

Folds and Thrusts in the Windermere
Supergroup: Gawthwaite Moor,
Gawthwaite High Quarry, & Kirkby
Moor

Rocks Caught in a Vice!

by Clive Boulter

If you approach from the east, as you drive up the long climb to Gawthwaite you will see the notch in the skyline that is Gawthwaite High Quarry. The quarry was worked along a fold closure which plunges towards the viewer.



INTRODUCTION

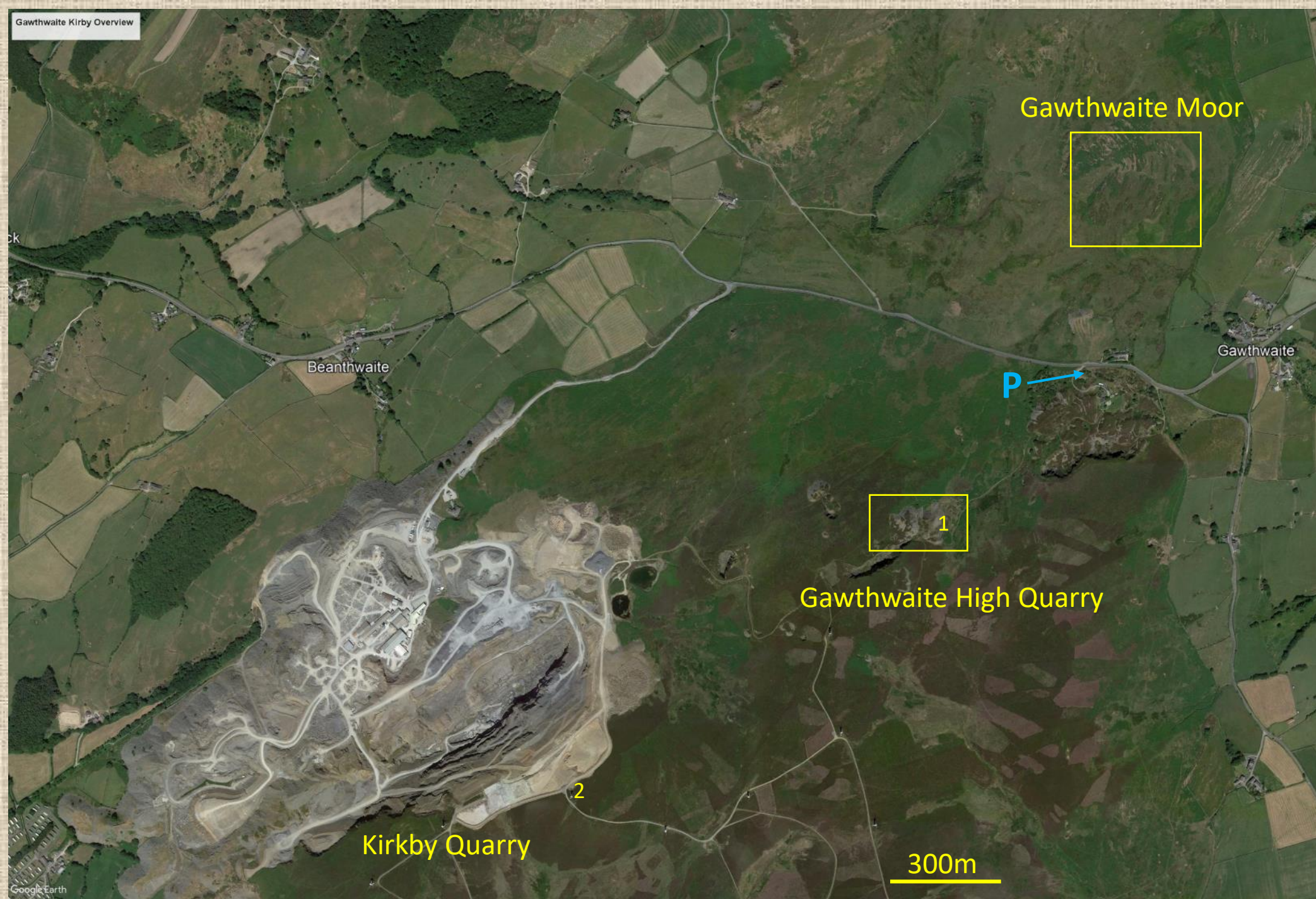
Gawthwaite and Kirkby moors provide an excellent opportunity to examine fold-thrust relationships in a well-bedded sequence with the added bonus of considering the geological controls on commercial exploitation of slate in this part of the Windermere Supergroup stratigraphy. Acadian deformation was sufficiently intense to produce slates in original mudrocks and siltstones. Originally sandy rocks responded to the regional shortening by folding and by creating a locally-strong spaced-cleavage.

Bracken, at its peak, may have to be flattened at a couple of localities and gorse also gets in the way locally but most of the itinerary-stops avoid these problems.

For advanced students the analysis can be taken much further to consider stages in the evolution of the thrusts in relation to the folding and the implications of the cleavage/fold relationships for regional tectonics. Gawthwaite Moor was the subject of a Cumberland Geological Society project written up in the volume one of the Cumberland Geologist [2020].

The attitude of planes is recorded here using the British Right Hand Rule where the strike quoted is clockwise from the dip direction e.g. a bed dipping 30° to the SE is 30/215. Dips are always two digits and strikes three, so it does not matter the order they are written in.

Parking is available at a lay-by on the north side of the A5092 [SD 26717 84794] or just opposite [P on the next slide] off a track that originally was for access to Gawthwaite High Quarry.



Overall location map based on Google Earth.

To get to Gawthwaite High Quarry follow the track up past the parking area P, past some houses, and through the old waste tips of the quarry near the road. Once past the lower quarry, the track leads directly to Gawthwaite High.



A closer view of Localities 1 & 2 on a Google Earth base.

The ellipse is an area of tipped boulders by the track side. One boulder has a good example of a kink-band and another shows the sedimentary style of the slates as described for Locality 1.



A block of Wray Castle Formation slate split along the cleavage plane. Prominent in this view are the "strips"; dark mud turbidites spaced at 10s of cm. Sheep droppings for scale.

Surface Geology 3D Models Borehole Scans Earthquake Timeline

Surface Geology

- Superficial only
- Bedrock only
- Bedrock and Superficial

Visible geology:
1:50 000 scale

Geology Key

More on digital geology

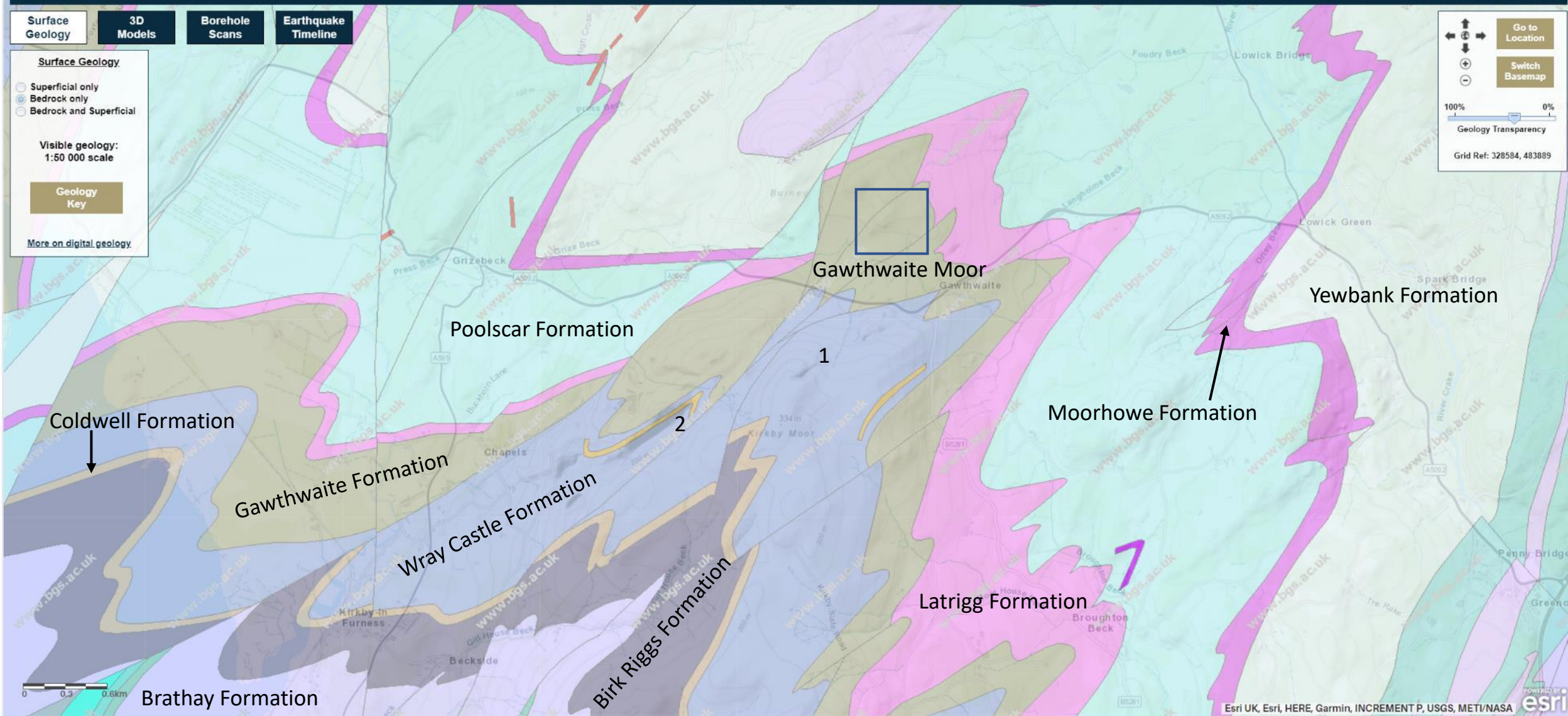
Go to Location

Switch Basemap

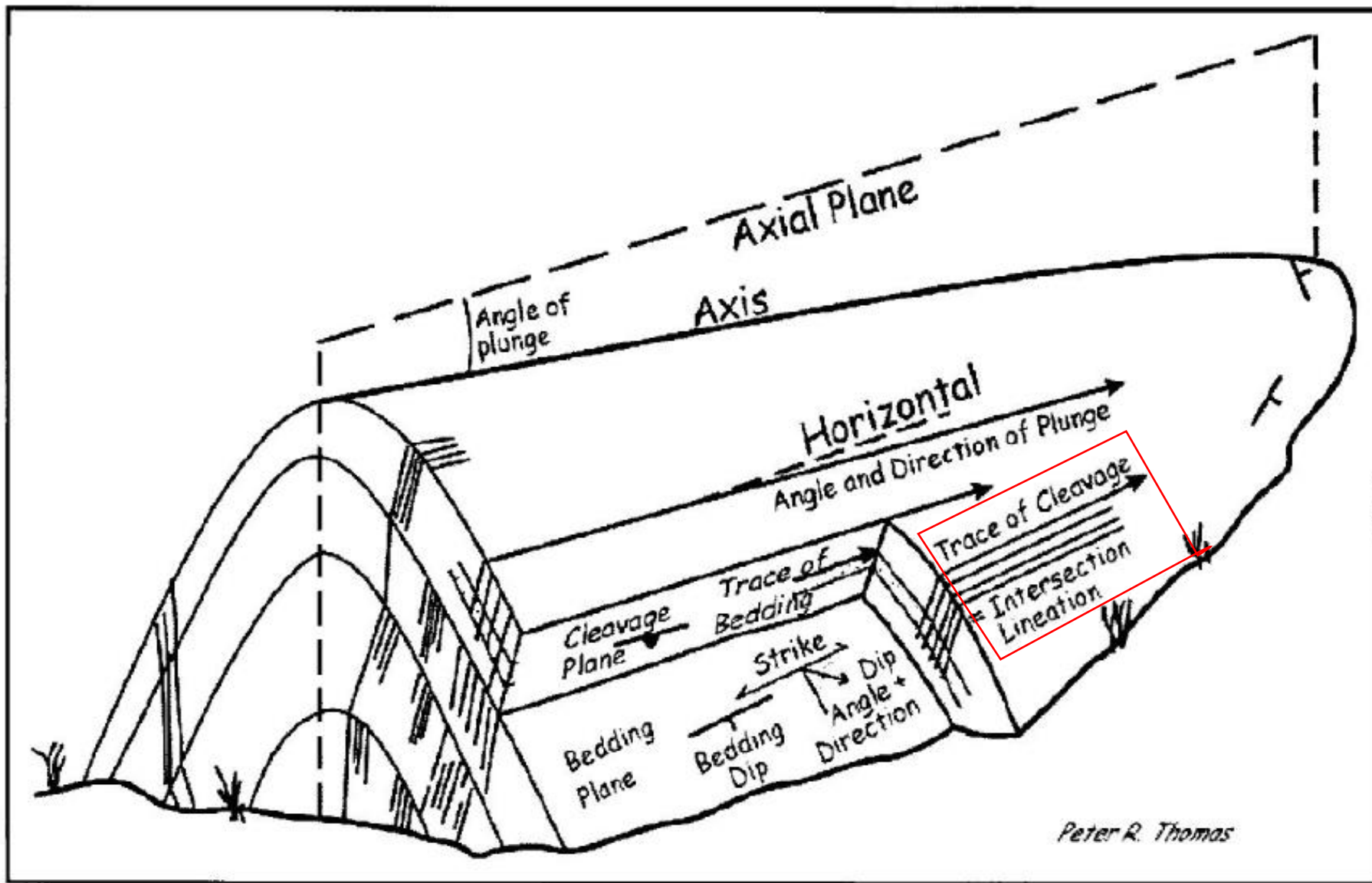
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Geology Transparency

Grid Ref: 328584, 483889



Regional geological map from the British Geological Survey providing the setting for the field itinerary. Localities 1 & 2 and the box for Gawthwaite Moor are as shown on the Google Earth location map.



Documenting folds often requires piecing together information from many small exposures. An important technique in this process is to measure the trace of cleavage on bedding planes [or vice versa]. This is the intersection lineation – see red box. There is normally a close relationship between this line and the fold plunge, both in direction and amount.

In the Gawthwaite and Kirkby moors area, the trace of cleavage on exposed bedding planes is a common sight. The trace of bedding on cleavage planes is only seen in a few places.

P Thomas 2002 The Winster Valley: aspects of the WGS mapping project. Proceedings of the Westmorland Geological Society, pp. 46-50.

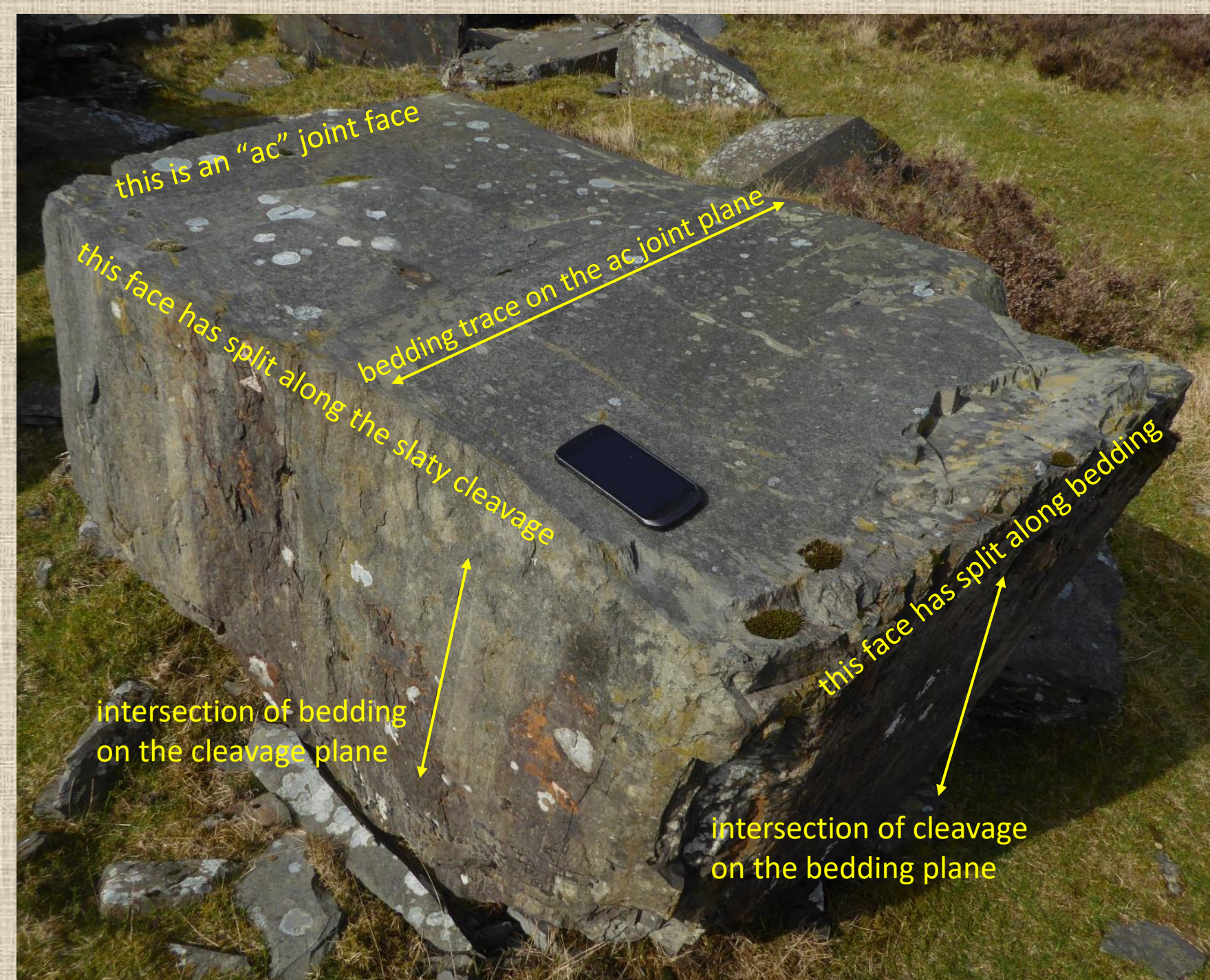
A detailed locality map for Locality 1 on a Google Earth base. The boulder to be examined is circled in yellow.



Locality 1 Gawthwaite High Quarry

At **SD 26340 84364**, one block of slate is an excellent representative of the requirements for economic working of slate in the area. Bedding and cleavage have to be close to perpendicular; if not, blocks will split both along the cleavage, and the bedding, rendering the material useless. Gawthwaite High Quarry is elongate along the plunge direction of a fold where the high bedding/cleavage angle is found in a wide enough zone to make quarrying economic. Angular folds with no closure zones do not produce workable slate in this stratigraphic sequence. The block is a very graphic demonstration of intersection lineations of both bedding on cleavage and cleavage on bedding.

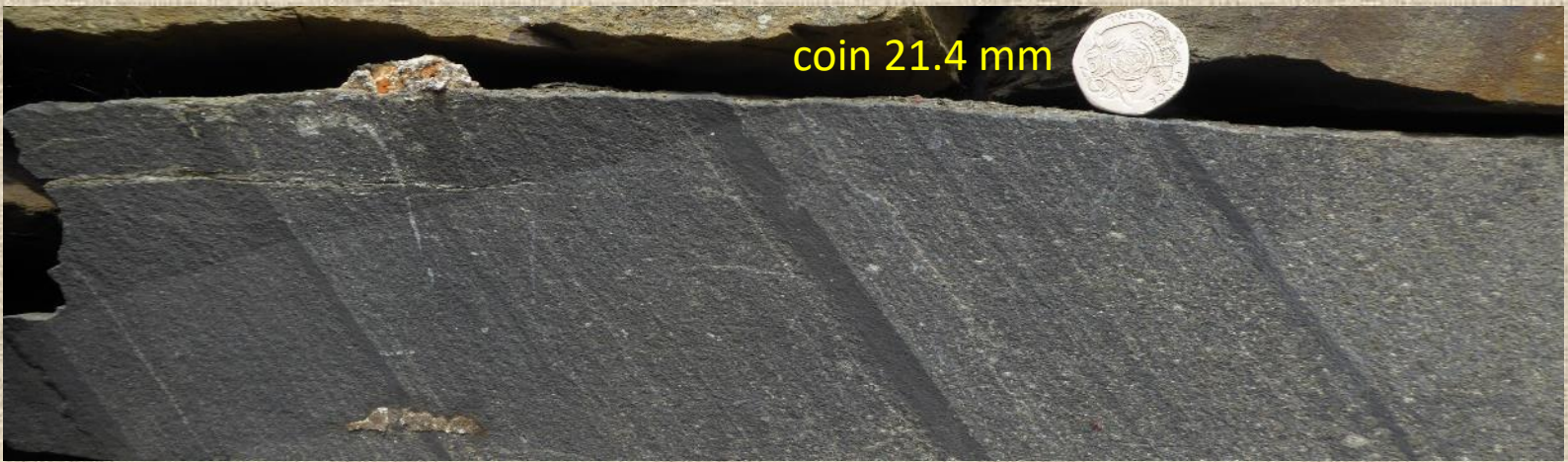
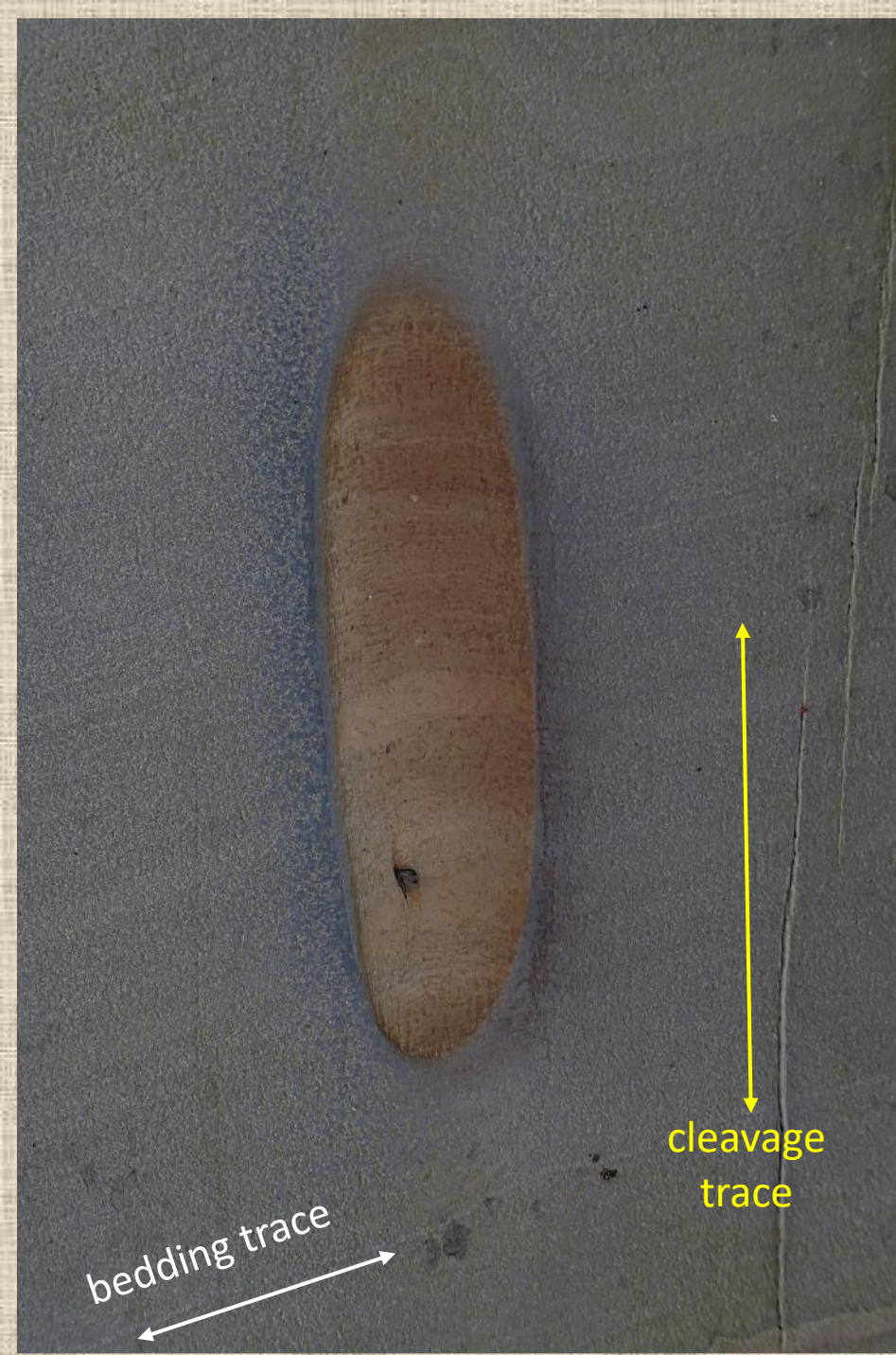
Advanced Project: if you wish to test your skill at compass-clino work and know how to drive a stereographic projection try the following. Measure on the block the dip & strikes of the bedding and cleavage. Also measure the plunge and bearing of the intersection lineation. Plot all three elements and see if the lineation you measured is where the great circles for the planes intersect.

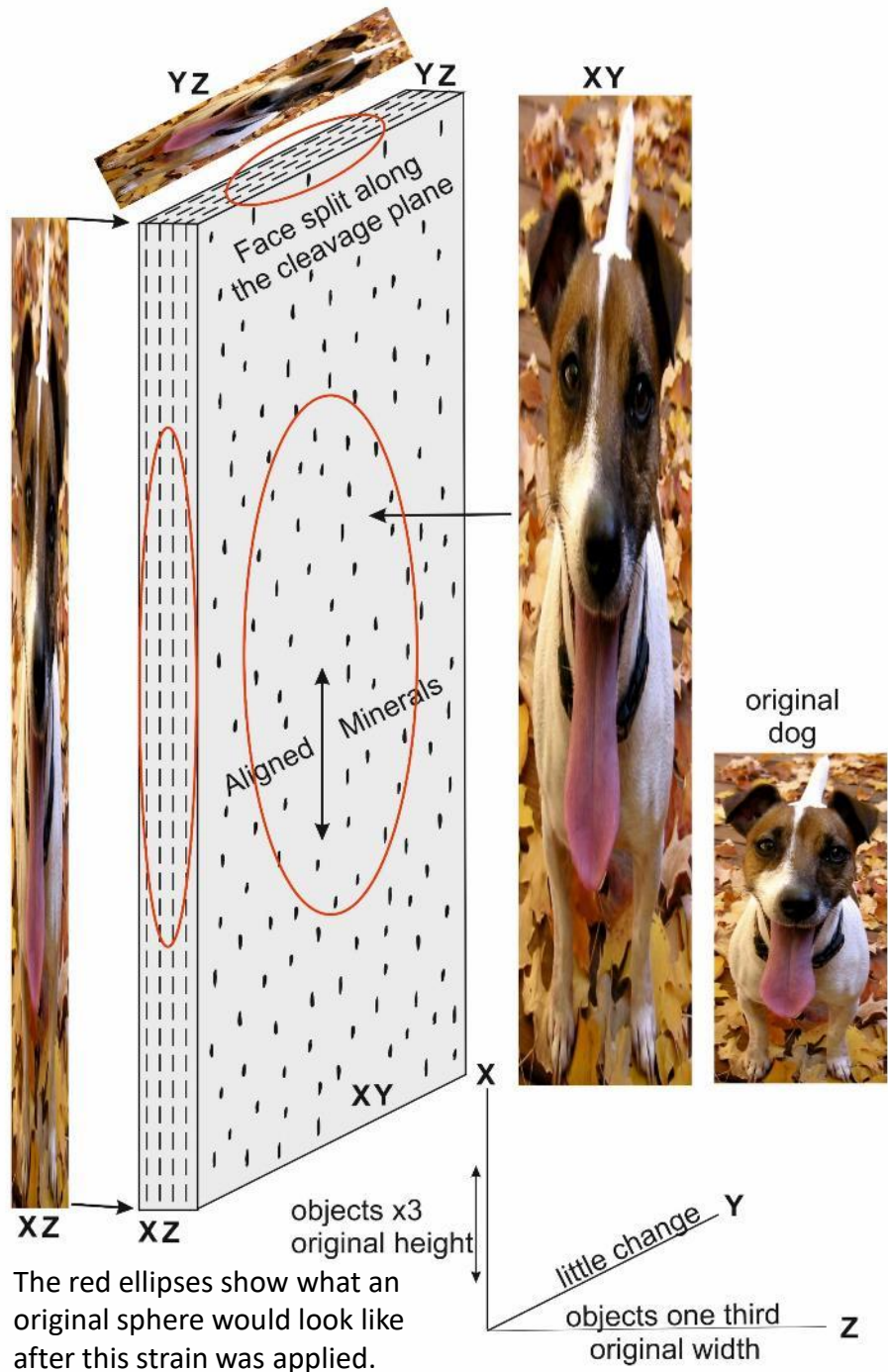


A saw cut block from Kirkby Quarry through a carbonate concretion which is elongated in the slaty cleavage direction. Concretions are common on the Kirkby and Gawthwaite moors though it typically needs a saw cut to reveal their key features. They are mainly found in greywackes but can be locally abundant in slaty horizons as seen at Locality 1. Because layers within the concretions are thicker than their equivalents outside it shows that they formed very early in the process of diagenesis which transforms sediment into rock. The deformation overprint causes a little uncertainty, but there is no sign of layer thickness changing towards the margin of the concretions which means they formed before compaction was noticeable. To form a slaty cleavage the rock has to be shortened perpendicular to the cleavage by around 50 to 70% [see next slide]. This distortion explains the final elliptical shape of the concretions but we do not know if the concretions, prior to the Acadian Orogeny, were spherical or aligned along the bedding.

Jim Marshall and Duncan Pirrie published an excellent article on concretions in *Geology Today*, 2013, vol. 29, pp. 53-62, entitled "Carbonate concretions explained".

Many of the slaty units in this area are very finely laminated alternations of light and dark grey punctuated by dark cm-scale muddy bands. The latter are mud turbidites and the fine-scale laminations were generated by seasonal variations in organic productivity – count the years!



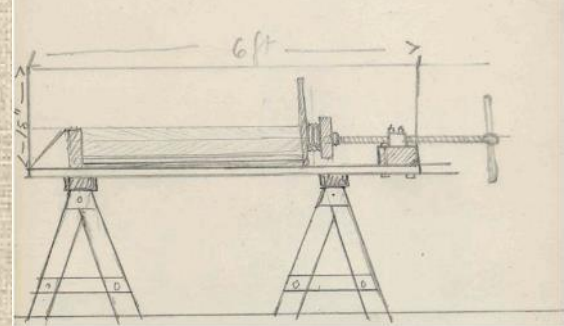


Slates split readily along cleavage planes which have been created in response to considerable shortening – see Cadell’s experiment. At the microscopic scale, the planar fabric produced is complex and is typically a mixture of aligned platy minerals and seams of differing compositions. Even though almost all slaty cleavages are spaced, this term is reserved here for cleavage in sandstones where the spacing is easily seen in the field.

The diagram to the left gives an impression of the distortions associated with typical slates in the Lake District. Given favourable original grain sizes a mineral lineation can be identified on the cleavage plane – this is the maximum stretch in the rock. A slice [XZ] through the slate along this lineation and perpendicular to the slaty cleavage shows the maximum distortion [strain]. The image of the dog is used to give an idea of the distortions involved. In many Lake District slates near perfect preservation of original sedimentary features can be seen on the cleavage plane – the lowest distortions of the dog help to explain why it is best to examine this plane if you wish to understand depositional conditions. If exposures are of the XZ plane, then original features are highly modified and hard to interpret.



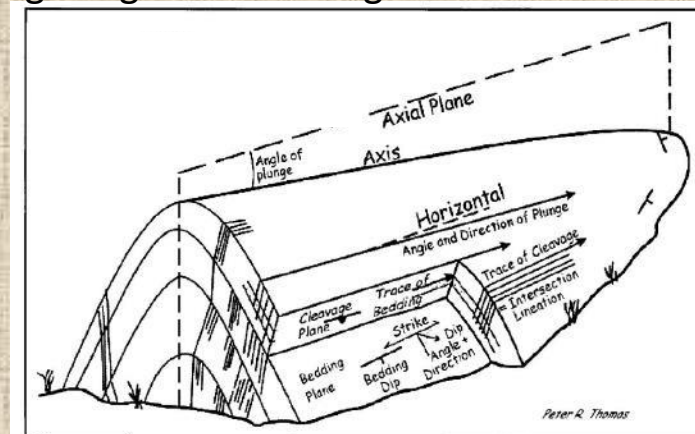
*Experimental Researches in Mountain Studies -
 Experiment by H. M. Cadell at
 Grange 25 Jan. 1887*



From Geological Society of London
 Special Publications 490, RWH
 Butler, CE Bond, & MA Cooper.

To get to Locality 2 it is best to take the path on the NW side of Upper Gawthwaite Quarry which affords views of the far side of the quarry wall which is split roughly along the slaty cleavage. On the more planar sections of this wall you will see the trace of the bedding on the cleavage which in several places is emphasised by white weathering layers a few tens of centimetres thick; these are bentonite layers formed when rhyolitic ash, from distant mega-volcanic eruptions, landed on the sea surface and settled through the water column. During diagenesis the original mineralogy of these layers was transformed into clays.

Reference to the diagram from Peter Thomas will show that the cleavage/bedding intersection lineation is typically very close to the fold axis/hinge line. This means that the lineation on the quarry wall is giving the fold plunge which here is approximately 25 degrees. At the top of the quarry if you approach the barbed wire fence you will be able to look down the beds at the fold closure which dip down the plunge of the fold and also see the cleavage at high angles to bedding.



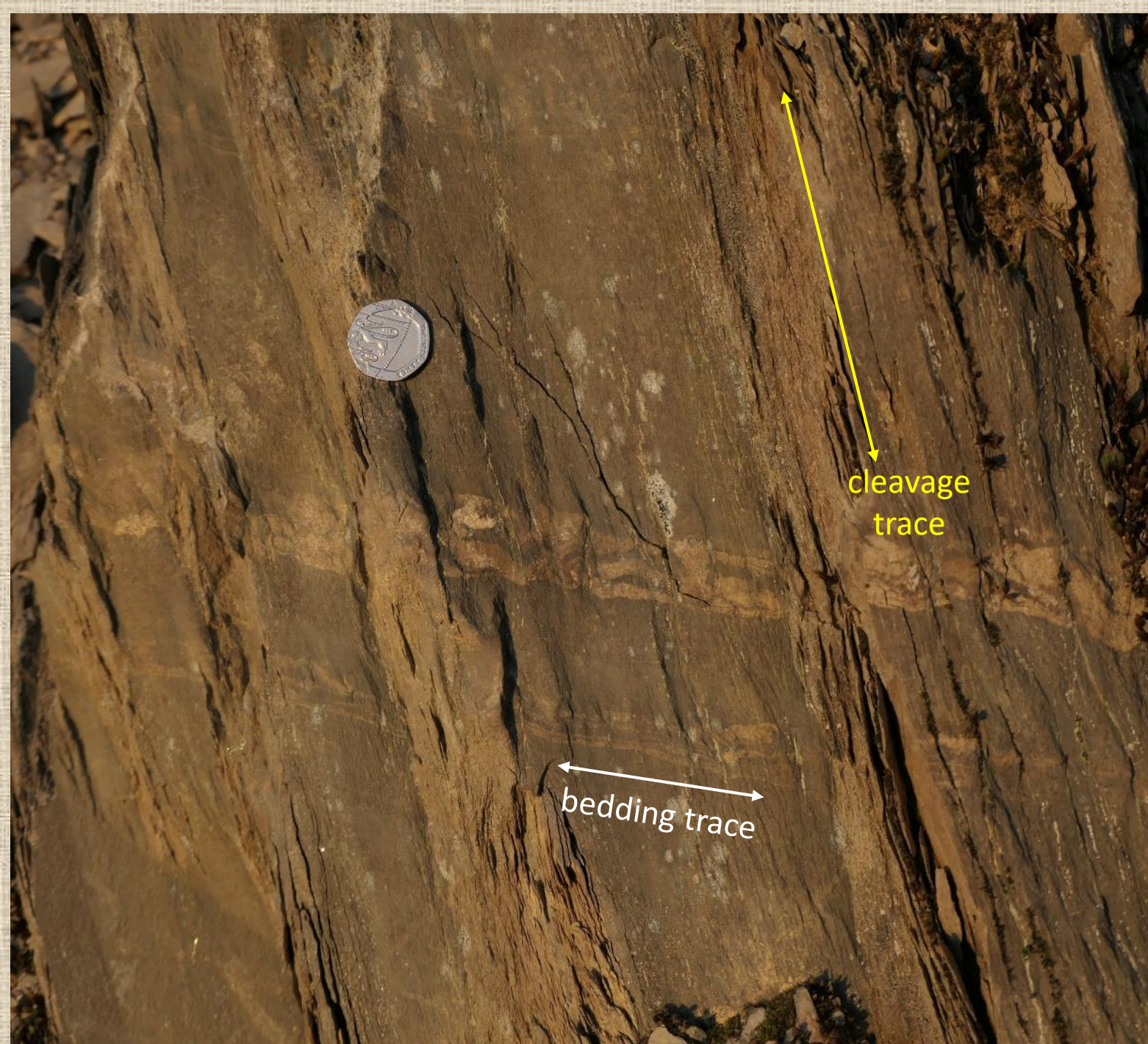
Locality 2 Kirkby Quarry Margin SD 25367 83686

In 2021 Locality 2 was as shown in the next slide. Since then this exposure has been caught up in the minor, but very significant extension to the main Kirkby Quarry. This work covered the exposure at Locality 2 but at the time of writing [mid-2022] plans are being developed to create a viewing platform for the main quarry together with information boards covering the quarrying operation and the geology of slate extraction. Additionally, large blocks of slate, from various Burlington Slate Ltd. operations, are to be placed at this site to show some of the materials and the geological relationships associated with slate in the wide variety of settings worked by the company.

Despite the loss of the exposure at Locality 2, and even before the viewing platform is constructed, it is still worth visiting the site because you can see the scale of the operation at Kirkby and as for Gawthwaite High Quarry the plunge of the main fold is defined by the intersection of bedding on the walls of the quarry which approximate the slaty cleavage. The high angle between bedding and cleavage seen on the next slide typify the extension area of the quarry which is why the quarry can enlarge.



A distant view of the NE end of the main quarry at Kirkby where the slaty cleavage is at high angles to the bedding.



Locality 2 Kirkby Quarry Margin SD 25367 83686

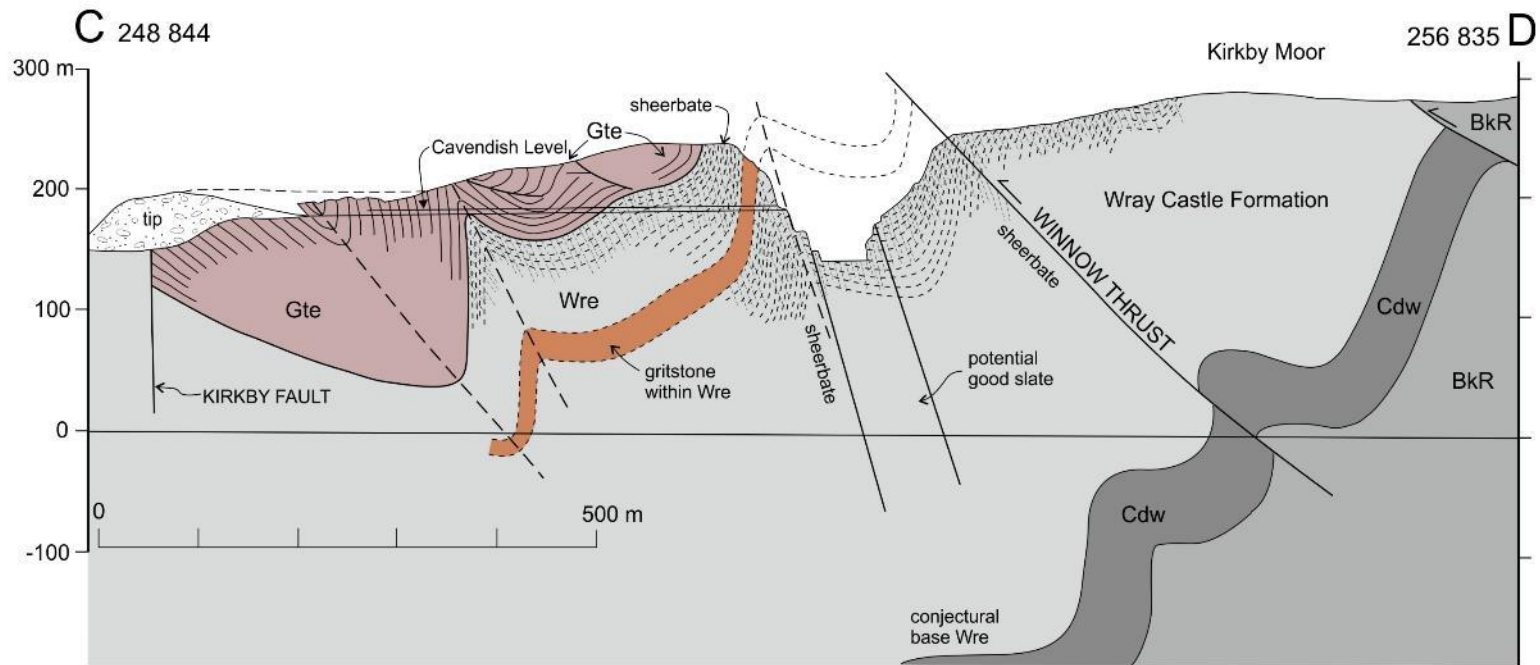
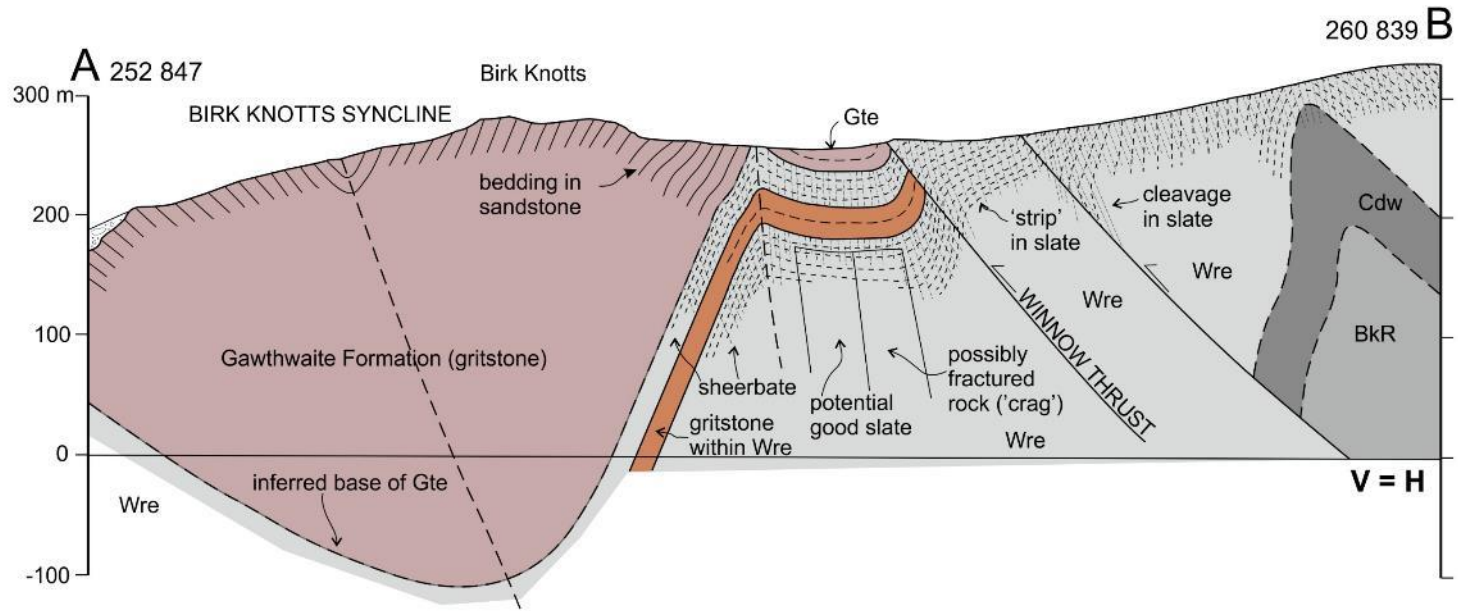
Walking along the track parallel to the edge of the quarry gives a good impression of the size of the void created by slate extraction. The small exposure near the base of the wind turbine is a scaled down version of the high-angle relationship between bedding and cleavage that gives rise to the economic working of slate in this area. At some points along the dirt road on the edge of the quarry, you should be able to see the same relationships on the NE end wall of the main void. On the Locality 2 side of the quarry, the cleavage dips towards you which means as the quarry gets deeper an overhang develops, termed **backway** by the quarry workers. On the opposite quarry faces, where split along the cleavage, they are inclined less than vertical and this known as the **rightway**. Looking at the NW sides of the quarry you will also see the trace of bedding on the cleavage, again plunging to the NE as at Gawthwaite High Quarry.



A closeup view of the NW wall [rightway] of the main quarry at Kirkby. Arrowed in yellow is the trace of bedding on the cleavage which gives the direction, and amount of plunge, of the main fold. This lineation is particularly well defined by the white bentonite layers.



In good weather there are good views of Coniston Old Man and more distant fells. You may be able to make out quarries on the Old Man; those on the SW side of the South Ridge follow a horizon in what was an exceptionally deep caldera lake in the Borrowdale volcanics.

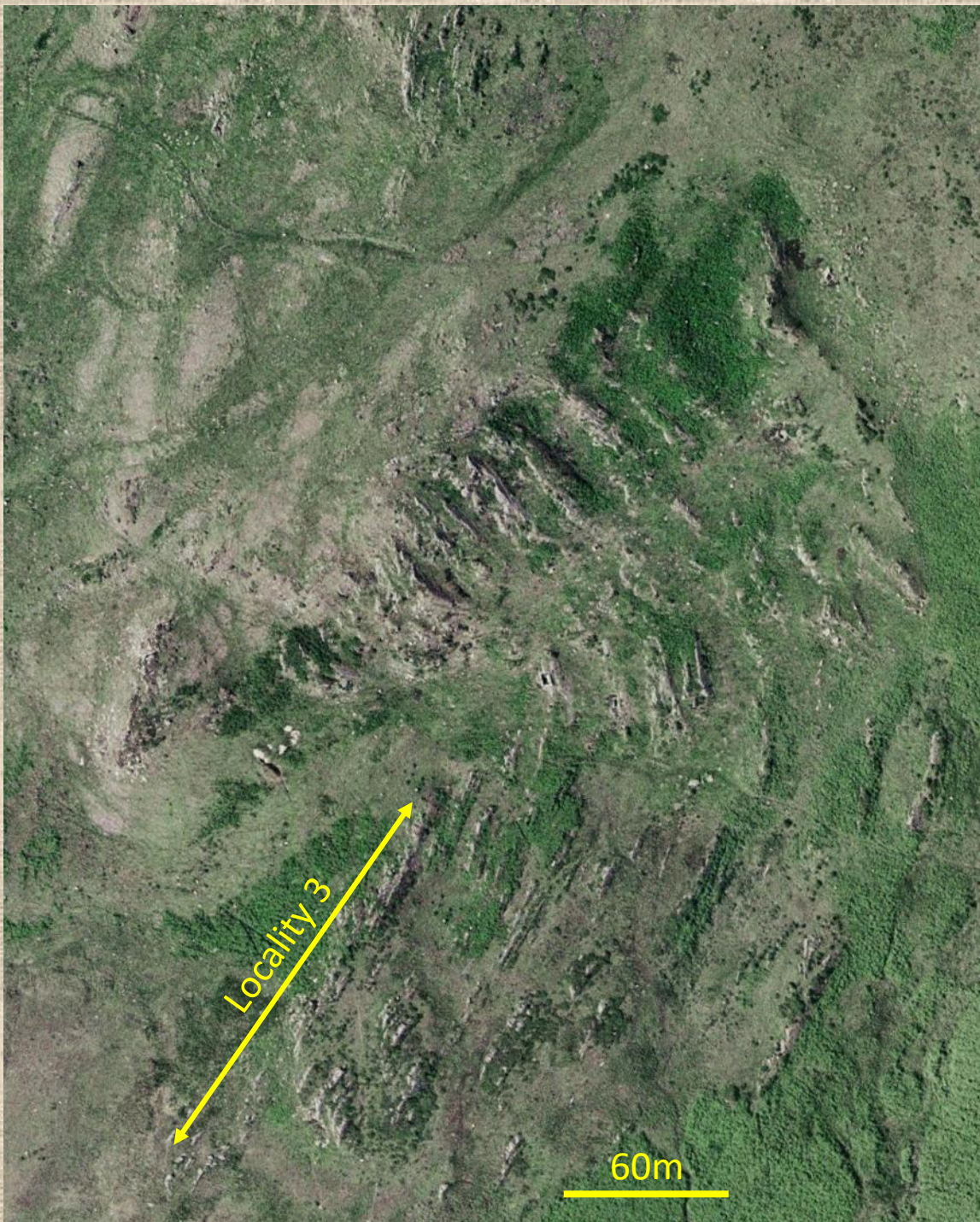


Cross sections through the slate quarries on Kirkby Moor looking in the plunge direction towards the NE. This is the same viewing direction as the Locality 2 slide so the cleavage attitude in the main Kirkby Quarry matches that of the small exposure at Locality 2.

From: Soper, N.J., Kelly, I. & Boulter, C.A. 2020 Kirkby Moor slate: geology and the quarrymen's language. *The Cumberland Geologist*, vol. 1, pp. 47-51.

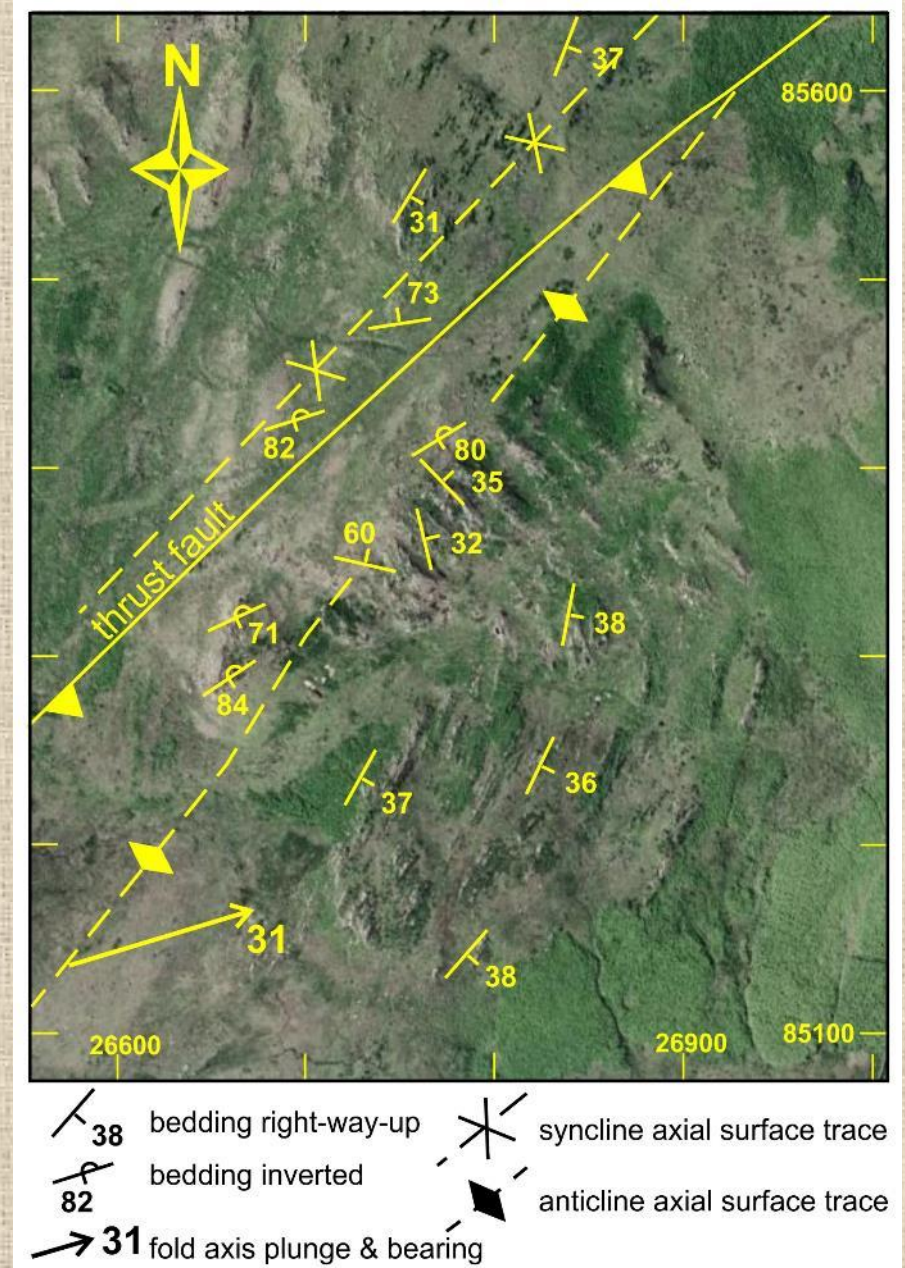
Locality 3 Gawthwaite Moor

Locality 3 is a series of closely spaced exposures.



Google Earth
Imagery dated
01.01.2003

Structural Data from Gawthwaite Moor



From Boulter ET AL. 2020 Cumberland Geologist

Locality 3 SD 26682 85152 A very common exposure style on Gawthwaite Moor where erosion has attacked a slate layer and left the top of a sandstone bed exposed. The prominent lineation on this bedding plane is created by the intersection of the main Acadian cleavage and the bedding. If the fold geometry was perfect, and a couple of other conditions hold, this lineation would give the attitude of the fold axis. At Gawthwaite Moor it is very close to the fold axis but not perfectly so. The intersection lineation plunge and bearing [30 → 070] shows little variation throughout Gawthwaite Moor.



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Locality 3 SD 26725 85160 [the grid ref is for the lower end of this exposure] Carbonate concretions are another common sight on Gawthwaite Moor. The top 20 cm of the sandstone unit is cross laminated – a T_c part of a turbidite – which is most easily seen at the lower end of the exposure. Cross-bedding truncations in the C division of the turbidite show the beds are right-way-up.



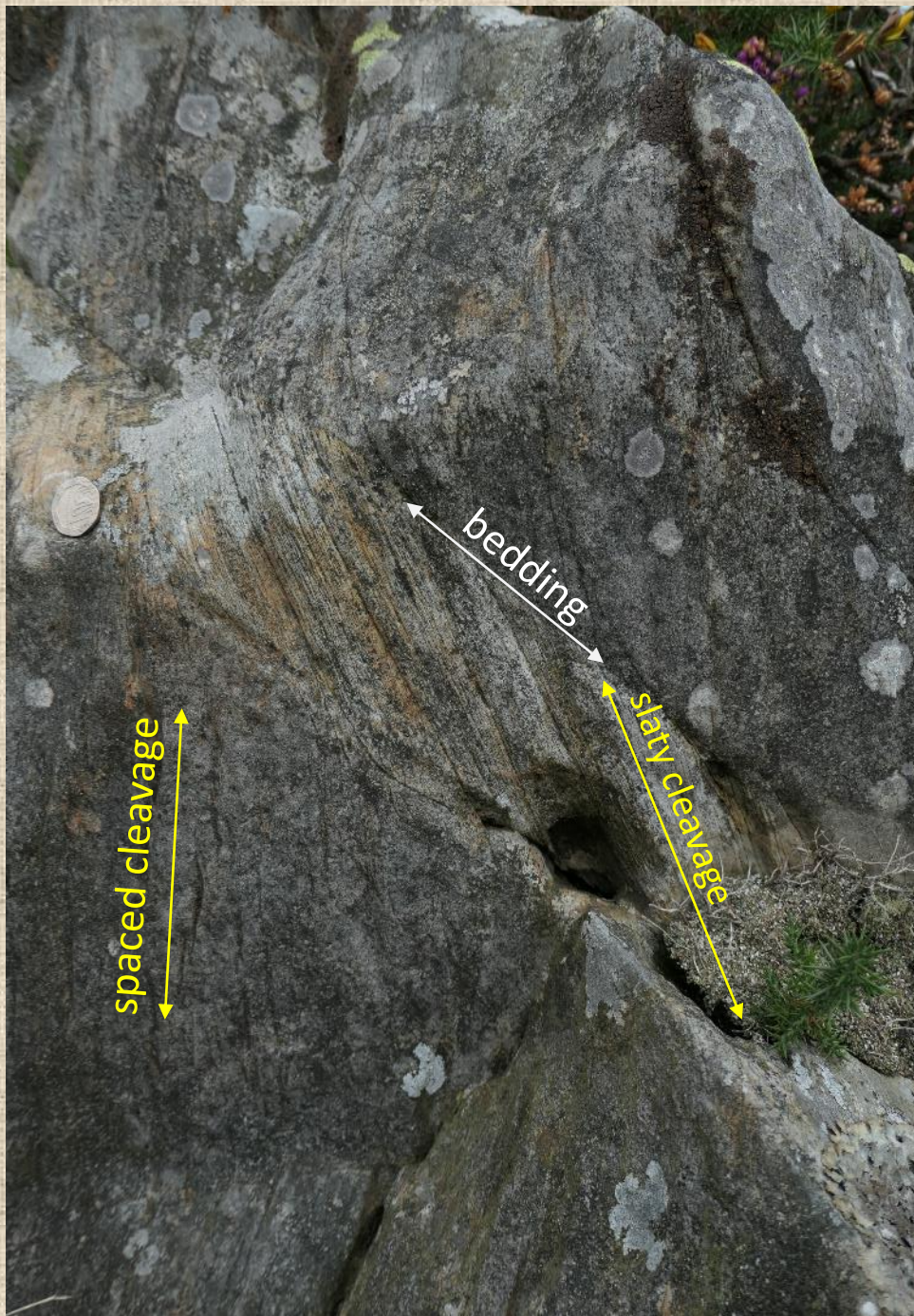


A close up view of the layer of carbonate concretions [nodules] showing distortion associated with Acadian Orogeny. Originally they may have been roughly circular or elliptical along the bedding.

The double headed yellow arrow is along the length of the concretions and is parallel to a spaced cleavage in the wacke sandstones. This cleavage [see title slide] is recessive and typically spaced at around a couple of centimetres. In thin section it is nearly pure mica and was formed by other minerals like quartz going into solution and being removed. The spaced cleavage is not the only result of strain in these sandstone layers otherwise the concretions would not be deformed in the way they are. Between the spaced cleavages the rock has also been strained. The spaced cleavage is termed disjunctive because it is independent of any pre-existing structure in the rock such as bedding or compaction fabrics.

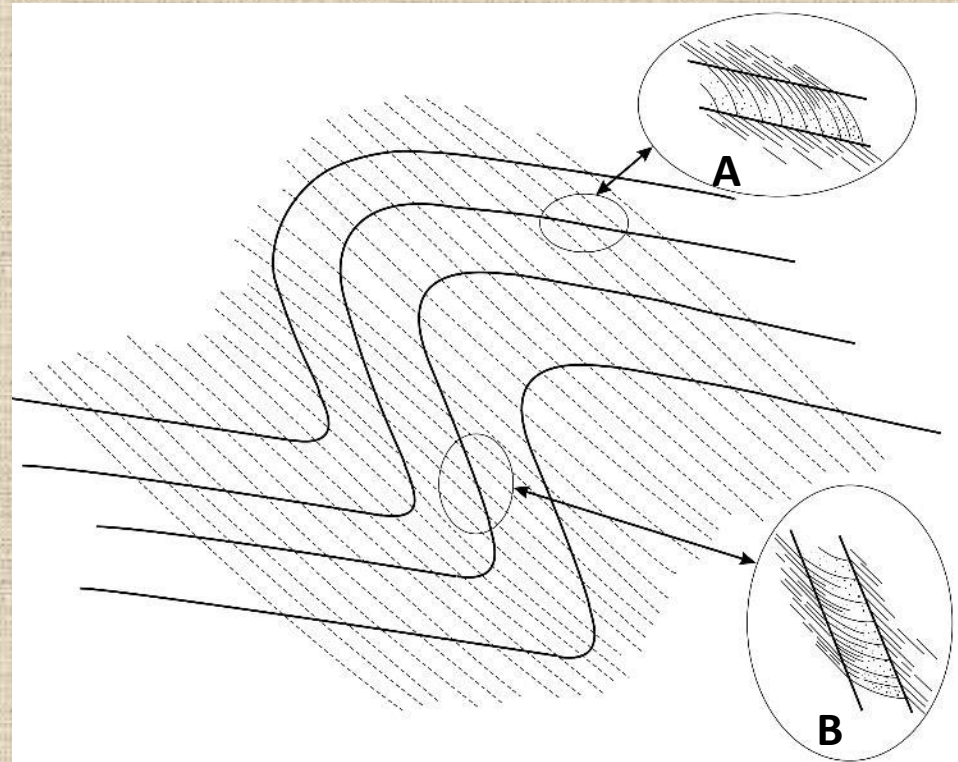


A 3.5 mm wide view, in a thin section, of a spaced cleavage similar to those seen on Gawthwaite Moor.



Locality 3 SD 26713 85183

At this grid reference four greywacke beds are separated by thin slate beds of varying thickness. Where the slate is several centimetres thick the slaty cleavage is easily seen as well as the different attitude of the spaced cleavage in the sandy beds; this is cleavage refraction. Both of these cleavages were created during folding and the angular relationships of both can be used to determine where this locality is on the fold structures. This locality is equivalent to position **A** on the diagram which shows idealised graded beds where the cleavage continuously curves as the grain-size



decreases. Most of the turbidites on Gawthwaite Moor have delayed grading where the finer grained material only occupies a few percent of the bed. This delayed aspect also means that the structureless A division of the medium-grained turbidite family [Bouma] dominates.

The slaty cleavage is close to the attitude of the fold axial surface.

Locality 3 SD 26719 85170

Having seen the cleavage/bedding relationships at SD 26713 85183 retrace your steps just a few metres and you will see even the thinnest slate beds have the same bedding/cleavage relationships showing that an antiformal anticline closure is to your left-hand side as you look onto the exposure. The bedding/cleavage angular relationships deal with fold shape [**antiform** closing up & **synform** closing down] whereas the sedimentary structures give the relative ages of the rocks [**anticline** – oldest in the fold core & **syncline** – youngest in the fold core].

At SD 26719 85170 the thinnest slate bed is discontinuous possibly indicating that the surrounding greywacke beds amalgamated. The upper of the sandy beds has a well-developed C division. The upper layer has carbonate concretions.

SD 26714 85194

A 45 cm wide recessed slot has had nearly all of its slate removed but a small amount has been left on the roof of the cavity clearly showing the attitude of the slaty cleavage. The cleavage/bedding intersection lineation is strongly developed on the underside of the upper greywacke.





Locality 3 SD 26735 85232

An almost totally eroded slaty bed leaving a slot and a slab of unsupported sandstone.

Underneath this slab there is a remnant of slate which has in part broken along cleavage planes to allow the attitude of the slaty cleavage to be clearly seen. There is pronounced cleavage refraction between the sandstone and slaty layers and the intersection lineation is strongly developed on the underside of the slot. Below the slot you can see, in profile, cleavage refraction between sandy and slaty layers.

SD 26760 85264

Approximately a further 45 m along the edge of the exposures, there are C Bouma divisions in two greywacke beds.

Locality 4 SD 26715 85328

This is the antiformal anticline fold closure. In a matter of a few metres the layers go from moderately-dipping right-way-up beds to sub-vertical and overturned. The yellow line matches the trace of the bedding around the fold closure. Cleavage is strongly developed in the greywackes and the cleavage/bedding intersection lineation is well developed on the bedding surfaces. Just a few metres below this photographed area, the bedding dips steeply to the SE. The fold is angular and is of no use for slate extraction even if there were thick slate layers.

In the bracken season this hinge zone can be almost totally obscured.



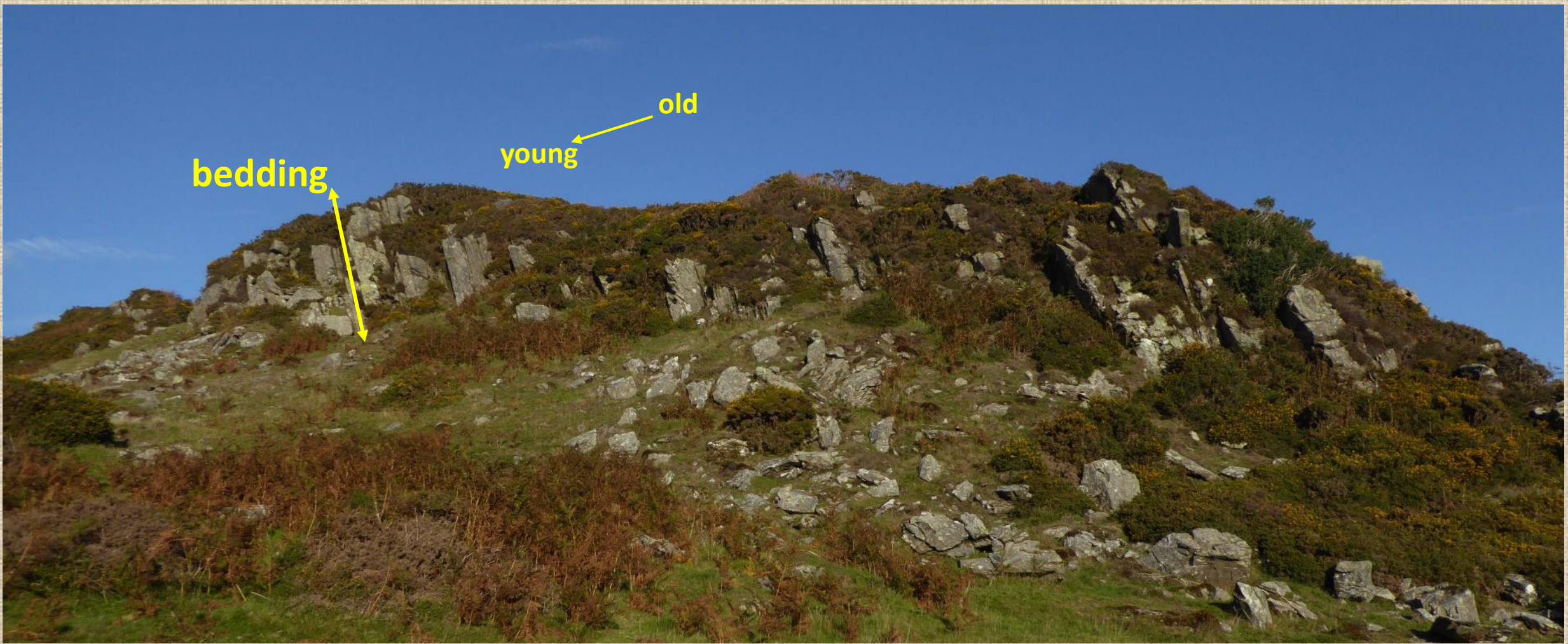
Locality 5 SD 26769 85397 Two views of the same exposure.



Looking end on to the exposure: the GPS unit is lying on a surface that has split along the spaced cleavage and the bedding is at high angles to the cleavage showing that the locality is close to the fold closure.



This face is where the GPS was lying in the adjacent photo – it is the spaced cleavage plane and on it the widely spaced lineations are the trace of bedding on the cleavage. It has the same geometric significance as the widespread lineations on the bedding planes in that it is close to the fold axis in attitude. Not far downhill from here there are extensive exposures of lineated bedding planes.



Locality 6 viewed from SD 26644 85298

Steeply dipping bedding which has been rotated more than 90° and is now upside down. This inverted state is shown by turbidite subdivisions and sole structures. Approach the rocks to the left to examine cleavage/bedding relationships and sedimentary structures.

Detail of exposures at Locality 6. The image on the left shows strong cleavage in a silty/slaty bed. Several beds have A/B/C turbidite divisions to show that the beds are upside down. This shows the locality is equivalent to position B on the fold-cleavage diagram used at Locality 3 [SD 26713 85183]. Some beds show some curvature of the cleavage [right] which reflects grading.

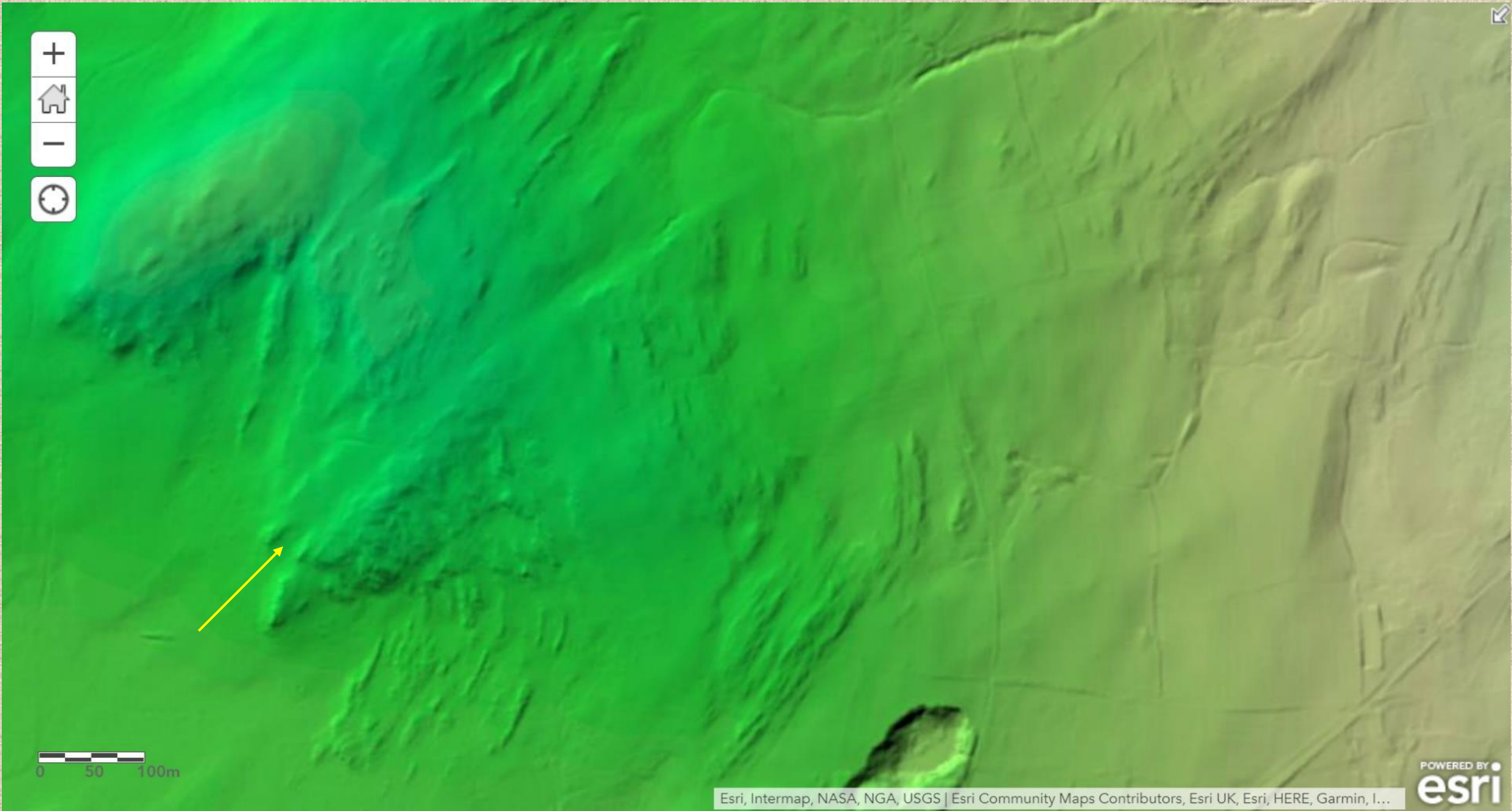


Locality 7 SD 26753 85483 Not the clearest exposure but it is the patchily exposed closure of the synclinal synform. Bedding attitudes are outlined in yellow. The spaced cleavage in the sandy beds [white line] is strongly developed. On the walk from Locality 6 a thrust fault has been crossed. This contractional fault has a topographic expression as a gully but there are several candidate gullies so care is needed in selecting the most likely. On a LiDAR image [see next slide] there is a prominent trough which defines the location of the thrust fault.



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A LiDAR image from the Environment Agency showing the topographic expression of the thrust fault between Localities 6 & 7.



Locality 8 SD 26750 85517 Dips return to moderate/gentle, and right-way-up, past the synclinal closure.



At this locality you can see carbonate concretions, B & C divisions of Bouma turbidites [delayed grading], locally pronounced spaced cleavage, and cleavage refraction from slaty to sandy layers.

Some Sedimentary Features

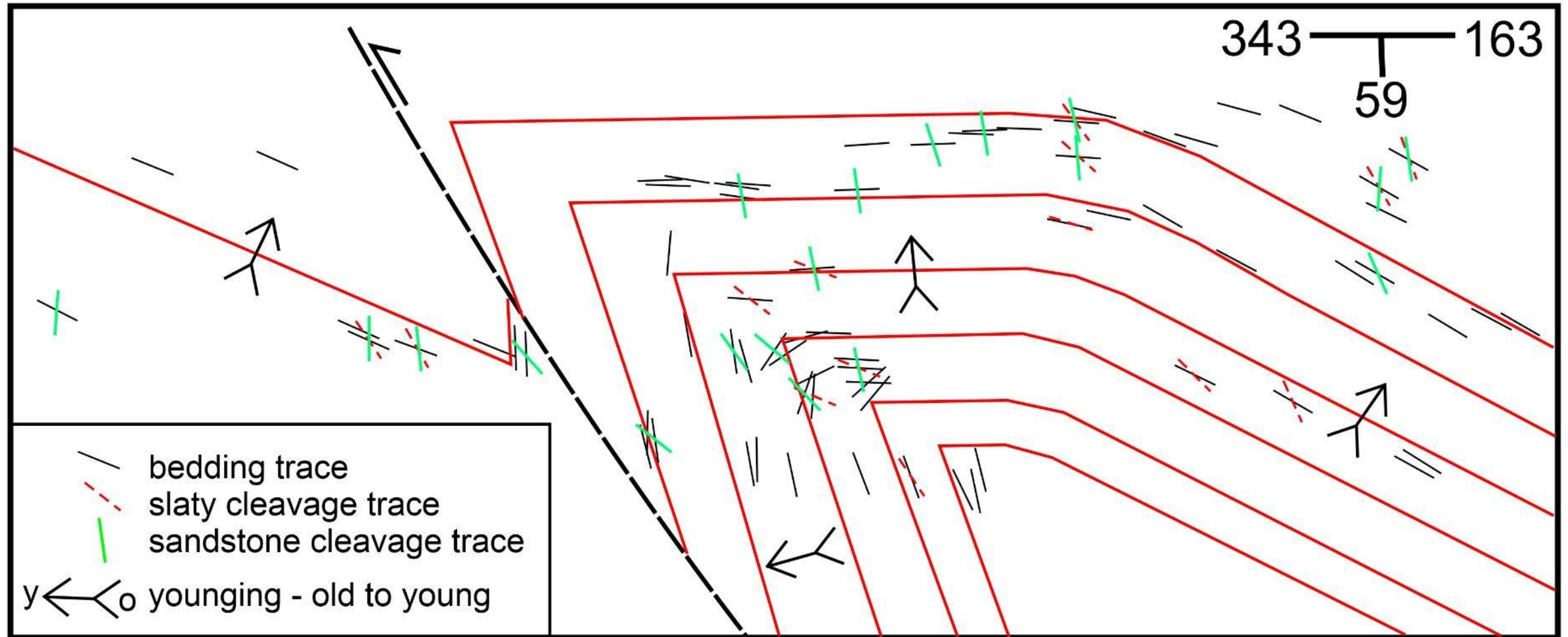
SD 26751 85615 An unusual development of a Bouma C division in this area in that it occupies most of a sandy bed [smartphone for scale].



SD 26772 85686 Convolute lamination formed when water escaped as the grain framework collapsed [20p scale]. The laminations are in B & C turbidite divisions.



This is an inclined cross-section perpendicular to the fold axis with a dip of 59° towards 253° and a strike of $343/163$. Localities, and orientation data, have been projected using the fold axis and the planar data [bedding and cleavage] are shown as intersections on this inclined plane. In this down plunge view, beds dipping 30° down the fold axis would appear horizontal. As is evident on the map the antiformal structure has two axial surfaces [polyclinal] and the slaty cleavage is close to the attitude of the antiform closest to the thrust. The red lines are a form surface to the overall data for bedding. There are no marker beds in the immediate area to give the sense of offset on the thrust. Its contractional nature is demonstrated by regional mapping of the offset of formation boundaries.



If you haven't seen the sole structures at Great Burney they are worth a visit. They are very close to Gawthwaite Moor.



Flute Casts/Sole Marks at the base a turbiditic muddy sandstone [wacke], Yewbank Formation, Great Burney [SD 257859]