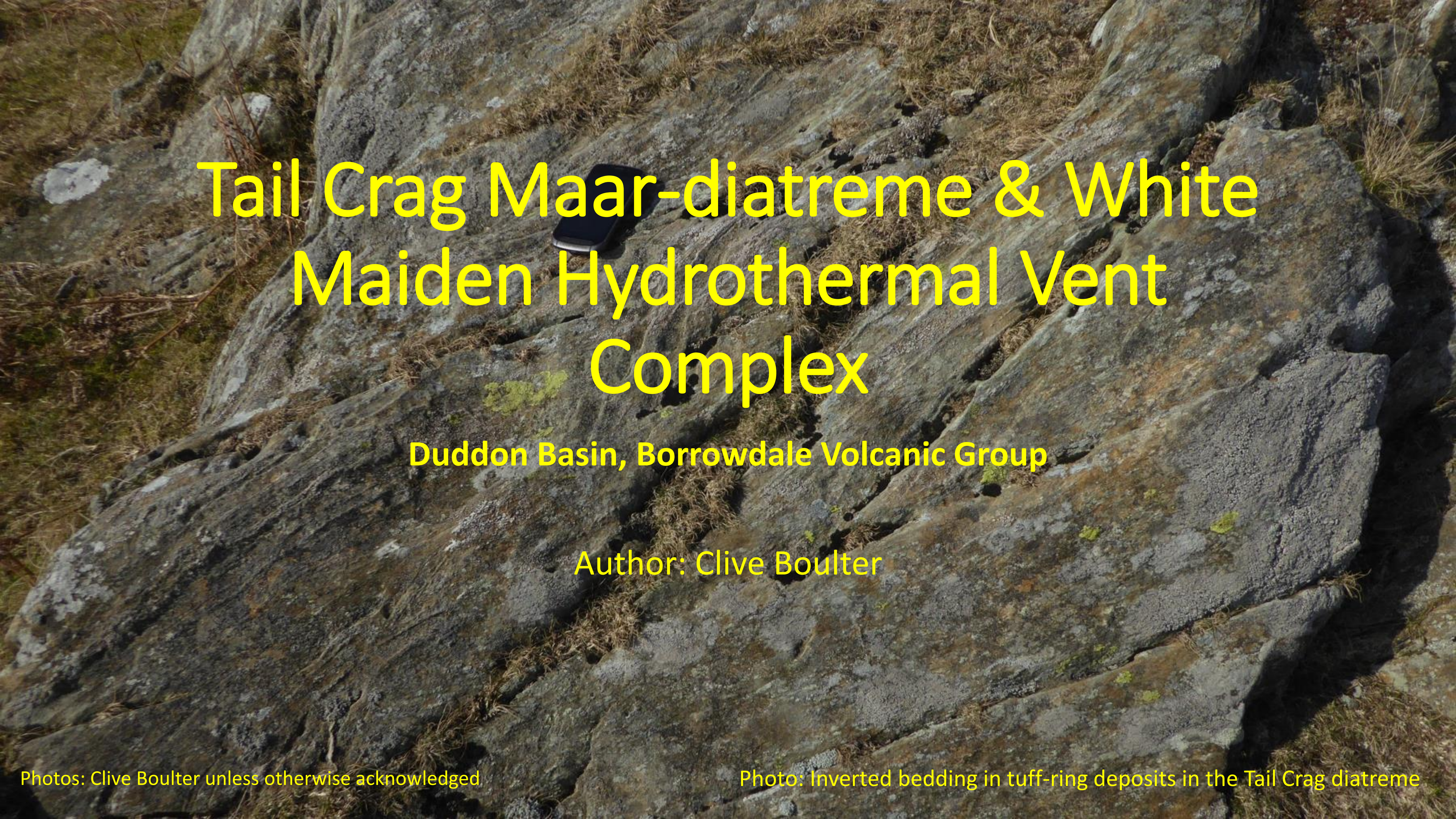


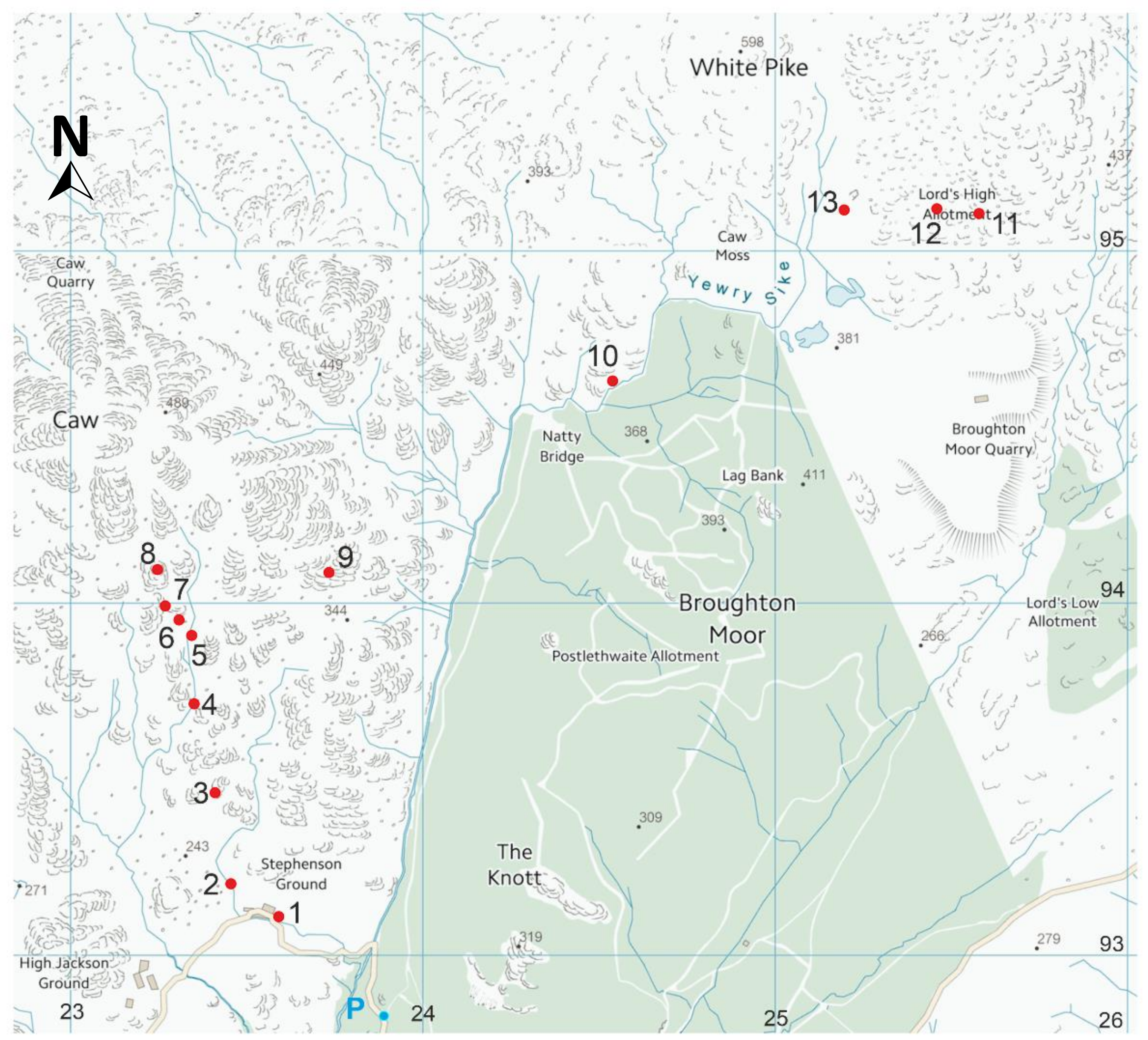
Tail Crag Maar-diatreme & White Maiden Hydrothermal Vent Complex

Duddon Basin, Borrowdale Volcanic Group

Author: Clive Boulter

Photos: Clive Boulter unless otherwise acknowledged

Photo: Inverted bedding in tuff-ring deposits in the Tail Crag diatreme



LOGISTICS

An almost round trip of 8 km starts at SD 239928. Walk up the road to Stephenson Ground and after looking at the features here take the path northwards to follow the itinerary. Once the geology has finished head for Natty Bridge and take the forestry road to return to the parking place.

About half the distance is on open fellside and the other half on roads, paths, and poorly-defined tracks. Caw Moss is boggy in parts.

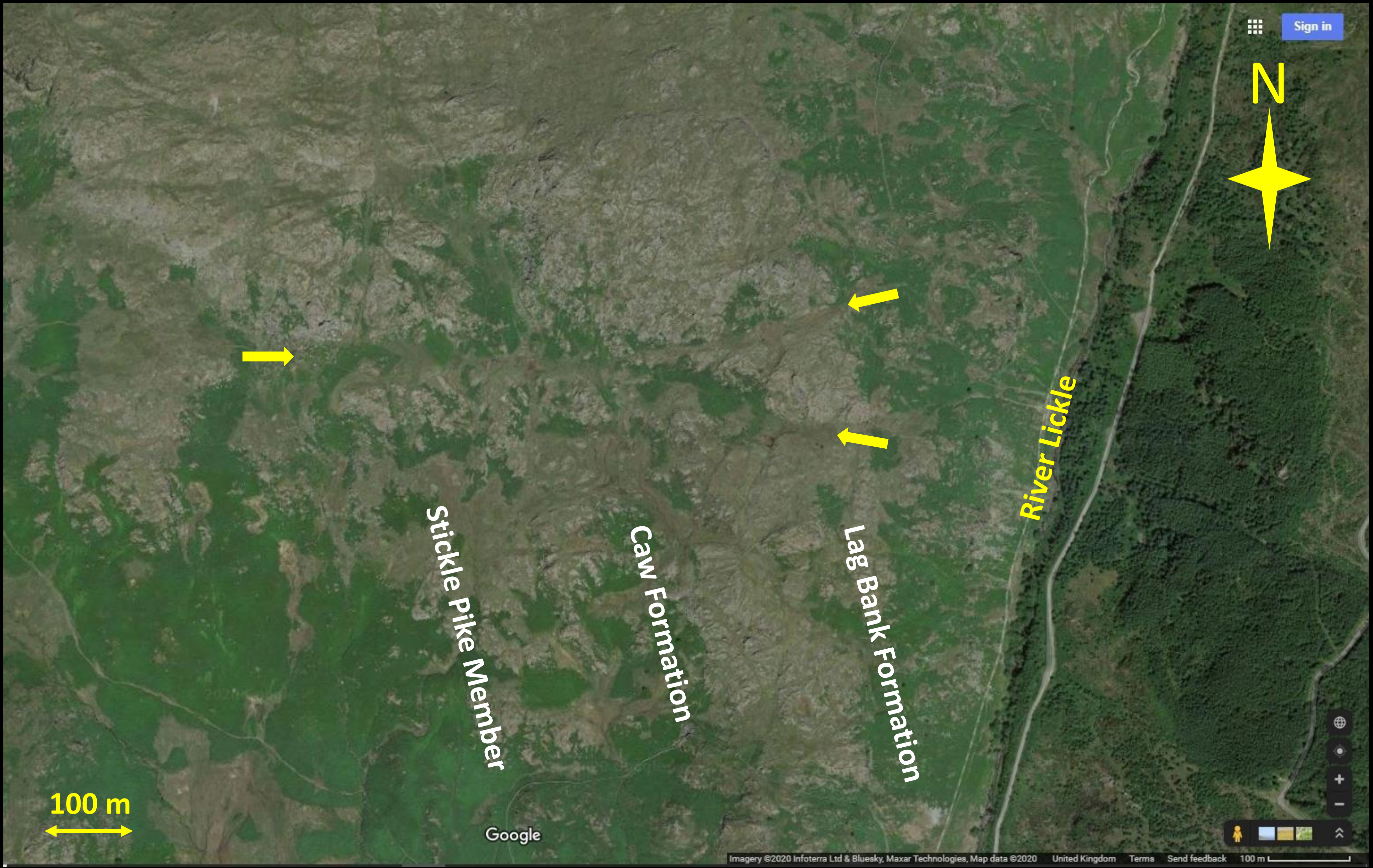
Ordnance Survey Open Data.

Kilometre grid.

Introduction to the Tail Crag maar diatreme

On the southern slopes of Caw the stratigraphy published at 1:50,000 scale is a triple layer stack of the Stickle Pike Member [Lickle Formation], Caw Formation, and Lag Bank Formation. The Caw Formation in the centre is volcaniclastic sandstone and conglomerate whereas the two units on either side are ignimbrites. There is much evidence that, prior to deposition of the Caw Formation, the upper surface of the Stickle Pike had a topography defined by volcanotectonic fault [VTF] scarps which influenced sedimentation. A VTF at Tail Crag, with a very weak landscape expression, has a pronounced effect on the sedimentary style in the Caw. South of the VTF the Caw is mainly fairly thinly-bedded fine- to medium-grained turbidites [Bouma model] contrasting with deposits to the north which are mainly thickly bedded coarse-grained turbidites [Lowe model] though some debris flows might have been involved. Coincident with this contrast in sedimentological styles are abundant Neptunian clastic dykes in the underlying Stickle Pike, the intense fracturing being attributed to continuing seismic activity on the VTF after explosive eruptions had ceased. The VTF topographic expression extends from part way below the Stickle/Caw boundary, through the Caw up to just into the Lag Bank. At the Caw/Lag Bank contact there is a tuff-ring style deposit that only extends for a few tens of metres either side of the intersection of the VTF with this boundary. Overlying the dilute PDC deposit there is an ignimbritic lag breccia which is laterally only a little more extensive than the underlying well stratified ignimbrite. Along the trend of the VTF, but only extending a little way down into the Caw, there are metric-scale blocks of the tuff-ring style deposits disoriented such that, in some cases, bedding has been overturned; this is interpreted as a diatreme of limited depth. A possible scenario involves reuse of a Stickle Pike Member magma conduit which was propagated through the Caw Formation partly guided by the contrast of sedimentary types. Seismic activity may have continued along the VTF during much of the evolution of the Caw. When the initial Lag Bank magmatism was close to the palaeosurface it generated phreatic eruptions forming the very limited tuff-ring. Expansion of the feeder zone caused break up of blocks of the stratified tuff-ring deposits which now have a range of steep attitudes. The Caw was probably poorly consolidated during these events and probably disaggregated into its constituent parts – a soft-rock environment. Subsequently the lag breccia which is localised around the VTF/Caw-Lag Bank intersection was fed from the same conduit.

Volcanotectonic fault lineaments on Google Earth south of Caw



Weakly-defined approximately east-west features on Google Earth are VTFs. The Tail Crag VTF is highlighted by arrows together with a southerly splay. Less persistent VTFs, or those with less offset on the Stickle/Caw boundary, are not resolved at this scale. On the Tail Crag VTF there is a twenty metre offset [strike separation] of the Stickle/Caw boundary.

The fault along the River Lickle offsets the Borrowdale volcanics/Windermere Supergroup boundary but when it was initiated is another question.

Locality 1

Walking up the road towards the large barn at Stephenson Ground, have a look at the lintels over the door and windows onto the road. They are welded ignimbrite. The source is not known with certainty but they might be from the Stickle Pike Member of the Lickle Formation.

Before you head out onto the fells it is worth a brief look at the copestones on top of the wall outside Stephenson Ground which include local geology not seen on this itinerary.

To the right is a block from a quartz vein.

Classic caries texture in the calcareous siltstone of the Kirkley Bank Formation [Coniston Limestone that was]. Many of the copestones are of this material.

At the western end of the wall is a water yeat made from columnar cooling-jointed welded ignimbrite. The source of the columns is not certain but they probably came from the "rhyolite quarry" at SD 2454 9463 in the Lag Bank Formation – Locality 10.

Locality 2 SD 23451 93202

Columns from a columnar cooling-jointed welded ignimbrite used as a water yeat in a dry stone wall. The source of the columns is not certain but they probably came from the "rhyolite quarry" at SD 2454 9463 in the Lag Bank Formation [Locality 10].

Locality 3 SD 23413 93461

This locality can be observed from SD 23377 93433 otherwise it is quite a hike to get to the rock face via an Open Access route.

Fanned columnar cooling-joints in welded ignimbrite of the Stickle Pike Member, Lickle Formation, Stephenson Ground Crags. Exposure approx. 7 m high.
The welding fabric defined by flattened pumice clasts is at high angles to the length of the columns [just about visible in the photo].

If you wish to have a more in-depth look at the sedimentary style of the Caw Formation the following are of note:
SD 23467 93662 accretionary lapilli reworked in turbidite/debris flow beds.
SD 23454 93595 a metric scale debrid flow bed crowded with accretionary lapilli.
SD 23444 93578 a 3.5 m long clastic dyke in the Stickle Pike Member.
These three exposures are associated with a 10-15 m step in the Stickle/Caw contact.

At SD 23426 93667 there is a good exposure of the turbidite style south of the Tail Crag VTF.

Locality 4 SD 23358 93726

An exposed contact between the Stickle Pike Member and the Caw Formation which gives a good opportunity to see the sedimentary style of the Caw. The grainsize and bedding characteristics of the Caw are typical of medium-grained turbidites. It is easy here to identify the contact between the two units in contrast to north of the Tail Crag VTF where the Caw is coarser grained and poorly bedded making distinguishing the two difficult.

Just a few metres into the Caw [next slide] accretionary lapilli have been reworked by the turbidity currents.

Locality 4B SD 23371 93725

A few hundred metres south of Locality 4, around SD 23467 93562, accretionary lapilli are common and may in part be primary pyroclastics though at SD 23455 93595 they are clearly reworked in a debris flow. By the time you reach Locality 4 accretionary lapilli are restricted to one or two layers and all are reworked. Sparse accretionary lapilli are seen as far north as a few metres above the section shown in the photograph of Locality 5.

20p coin, amongst the accretionary lapilli, for scale.

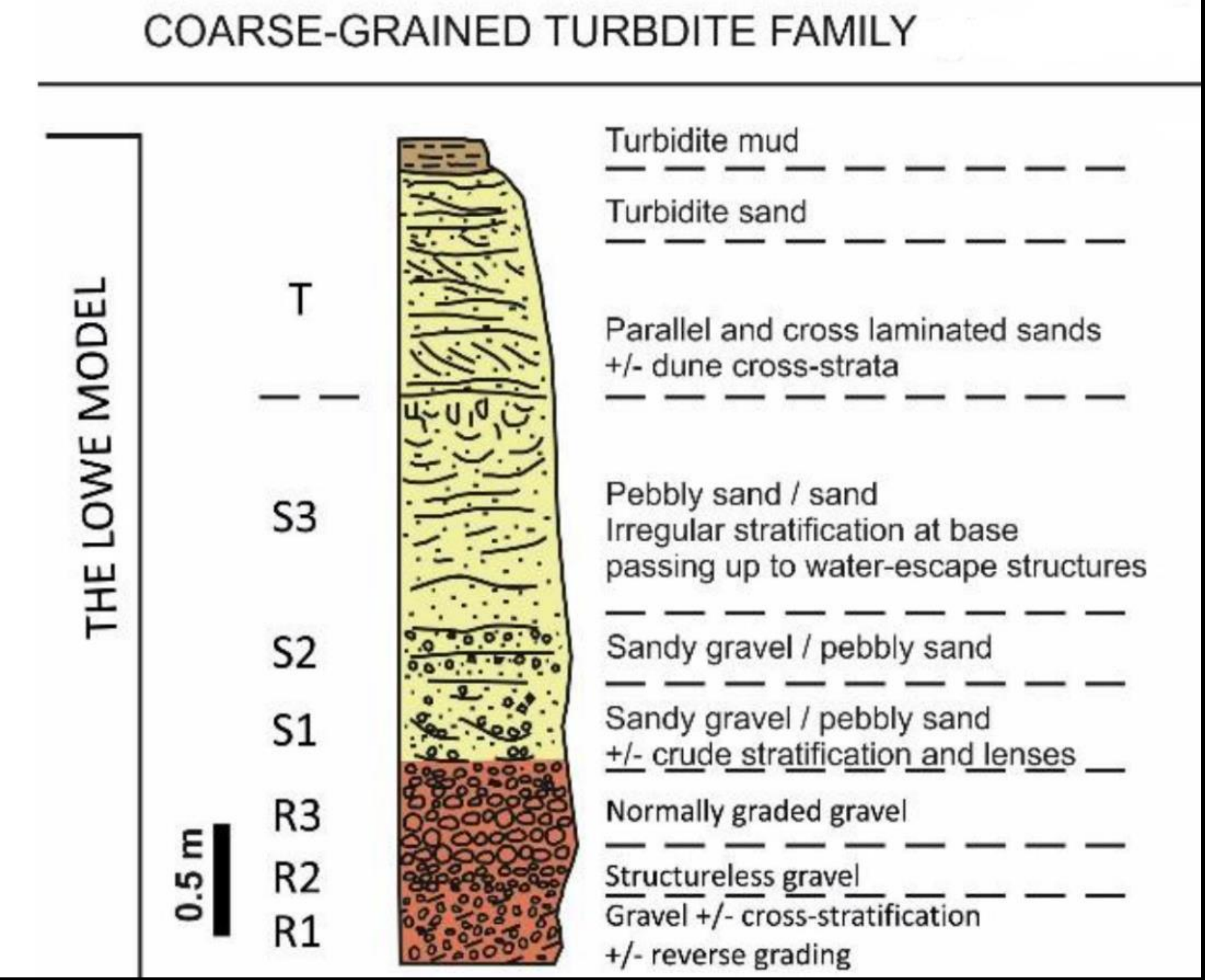
Locality 5 SD 23355 93906

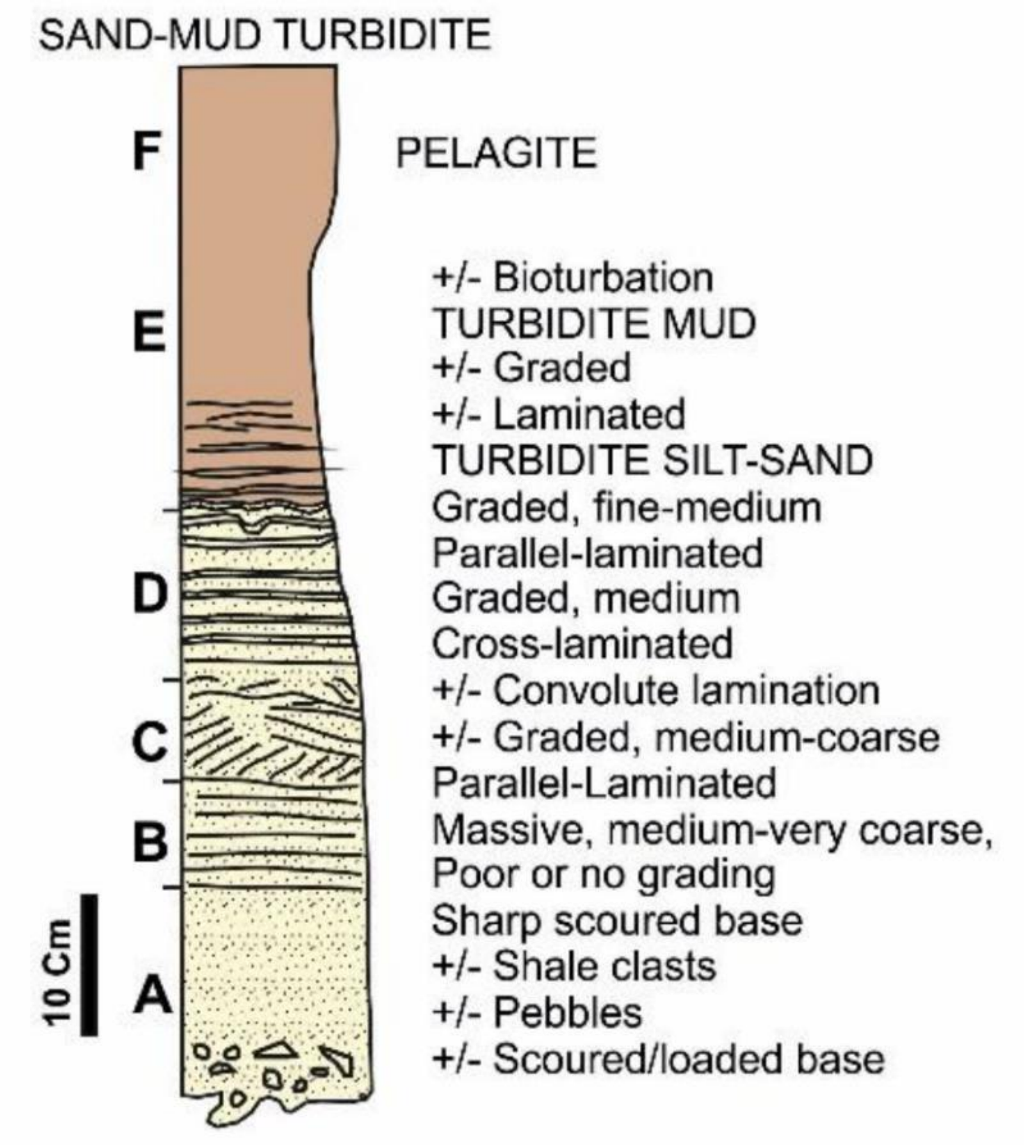
A fairly typical example of the sedimentary style of the basal several tens of metres of the Caw Formation south of the Tail Crag VTF. These are medium-grained turbidites with Bouma-model internal structures. Bedding is mainly on the centimetre to a few tens of centimetre scale. C divisions up to four cm thick are common. Fine-grained to medium-grained sand is dominant in the exposure.

[mobile phone for scale]

Contrasting Sedimentary Styles North & South of the Tail Crag VTF

To the south [SD 23355 93906] of the Tail Crag VTF fairly thinly-bedded medium-grained turbidites have Bouma-model internal structures whereas to the north [SD 23273 94098] bedding is much more massive, grain size is coarse to very-coarse sand and beds have Lowe-model internal structures.





Typical coarse-grained and medium-grained turbidite sedimentary structures compared.

From: Dorrik Stow and Zeinab Smillie, 2020, Distinguishing between Deep-Water Sediment Facies: Turbidites, Contourites and Hemipelagites. Geosciences, 10, 68; doi:10.3390/geosciences10020068.

← Locality 6 SD 23316 93955
Abundant Neptunian clastic dykes in Stickle Pike Member

From SD 23444 93578 [where there is a very large clastic dyke, 3.5 m x 15 cm] to Locality 6 there are localised clusters of dykes some of which are at abrupt steps in the Stickle/Caw boundary considered to be caused by VTFs. From Locality 6 to the Tail Crag VTF clastic dykes are abundant.

An example of clastic dyke arrays north of Locality 6.

In the area north of Locality 6 some infills of the abundant clastic dykes display turbiditic sedimentary structures showing that turbidity currents operated from the start of the depositional process on the south side of the Tail Crag VTF. The dyke internal features, and the nature of the ignimbritic host, indicate a passive infilling process rather than forceful injection. They are Neptunian dykes.

Locality 7 SD 23277 94000

A perfect exposure of part of the Stickle/Caw contact where there is an overall four metre step. Clastic dykes in the Stickle emphasise the boundary between the two units, a task helped by the good definition of bedding in the Caw. The Caw built up against the steep edge of the Stickle Pike Member. A scour within the Caw possibly reflects turbulence generated by the palaeotopography at the top of the Stickle Pike Member.

Shadows on the photographs can create a pseudoscopic effect where positive features appear recessive. The clastic dyke labelled +ve stands out from the weathered surface – blink hard if it is recessive!

A couple of metres south, the contact is sub-parallel to the bedding in the turbidites.

SD 23250 94015

Just north of Locality 6 there are gently dipping surfaces in the Stickle Pike Member with abundant clastic dykes.

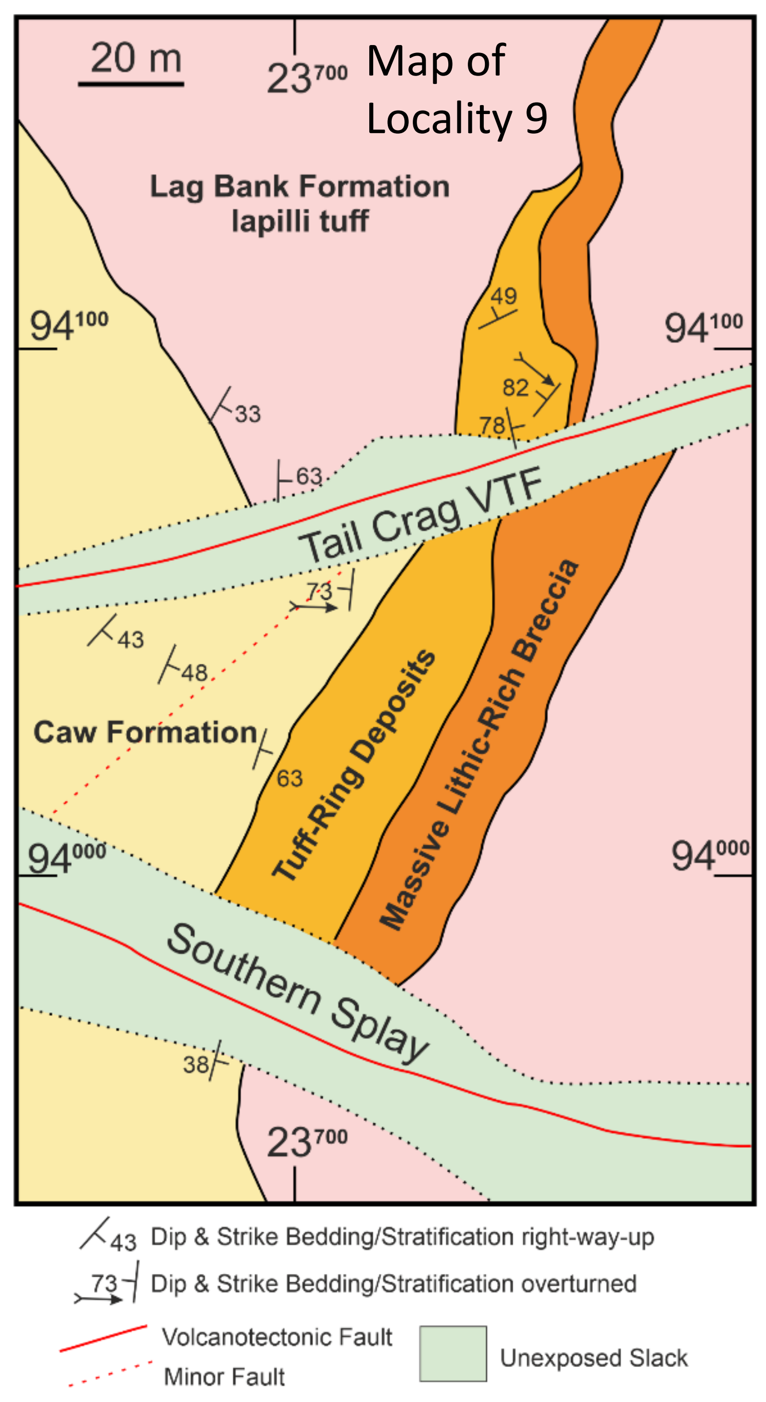
Locality 8 SD 23273 94098

The Stickle Pike/Caw boundary north of the Tail Crag VTF is at SD 23255 94096 where the depositional style in the Caw Formation is markedly different to that south of the VTF. Coarse to very coarse sand dominates with some granule conglomerate. A better view of the sedimentary structures is gained a little way into the Caw at SD 23273 94098 on a 2.1 m tall joint face; these are characteristic of high-concentration turbidity currents [Lowe model]. Possible amalgamation of beds makes it difficult to assess bed thickness but it is significantly greater than to the south of the Tail Crag VTF.

The Stickle/Caw contact is exposed at 23234 94117.

Contrasting Sedimentary Styles North & South of the Tail Crag VTF

To the south [SD 23355 93906] fairly thinly-bedded medium-grained turbidites have Bouma-model internal structures whereas to the north [SD 23273 94098] bedding is much more massive, grain size is coarse to very coarse sand and beds have Lowe-model internal structures.



Locality 9 Start at SD 23735 94082

Identifying mappable boundaries, particularly the Caw/Lag Bank, is fraught with difficulty. The Caw is a poorly-sorted, poorly-bedded coarse volcaniclastic water-lain deposit whereas the Lag Bank is a poorly-sorted, poorly-stratified pyroclastic. In the field it can be very difficult to tell them apart. The tuff-ring deposits are well-stratified with cross-stratification and some accretionary lapilli but they have very variable attitudes and are pervasively faulted in places. The massive lithic-rich breccia has a variety of blocks up to 3 x 2 m which despite their size are matrix supported; it has the style of units commonly referred to as lag breccias often found as proximal deposits in ignimbritic sequences. There is a gradational contact with the background Lag Bank generally massive lapilli tuff though locally there is weak stratification.

There is a marked asymmetry either side of both branches of the Tail Crag VTF. To the north the first pyroclastic deposits are typical of the bulk of the Lag Bank. Between the two splays this material is too thin to map and has been incorporated with the tuff-ring unit which is not found south of the southern splay and thins rapidly beyond the northern branch. The massive breccia is represented by several thin layers south of the southern splay which taper within a few tens of metres. North of the area shown on the figure the breccia tapers rapidly but there is a similar breccia that tapers from the north at a slightly lower stratigraphic level, possibly from a separate VTF.

Because the tuff-ring deposits are highly localised around the intersection of the Tail Crag VTF and the top of the Caw Formation, it would appear that the VTF was the conduit for magma rise in the Lag Bank event. This conclusion is reinforced by the comparable distribution of the massive breccia. There is no way of knowing the time difference between the Lickle and Lag Bank ignimbritic eruptions and hence there is no control on understanding the state of lithification of the Caw when the Tail Crag VTF was propagated from the earlier parts of the stratigraphy. Caw lithics are not evident in the Lag Bank pyroclastics so the Caw probably was not well lithified.

Locality 9A SD 23735 94082 Following the slack created by the Tail Crag VTF eastwards leads to a low-profile exposure of well-stratified mainly parallel-bedded rocks of variable grainsize. Taken on its own this exposure gives little definitive evidence indicating the transport and depositional processes but going a few tens of metres north and south reveals accretionary lapilli, possible impact sags, and cross-stratification of several styles. This unit is an ignimbrite from dilute and moist PDCs of the type commonly associated with tuff-rings. Significantly the bedding in this block is sub-vertical.

Locality 9B SD 23746 94086
Part of the tuff-ring sequence with trough cross-bedding. Truncations of the cross-beds show that the stratification is overturned. The bedding attitude here is a strike of 041/221 dipping 82° NW.

The tuff-ring style deposit is on top of the Caw Formation and at this locality it close to, but not at, the base of the Lag Bank Formation.

20p for scale near cross-bed truncation giving way up.

Locality 9C SD 23737 94128

An exposure of the tuff-ring style of deposit with accretionary lapilli, cross-stratification, and possible pre-lithification folds.

Locality 9D SD 23746 94038

Overlying the stratified pyroclastics is a massive lithic-rich breccia which is coarsest to the south of the main northern branch of the Tail Crag VTF with blocks up to 3 x 2 m. In the absence of access to laboratory facilities it has proved difficult to identify the nature of the blocks with certainty especially as none of the source units have been found. Low down in the block shown here there is a possible indication of a welding fabric. Many blocks are either flow-banded rhyolite or high-grade welded ignimbrites. A small proportion, but amongst the largest are nodular on the 5 to 10 mm scale as is seen in the block just visible in this photo. These blocks could be nodular felsic ignimbrite or rhyolite [see next slide]. Hydrothermal alteration is another factor in obscuring the origin of the blocks.

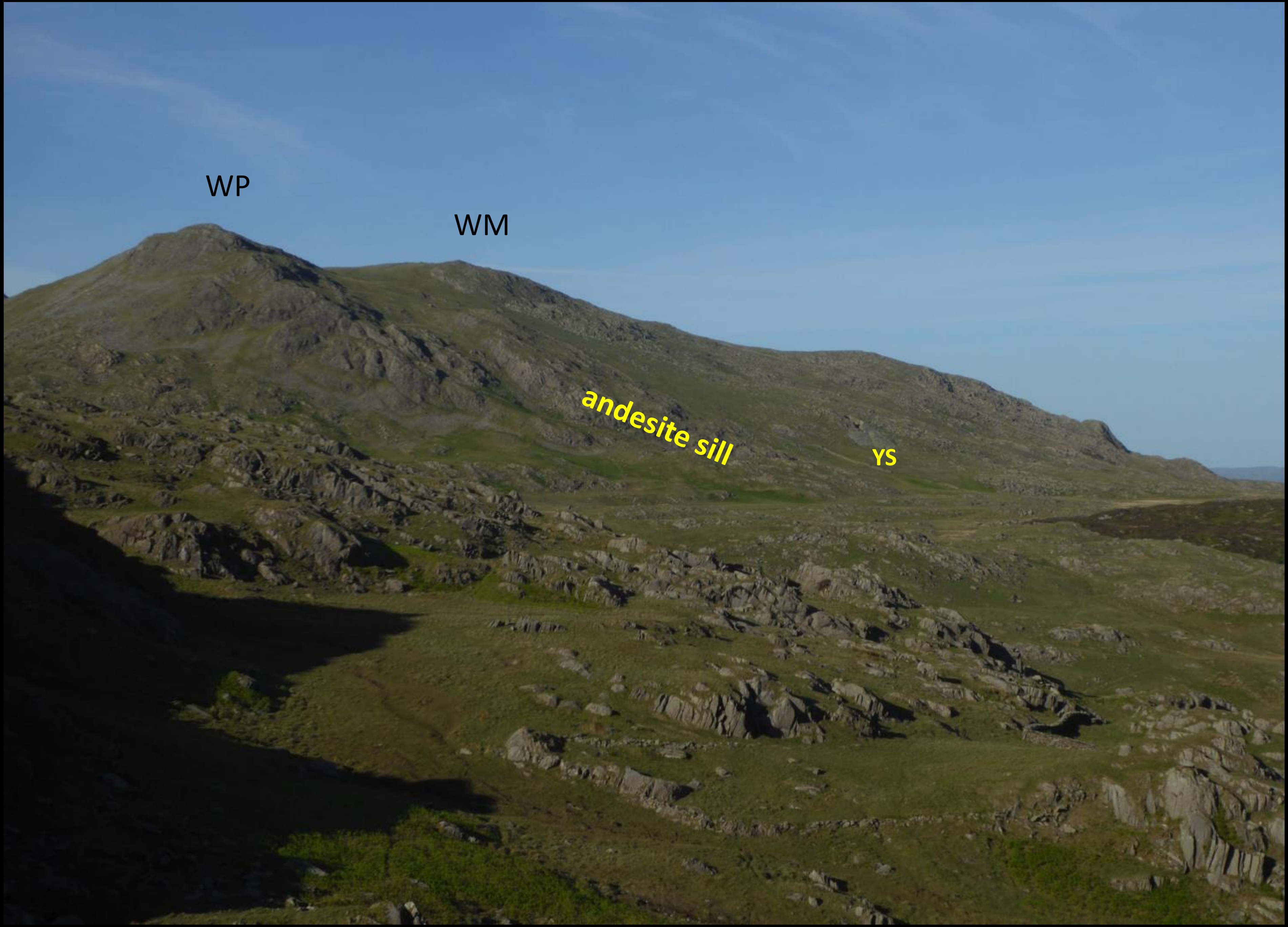
The pairing of the stratified pyroclastics, and the massive lithic-rich breccia, was mapped by Mitchell [1956] as rhyolite. The Ambleside Memoir described it as a basal breccia that formed in situ because of interaction between hot ignimbrite and the underlying wet sediments. Soft-sedimentary deformation structures in the underlying Caw Formation were attributed to loading by the Lag Bank Formation.

Locality 9D
SD 23734 94035 &
SD 23702 94028

Large blocks of nodular rhyolite/ignimbrite in the massive lithic breccia.

Locality 9E SD 23724 94044

Fractured well-laminated tuff-ring deposits with standard Lag Bank ignimbrite immediately to the north.



A view from the eastern end of the Tail Crag VTF looking towards White Pike and White Maiden. The small quarry is Yewry Sike Quarry [YS]. The ground beyond the flat area up to White Maiden is in the Tilberthwaite Formation which appears on the Ambleside 1:50,000 sheet as Seathwaite Fell Formation [see the Langdale Caldera itinerary for an explanation of the change to the stratigraphy].

From Locality 9 the best way to get to Locality 10 is to first head for SD 23872 94223 which is a triple junction between a very old dilapidated dry stone wall and a right-angle bend in a newer wall. From there stay above, but follow, the newer wall and where it turns downhill head for SD 24312 94671. At this point a weakly defined old quarry track goes east and should be rejoined after visiting Locality 10.

Locality 10 SD 2454 9463 – source of the stone water-yeats

The “rhyolite quarry” as named in a local archaeological publication was worked for hexagonal rock columns [Lag Bank Formation]. This is columnar cooling-jointed welded ignimbrite and probably was the source of the bars in the local water yeats.

Cross section view of columns showing the distortion caused when the Acadian cleavage was superimposed on the region.

A reasonably regular column.

Various views of material from the “rhyolite quarry” at SD 2454 9463

Welding fabric fairly well defined

Columns: good for through stones and copestones but not so great for building stones.

Images of dry stone walls next to the “rhyolite quarry” at SD 2454 9463 showing how columns were used in constructing the walls.

Before getting stuck into the sill-related hydrothermal activity it is worth visiting some beautifully exposed turbidites in the Tilberthwaite Formation. To get here you cross some poorly exposed ground along strike from the Broughton Moor Quarry. This quarry works a part of the Tilberthwaite characterised by wonderful turbidite sedimentary structures seen in many outlets selling green slate in the Lake District. The quarry's products are distinctive because of blebby spots probably caused by hydrothermal alteration associated with peperitic sills.

The broken slab shown here will make a fantastic place mat or cheese board. The various lower layers are a reminder that the Bouma model for medium-grained turbidites is only a guide and there are many variants on the theme. The upper layer shows that load & flame structures can be complex.

This is a view onto the slaty cleavage which is a low strain section. This means that the exaggerated ripple was exaggerated before the Acadian worked its magic and created the slate.

Locality 11 SD SD 25586 95098
Tilberthwaite Turbidites

A wonderful display of Bouma-model turbidites with classic internal divisions and soft-sedimentary deformation. In particular C divisions are prominent. Carbonate alteration has selectively picked out the medium to coarse sandy parts which in turn have been etched by weathering.

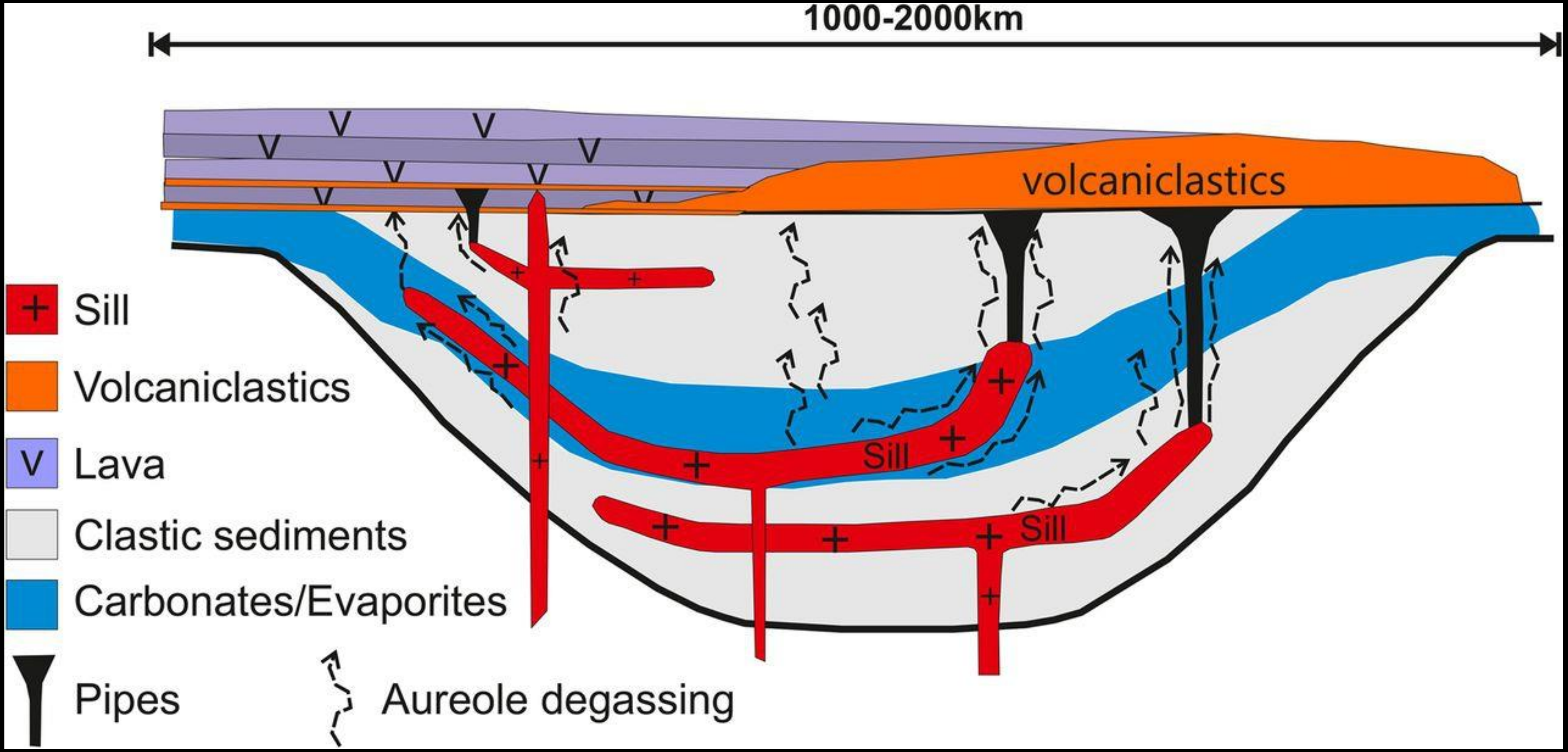
Locality 11A SD 25587 95106

In many cases we are left to speculate about the cause of soft-sedimentary deformation but in this example it was clearly the result of a debris flow many metres thick arriving over the top of this well-bedded sequence. The debris flow eroded down into the previous sediments no doubt aided by its weight fluidising the sub-strata but leaving a trail of angular fragments of the finer-grained materials.

Excellent examples of climbing ripples in turbidite C divisions are a few metres north of here.

Sill-Related Hydrothermal Vent Complexes

The Ambleside 1:50,000 sheet shows a thick andesite sill extending along the Walna Scar ridge and down from White Pike to the valley floor where it sharply terminates. Spatially related to this termination is a broad zone of hydrothermal alteration in the Tilberthwaite Formation which can be traced to the summit of White Maiden. It is suggested that the alteration is a hydrothermal 'pipe' of the style seen in many sedimentary basins in outcrop, or on seismic sections, where hydrothermal fluid transport tends to be focused within the thermal aureoles of the sills towards the sill terminations and then are directed to the palaeosurface. Interaction between incompletely consolidated sediments and the hot magma creates the hydrothermal fluid. The alteration in this case is most obviously expressed as patchy silicification and veining. Some silicification nucleates around compositional differences within layers and others are strata-bound replacements.



From: H. H. SVENSEN, T. H. TORSVIK, S. CALLEGARO, L. AUGLAND, T. H. HEIMDAL, D. A. JERRAM, S. PLANKE & E. PEREIRA, 2018, Gondwana Large Igneous Provinces: plate reconstructions, volcanic basins and sill volumes. In: SENSARMA, S. & STOREY, B. C. (eds) 2018. Large Igneous Provinces from Gondwana and Adjacent Regions. Geological Society, London, Special Publications, vol. 463, pp. 17–40.

Locality 12 SD 25464 95117

This is a distal part of the alteration zone associated with the andesite sill. Irregular patches of silicification, typically about 20 cm in diameter, are scattered through a structureless debris flow deposit. On the right is a close up of a zone of silicification which has a sinter-like appearance. Just downhill from here the crags are flesh coloured which probably is a function of carbonate alteration. From here to Locality 13 there is patchy alteration.

Locality 13 SD 25199 95119

Just below the tip from Yewry Sike Quarry is another example of an irregular patch of silicification in the Tilberthwaite Formation. Weakly-defined lamination dips from left to right. Within a few tens of metres west of, and above, the quarry a variety of irregular silica patches can be seen. The examples of alteration shown are the most accessible but not the most intense.

It is quite a hike uphill to see arrays of veins so these have not been included in the itinerary. Planar arrays of silica replacement tend to resist weathering and are prominent features [e.g. SD 25250 95407 & SD 25271 95445].

Return to the parking area via Natty Bridge [SD 24331 94545] and the forestry track on the east bank of the River Lickle.

SD 25271 95445

Planar siliceous replacement zones in Tilberthwaite Formation.

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