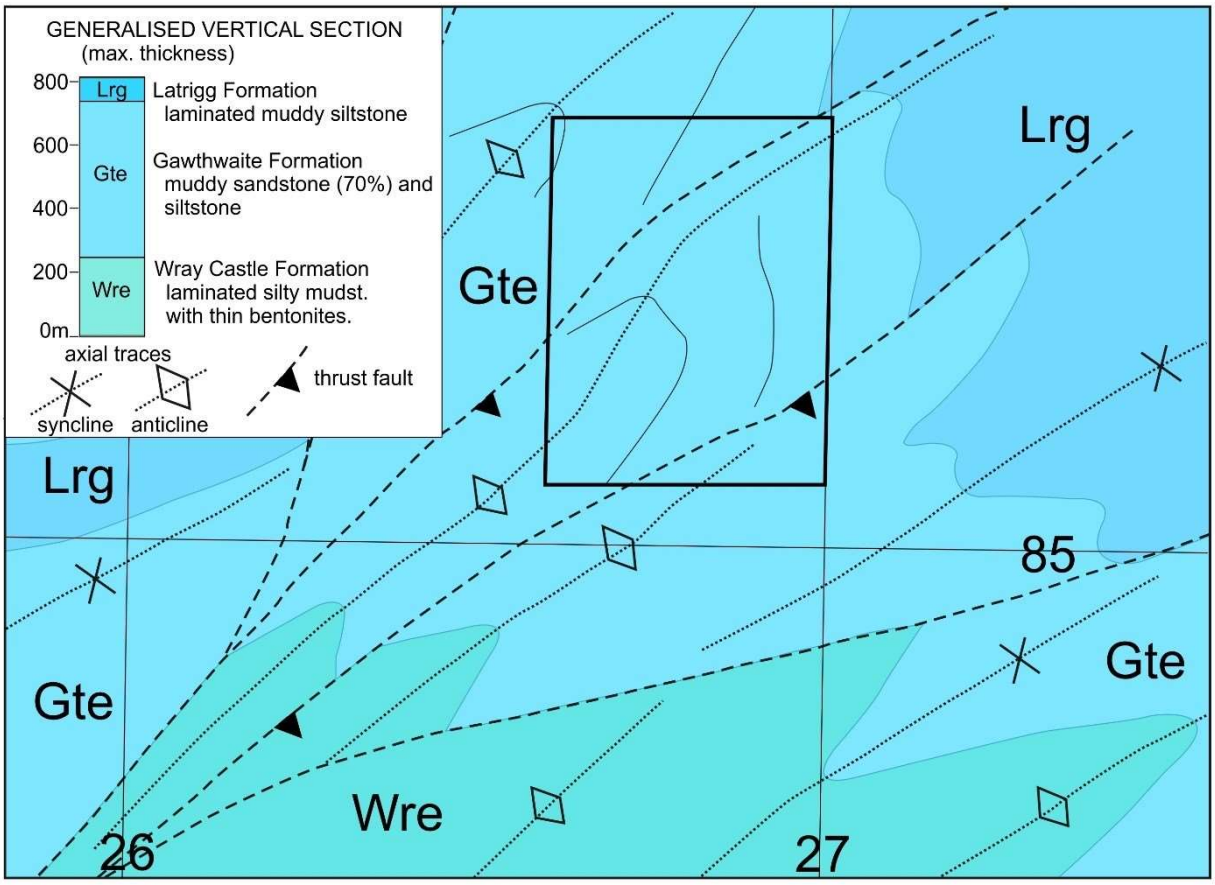



Figure 1 Geological map (Soper 1991) showing the context of the area sampled (box).

The Gawthwaite Formation is sandstone-dominated with minor siltstone and a very minor (<10%) slate component. Turbidite internal structures are abundant in the sandstones which are typically medium-sand grade and poorly sorted. Bouma Tb, Tc divisions occupy just a few percent of the typically metric-scale sandy beds displaying delayed grading. Convolute lamination is present in some of these laminated portions. Slate beds are mainly very thin being mostly a few tens of centimetres thick.

Soper (1991) documented the setting for the area examined in detail for this study. Steeply-dipping thrust faults are common in the Gawthwaite Moor to Kirkby Moor area and it is evident that folding is genetically related to these contractional faults. It is also clear from the prior maps that there is some complexity in the folds as shown by their polyclinal nature. Slaty cleavage is well developed in muddy protoliths and many of the sand-grade beds have a well-developed spaced cleavage. These two planar fabrics show pronounced refraction in many exposures implying a protracted history of development. In the sandstone beds the cleavage is of an anastomosing disjunctive type. It is commonly spaced between one and two centimetres though the spacing can be eight centimetres and in fine-grained wacke it is semi-planar and spacing is around five millimetres. It will be referred to as sandstone cleavage to differentiate it from the cleavage in the slates. The cleavage planes in the arenites are defined by millimetre-scale almost pure mica domains normally less than two millimetres wide. In the microlithons between the spaced cleavage planes there is a weak fabric created by shape alignment of detrital grains and possibly mica beards. Though this fabric is poorly defined in the field the deformation of diagenetic concretions implies moderate strain within the dominant medium-grained wackes. These mainly-elliptical carbonate concretions are exposed on joints approximately perpendicular to the fold axis (ac-joints) and mostly have axial ratios between two and three to one. These measurements were taken on planes that approximate the highest strain section, the XZ plane of the strain ellipsoid.

**Structural Data**

Bedding is commonly exposed as mini-dip slopes probably because erosion has preferentially removed the recessive slate interbeds weakening the overall weathering resistance of the sequence. Bedding orientation data have been gathered from the complete range of structural settings on Gawthwaite Moor and a representative selection is shown on Figure 2. All folds in the study area face upwards and hence synclines are synforms and anticlines are antiforms. North of the thrust fault there is a narrow band of steeply-dipping to overturned layers south of a synclinal fold closure and, to the north of this fold axis, the bedding attitude has the dominant trend (~210°) in the area of Figure 2. Immediately south of the thrust there is a belt of steeply-dipping, mainly overturned beds. Next south past the anticlinal fold closure a sub-area has moderately-dipping bedding with strikes of around 165° that contrast with the other areas of moderately-dipping beds in the northern and southern parts of Figure 2 with strikes around 210°. The 165° and 210° striking domains south of the main anticline define an angular anticline with a large dihedral angle.

Fold geometries have been determined from stereographic projections (Figures 3 & 4) and by constructing a down-plunge profile (Figure 5). Figure 3 plots all the bedding data and the best fit great circle (girdle) to these data gives a fold axis plunging 31° towards a bearing of 073° . Noticeable on this plot is the slightly poor fit of bedding data from the beds striking approximately 165° . To investigate this discrepancy bedding data from the two moderately-dipping areas south of the main anticline were plotted separately (Figure 4). These gave a fold axis plunging 32° towards 089°, significantly different to that derived from the total bedding data plot. This anticline has a dihedral angle of 153° (gentle) and an axial surface dipping 84° north, striking 086/276. It is an upright moderately-plunging gentle fold (Figure 5). The main fold, the anticline south of the thrust, will be described using bedding data from the overturned limb and the adjacent planar moderately-dipping segment striking around 165°. Using these data the fold axis plunges 32° towards a bearing of 074° and has an axial surface dipping 46° southeast, striking 218/038 (Figure 5). The dihedral angle is 72° placing it on the open/close boundary. It is a moderately-inclined moderately-plunging fold which has a fold axis pitching 48° on the axial surface. The main anticline is highly angular in that curvature at the hinge only occupies a few metres in relation to a fold that has an amplitude of several hundred metres.

Slaty cleavage is well developed but difficult to measure because the slaty beds are thin and recessive. As a result only a small number of readings could be included on the stereographic projections (Figures 3 & 4). Figure 3 shows that the slaty cleavage is approximately axial planar to the main anticlinal fold and somewhat fanned though some of the readings lie closer to the best fit great circle to the gentle upright

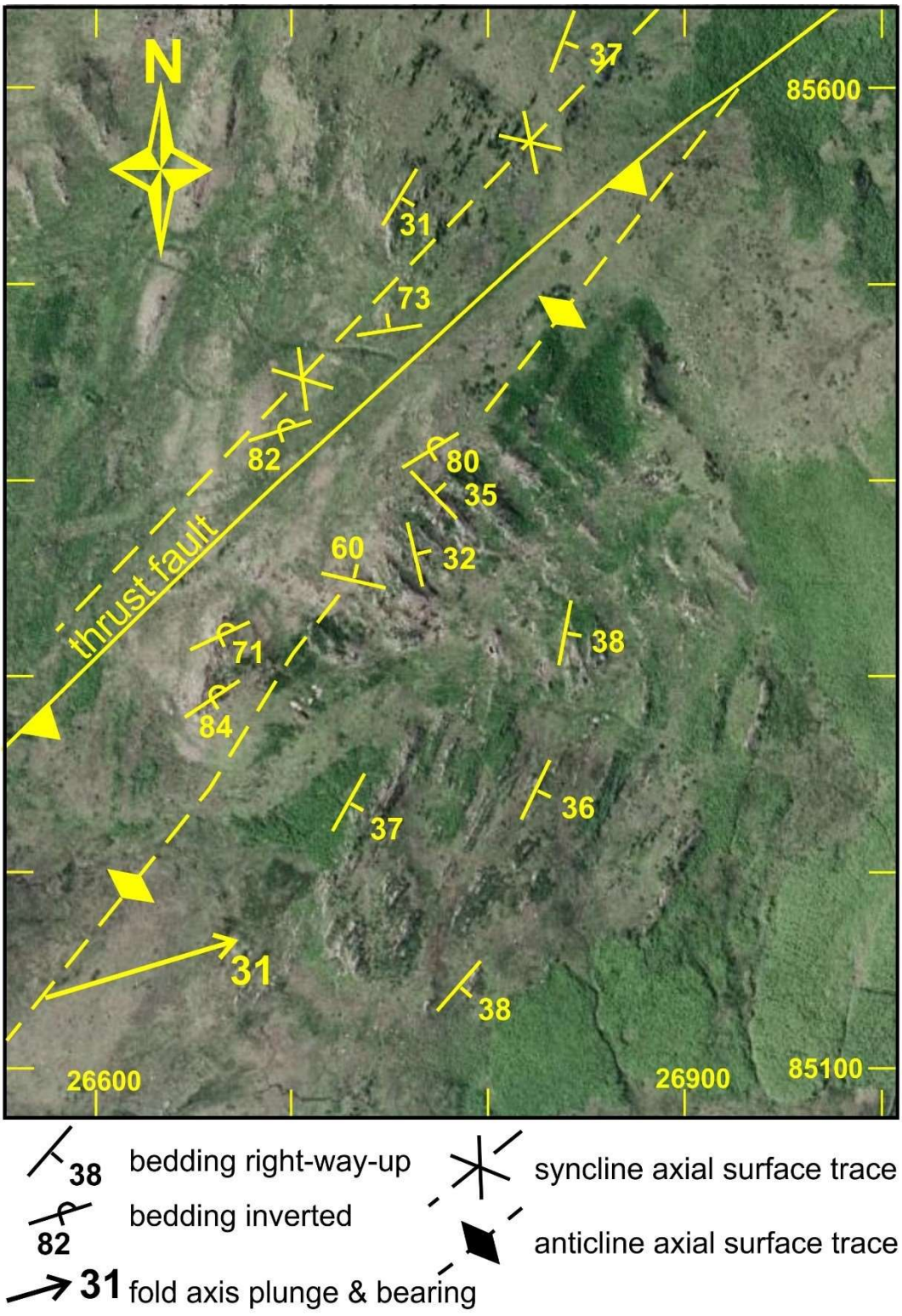



Figure 2 Bedding data together with fold and thrust positions superimposed on a Google Earth image.

fold (Figure 4). Orientation data for the sandstone cleavage mostly come from the moderately dipping fold limbs and all the examples from overturned and steeply dipping beds have dips less than 60°. All the sandstone cleavage attitudes from the moderately-dipping layers have dips greater than 60° and are mainly within 30° of the axial plane of the upright gentle fold defined by these bedding data.

Cleavage/bedding intersection lineations are all generated by the sandstone cleavage. For the total data plot (Figure 3) these lineations are clockwise from the fold axis defined by the bedding. Considering data taken only from the gentle anticline with the moderately-dipping fold limbs (Figure 4) the intersection lineations are closer to the fold axis defined by these beds but in contrast to the main anticline they are anticlockwise from the axis.

The down-plunge profile (Figure 5) is drawn on a plane perpendicular to the fold axis, defined by the total bedding data, which is plunging 31° towards a bearing of 073°. The profile plane dips 59° to the west southwest and strikes 163/343°. All structural planar data (bedding, slaty & sandstone cleavage) are projected from where they were measured on to the inclined profile using a correction to account for topographic variation. Because this process involves the intersection of two inclined planes (the measured surface and the profile plane) the trace angle of each structural element on the profile is calculated and plotted. The thrust has a topographic expression as a slack over the crest of the high ground. Best fit form

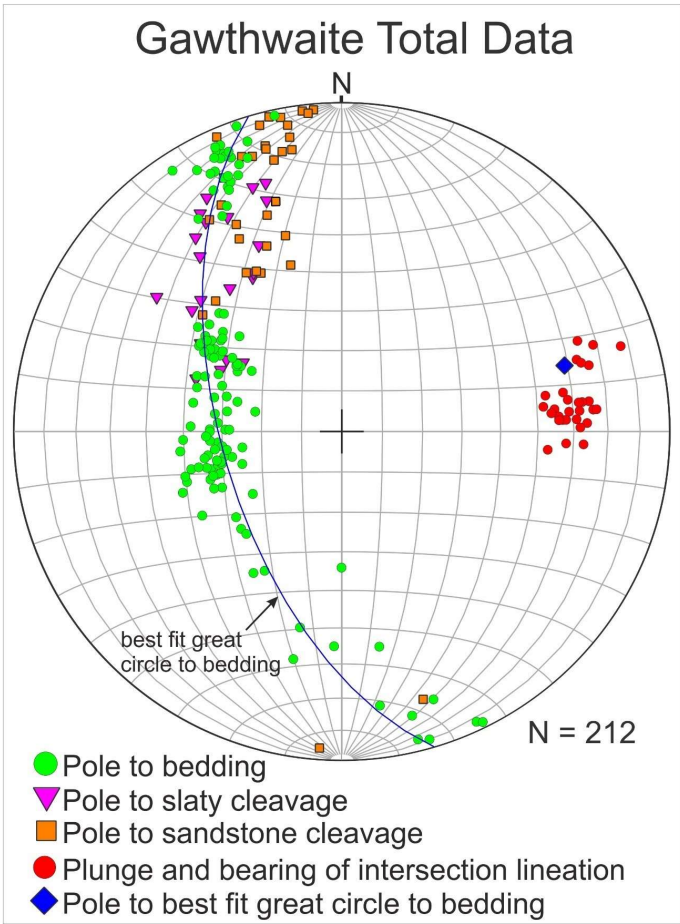



Figure 3 Equal-area lower-hemisphere stereographic projection of all the structural data collected from the area shown in Figure 1.Data analysis and plotting via Orient (Vollmer 2017).

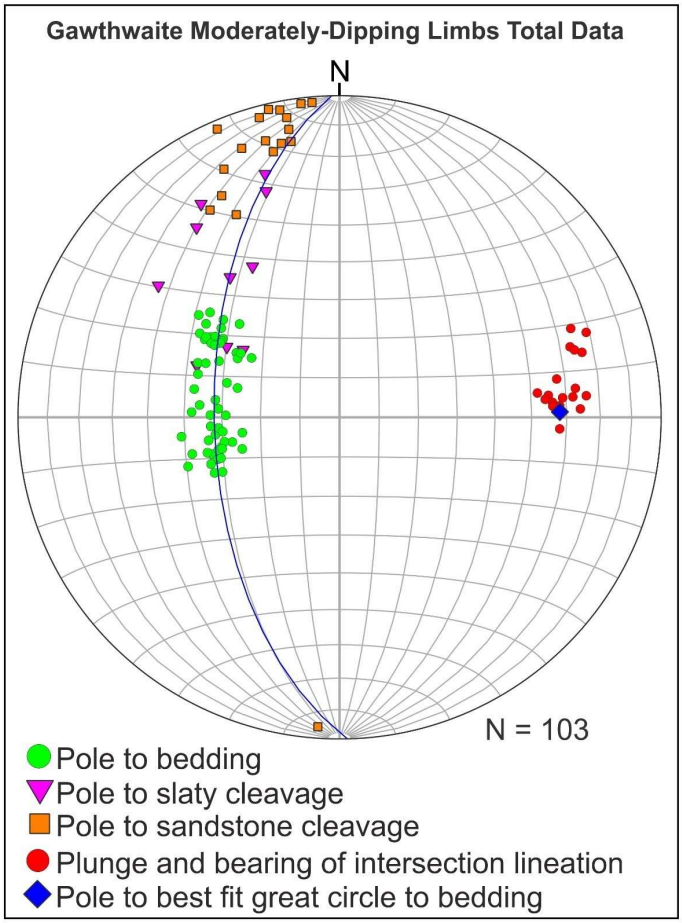



Figure 4 Equal-area lower-hemisphere stereographic projection of data from the moderately-dipping fold limbs. Data analysis and plotting via Orient (Vollmer 2017).

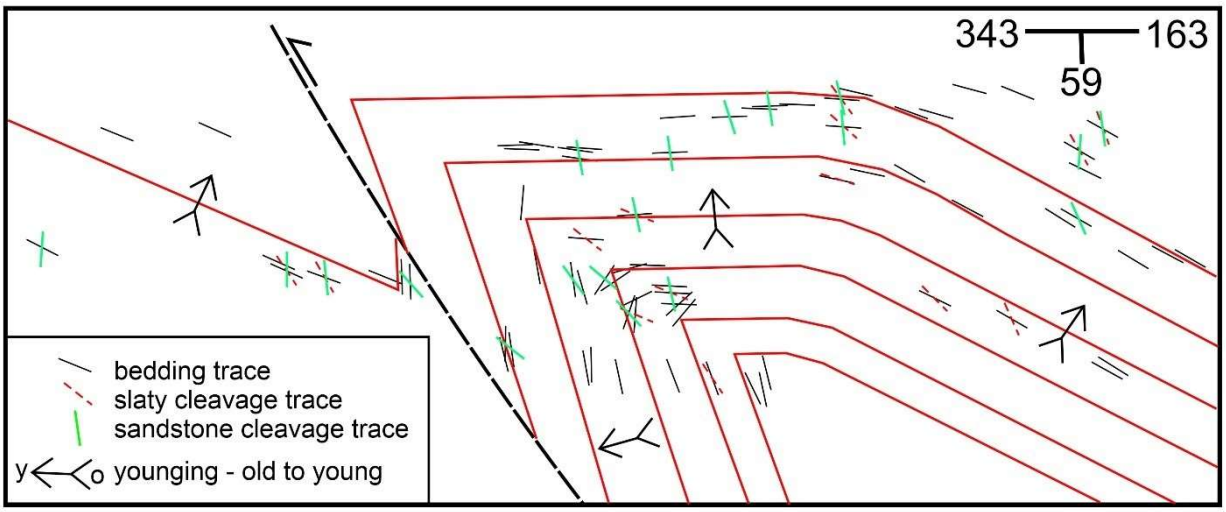



Figure 5 Down-plunge profile showing data from sample stations and form lines to fit the bedding data.

lines to the bedding data were used to outline the overall shape of the fold and whilst the fit is not perfect the discrepancies are minor. Part of this construction took into account the attitude of the slaty cleavage close to the anticline closure where it is approximately axial planar. Further confirmation of the construction comes from the match between the axial surface traces generated and the predicted values from stereographic methods; for the two anticlines these methods agree within three degrees.

## Discussion

There is a degree of transection evident on the stereographic projections i.e. the cleavages do not all plot on the girdles defined by the bedding, and the intersection lineations do not coincide with the statistical fold axes perpendicular to the girdles. Fold/cleavage relationships have figured extensively in discussions about obliquity during convergence in orogenic belts. In the Windermere Supergroup Soper (1986) and Soper et al. (1987) have used transected fold geometries to infer sinistral transpression during the Acadian Orogeny in the South Lakeland region and to invoke indenter tectonics as the cause. Folds of the style seen on Gawthwaite Moor probably evolved through several stages. Initially when the bedding planes are loaded along their length they respond mainly by thickening though very gentle folds are also generated. This is the layer -parallel shortening phase which is followed by fold amplification (buckling) mainly involving rotation of the layers together with any cleavages formed in the first phase. Typically sandstone cleavages form early so they are dispersed as the fold amplify. Eventually folds lock as flexural slip becomes mechanically more difficult and a grossly homogeneous strain is imposed in the flattening phase. Soper (1986) demonstrated that if cleavage development was confined to the layer-parallel shortening phase then sinistral transpression would result in anticlockwise transection. For Gawthwaite Moor the gentle anticline with moderately dipping limbs may represent early folds with little or no buckling component whereas the main anticline adjacent to the thrust progressed further through buckling and flattening. If the folds were evolving in a rotational stress environment this contrast between the two anticlines could be explained by the gentle fold not progressing beyond the layer-parallel shortening phase whilst the main anticline continued to develop in a changing stress field. However, several authors (e.g. Treagus & Treagus 1992) have urged caution in using fold/cleavage relationships to conclude that transpressive deformation is the cause of transected folds. These authors state that the full strain history of the folds has to be known before the fold/cleavage geometries can be extrapolated to infer the regional tectonic parameters. The polyclinal folds on Gawthwaite Moor may preserve some of the early strain history of the Acadian Orogeny thus supporting a transpressional interpretation.

## Acknowledgements

This study was initiated in 2017 as a group exercise for members of the Cumberland Geological Society with the aim of actively involving members in collecting their own structural data and going on to analyzing the geometry using stereographic projections, as detailed in the last issue of the Proceedings, (Boulter, 2018). Further data was collected in 2018 and the final analysis was completed.

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