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The depositional environments and structures of the Borrowdale Volcanic Group and the Windermere Supergroup in the Southern Lake District, England

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Abstract

Field studies have been undertaken on the Borrowdale Volcanic Group (BVG) and the Windermere super group (WS) in the southern Lake District. This study has been conducted to provide further work towards the understanding of the BVG's emplacement and the depositional environments of the WS. Formal unit descriptions and stratigraphic columns are compiled from field data and accompanied by stereonet, cross section, and thin section analysis. Numerous depositional features, including asymmetric ripples and aligned clasts, found within the BVG are supportive of a sub aerial and lacustrine setting for emplacement. Bow tie fiamme and rheomorphic flow structures also hold similar implications, by the necessity of heat input, to the environment of emplacement. An unconformable contact between the WS and the BVG is concluded by observations of parasitic folds passing below the WS at High Pike Haw. This is further supported by bedding anomalies uncovered by stereonet analysis. Four transgressions are linked with the deposition of the WS and show correlation with eustasy fluctuations and global cooling events, including the Hirnantian glaciation. Southward verging, open folds through Low Long Beck predate WS deposition and hold similarities with pre-Bala folding. A D2 folding event occurred post deposition to produce isoclinal folding along Dow Crag and a slatey cleavage throughout both units.

Introduction and study aims

Introduction

This report provides a description of structures, lithologies and mineralogies comprising the Borrowdale Volcanic Group and the Windermere Supergroup of the Lake District, northern England. A geological map and structural cross sections have been produced in tandem with stereonet analysis to develop further knowledge towards the nature of contact between the two units and the timing of tectonic events. Ancient depositional environments and proceeding climatic events are proposed with aid of thin section analysis and construction of unit descriptions with stratigraphic columns. Thus, this paper delivers further work towards the understanding of Britain's early Palaeozoic volcanism and the proceeding climatic and sea level changes.

Geological setting

The Lake District, northern England holds a lower Palaeozoic sequence defining an inlier of 2600km^2 surrounded by upper Palaeozoic rocks. The inlier is conventionally divided into three, south east younging, subdivisions. The lower Ordovician Skiddaw Group (SG) is the oldest unit and described by Millward *et al*., (2000) as a deep water, mud dominated turbidite sequence of 2-3km thickness. This lays beneath the 8km thick middle Ordovician, Borrowdale Volcanic Group (BVG) of basalts, rhyolites and pyroclastic rocks (Millward *et al*., 1994). The overlying Windermere Supergroup (WS) rests unconformably above and is composed of late Ordovician and early Silurian marine siliciclastics (Kneller, King and Bell, 1993). A fourth sequence has also recently been described, the Eycott Volcanic Group (EVG) (Downie and Soper, 1972), it includes andesitic lavas and tuffs which form a conformable relationship between the SG below and the BVG above.

The depositional settings and structural styles of the BVG and the WS have been debated extensively by various authors for over a century. Palaeomagnetic and faunal evidence (Fortey and Cocks, 1991) derived from trilobite and graptolite biofacies suggest the Avalonian continental terrane sat on the NE flanks of Gondwana, in a high southerly latitude during the Ordovician. Milward et al., (2000) and numerous others propose rifting followed which was consequently met with deposition of the SG on the continental shelf of Avalonia in the Iapetus ocean. Subduction of the ocean proceeded during NW migration of Avalonia, producing extensive volcanism and depositing the BVG. Subduction ceased in the mid Caradoc, but an accretionary prism was formed on the margin of Laurentia from continued subduction in the north west, (Kneller, King and Bell, 1993). At tropical latitudes the Iapetus ocean terminated and the Avalonian plate was underthrust beneath the prism to create a foreland basin on the Avalonian side of the suture, this was later filled with deposits of the WS (Soper and Woodcock 1990). An orogenic belt formed along the suture, producing a NESW striking band of Caledonides through northern England, Greenland and NE America.

The depositional environment and history of the WS and BVG is underpinned by our interpretation of plate migrations and interactions throughout the lower Palaeozoic. Our understanding of timing and manner of plate movements is largely drawn from structural and palaeontological evidence contained within the inlier's strata.

Therefore, field studies of the area provide invaluable evidence towards our knowledge of Britain's geological history and its nature of Palaeozoic volcanism.

Study aims

Abundant research has been undertaken over many fields of study within the BVG. However, the Windermere supergroup has attracted considerably less attention from workers and as a result shows greater opportunity for further work to be conducted. This paper brings forward new observations of lithofacies associations, structures and fossils within the WS, holding evidence to three transgressive events within the sequence. These events are interpreted through stratigraphic relations, direct field observations and mineralogical variations throughout the sequence. Correlations are proposed with global sea level fluctuations, to aid understanding of the timing and nature of events that lead to the deposition of the supergroup. Further study of the BVG is also provided, including new evidence for pre-Bala folding and proposals for the palaeoenvironment of BVG deposition. Structural interpretations leading to isoclinal folding through Dow Crag and Brown Pike are discussed, with further evidence provided for gentler folds through Low Long Beck. Conclusions derived from both volcanic and sedimentary interpretations are integrated with hypothesis from previous authors' work to construct a tectonic and depositional history of the area.

Study area and research methodology

Study area

Sedimentary, igneous and pyroclastic rocks laying immediately west of Coniston and Torver are the subject of study for this paper. The villages are located 160km north of Liverpool, on the NW coast of England (Figure 2.1). The mountainous terrane displays U-shaped valleys with steep ridges holding peaks up to 800m. The area has good access via footpaths, roads and car parks all year round and most areas do not require permission from landowners.

Exposure is at its best in the areas north of Walna Scar Road, this rapidly declines further south-east towards the two villages as vegetated and boggy terranes become more prevalent. The igneous and pyroclastic rocks in this study are situated in the north eastern, well exposed regions of the mapped area (Figure 2.1). Further south west, exposure and elevation decreases, this is met with the presence of the siliciclastics. Primary focus was applied to the area surrounding the contact between the BVG and the WS along Walna Scar Road (GR:28000,96700). This holds key data for interpretation of the palaeoenvironment and the relationship between the two units. However, considerable data has also been recorded from large peaks in the area including Dow Crag, Brown Pike and The Old Man (Figure 2.1) due to the excellent exposure present.

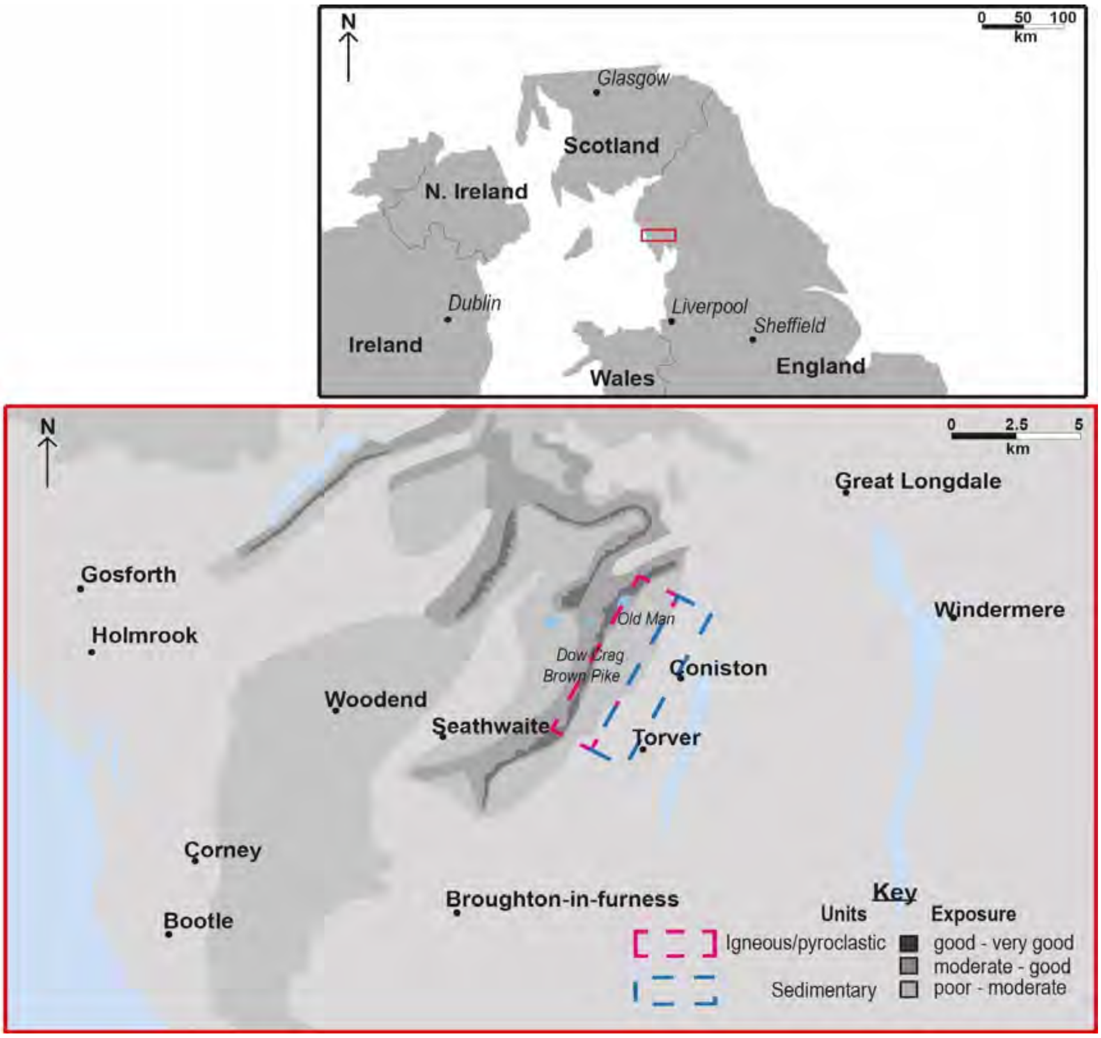

Figure 2.1 A location map for the area of study for this paper. The area constitutes the southern regions of the Lake District, 80km south of the Scottish border.

Research methodology

An area of 12km² was geologically mapped west of Coniston and Torver between Bleaberry Haws (GR:26500,94500) in the south west, and Levers Water (GR28000, 99400) in the north east over a period of 28 days.

Traditional geological equipment provided a cost effective and efficient means of data acquisition. Ordinance Survey maps were used to create field slips of the recorded data, which were plotted over standard British National Grid coordinates within the grid square SR. Ordinance Survey explorer maps also provided additional information on open access land and footpaths. Location positioning was acquired through a GPS tracker and photographs were taken with a camera to provide supporting evidence for field data and interpretations. A compass clinometer measured all structural data recorded and hand samples were gathered with a geological hammer, where clean surfaces were unavailable. The samples were later processed for additional thin section analysis under a microscope. Lithological and mineralogical properties were described using a hand lense, and carbonate proportions throughout the sedimentary succession were estimated using 5% hydrochloric acid.

A combination of traverse and outcrop mapping was employed to map formations of the area with dependence on exposure, vegetation and outcrop nature. Typically, traverses were undertaken for most sedimentary units due to linearity of the boundaries and restriction of outcrops to river sections. This aided construction of cross sections and stratigraphic columns but restricted the accuracy of boundary placement through well vegetated areas. As a result, many sedimentary boundaries are inferred but structural drawings and interpretations are well supported by linear, systematic field data. Green pen outcrop mapping was well suited for the large, disjointed outcrops of the igneous terrain. The units are well exposed, but the nature of deposition has caused poor lateral continuity throughout. Outcrop mapping mitigated the lack of continuity and still allowed for accurate boundary placement. However, larger scale correlation of boundaries, and structural drawings were hindered resulting from the lack of systematic outcrop localities. Therefore, this allowed for ample structural and lithological data to be acquired through a wide spread of the area but hindered the accuracy of data correlation between areas.

A variety of folds and faults were interpreted by bedding, cleavage and lineation data. Direct observations of folding were limited to parasitic folds, meaning the presence of large scale structures is based solely on data interpretation. Fold traces were incorporated into unit boundary placement, separating formations based on lithological and mineralogical properties. Sedimentary structures and fossils were measured, drawn and analysed before being used for paleoenvironment reconstruction. Few fossils were found throughout the sedimentary succession and those identified were correlated up to suborder. Fossils were unrecorded throughout the volcanics but sedimentary features abundant in both units were photographed with relevant attributes measured. Outcrops holding the best representation of the formation were assigned as a type locality and are recommended sections to visit when studying the area.

Stereonet, thin section and cross section analysis was undertaken in combination with the construction of graphic logs and stratigraphic columns. Stereonet analysis was derived from bedding, cleavage and lineation data to produce an interpretation of dip, plunge and interlimb angle of numerous folding styles. This was then integrated into a structural cross section to describe a fuller picture of the subsurface geology. Thin sections were produced from field hand samples and observed under 4, 10 and 40 times magnification to produce detailed mineralogical descriptions. Traverses, graphic logs and outcrop descriptions gathered in the field were then utilised to construct scaled stratigraphic columns of both units. This underpins correlation with other stratigraphic schemes. Palaeoenvironment interpretations in combination with structural styles and fundamental geological principles have been used to propose depositional environments of the area and where appropriate, provide correlation with past global events.

Field slips and data were processed with industry standard ArcGIS to produce a final top copy sheet displaying a map with cross sections, stratigraphic columns and stereonets.

Results

Formal unit descriptions of all formations recorded within the mapped area are compiled within this chapter. Thirteen formations are described in an order of oldest to youngest and a simplified stratigraphic column is provided for reference (Figure 3.1). Large and small scale features of each formation are described before providing a brief environmental interpretation, and a correlation with a BGS pre-existing scheme.

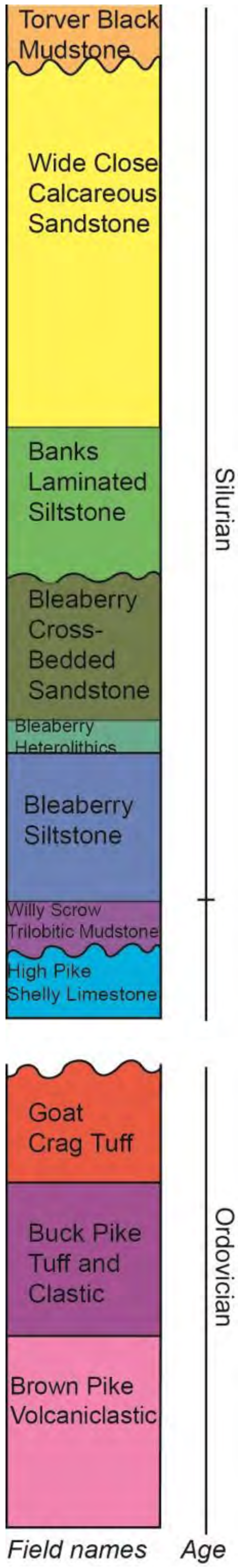

Figure 3.1 A stratigraphic column containing all formations recorded in the mapped area.

Brown Pike Volcaniclastic Fmt.

Area covered by unit

The Brown Pike Volcaniclastic Fmt. (BPV) forms the highest elevated outcrops in the area. It is commonly present at elevations between 600-750m along Dow Crag and Brown Pike and up to 800m atop The Old Man of Coniston. The formation also outcrops at lower elevations of 400m around Torver Bridge (GR: 27100, 96600), therefore displaying an overall disseminated outcrop pattern. Sizes of outcrops are typically small, with only 2-3m width on higher ground, although quarrying activity at lower elevations around Little Arrow Moor (GR: 27100, 97000) and Piked How can show localities up to 10m in height.

Approximate thickness

340m of thickness has been calculated from the unit's surface exposure and dip at Brown Pike (GR: 26000,96600).

Large scale features and subdivisions

At low elevations, for example Little Arrow Moore (GR:27200, 96950) larger outcrops up to 12m wide are common. Higher elevations are met with increased weathering and a decreased outcrop size, therefore Dow Crag and The Old Man both hold moderately-well weathered localities that are poorly exposed. A light-moderate grey colour is commonly observed, but tinges of green have been recorded atop of The Old Man. The unit displays a gradational fining up sequence best seen at Cove Hut (GR:27100,96770). Grain size increases from fine further south (GR: 27100, 96700) to med-coarse at Little Arrow Moore (GR: 27100,97000) over 300m. The formation consists of three recognisable members. The first, outcropping only west of Red Gill Beck (GR:25900,95500) has been faulted up through the top of the formation so it comes into contact with the Buck Pike Tuff and Clastic Fmt above, forming large cliff outcrops 10s of meters in height. The member consists of a fine cherty green rock, interpreted to represent a very fine variation of the volcaniclastic sandstone. The second member sits 150m below the top of the formation and represents only a metre of stratigraphic thickness, it shows small footpath outcrops best seen at GR:26140,96550 and is distinguishable by a discrete increase in grain size from fine-coarse to 30mm conglomeritic pebbles. The most stratigraphically and laterally abundant member forms the typical 2m outcrops of the formation consisting of a fine-medium volcaniclastic sandstone.

Features at outcrop scale
The formation commonly holds equidimensional outcrops between 2 and 10m showing two dominant morphologies. Massive, tabular rarely foliated outcrops persist in lower elevated areas such as Nettle Crag, these are moderately-well weathered and sit stratigraphically higher in the formation. The second morphology shows flaky, sheet like outcrops with a good cleavage, more commonly present at larger outcrops and best seen at Little Arrow Moore. The extent of weathering present on the formation's outcrops result in difficulty when locating individual beds.

Sedimentary features
The conglomeritic member displays an alignment of elongate grains (Figure 3.2) on the footpath to Brown Pike (GR: 26140,96550). The clast supported conglomerate shows a palaeocurrent of 342-162° produced by lenticular, angular clasts up to 30mm in width. Asymmetric ripples (Figure 3.3) have been recorded at Piked How Quarry (GR: 28150, 97350) within in the volcaniclastic sandstone member. An undulatory morphology holds a ripple index of 13.3 with a wave height of 9mm and a palaeocurrent at 002°.

Lithology
Moderately sorted, angular grains of medium size are common through most outcrops of the volcaniclastic sandstone member. However, lower elevations around Limestone Haws can show granular quartz and feldspar grains up to 3mm in width. Higher elevations associate grain sizes as small as 0.5mm along the Brown Pike ridge, before returning to medium sized at the highest elevation, atop The Old Man. Quartz is the most abundant constituent making up 50% of the grains along Dow Crag and Brown Pike. Feldspar and mica grains are also present, with abundancies commonly around 35% and 15% respectively, however, mica is exceptionally abundant along Brown Pike in concentrations up to 30%.

Interpretation
The BPV was deposited terrestrially, both sub-aerially and sub-aqueously. The asymmetric ripples at Piked How are the product of small waves propagating over the shallow northward shore of a large lake. The clast imbrication of the conglomeritic member is part of a gravel sheet from a braid bar, resulting from a southerly flowing braided river. Flow direction is interpreted by hypothesis of the braided river flowing towards the freshwater lake.

Age and correlation
The BPV can be correlated with the Seathwaite Fell Formation.

Type Locality
Piked How (GR: 28225,97148) due to the very good exposure, minimal weathering and asymmetric ripples present (Figure 3.3). Brown Pike (GR:26056,96571) also holds a good section displaying clast imbrication but is lacking in exposure.

Figure 3.2 *Brown Pike Volcaniclastic Fmt. GR: 26056, 96571.* Clasts of a volcaniclastic conglomerate showing a N-S alignment.

Figure 3.3 *Brown Pike Volcaniclastic Fmt. GR: 28173, 97398.* The type locality of the BPV showing a bedding surface of volcaniclastic sandstone displaying asymmetrical ripples.

Buck Pike Tuff and Clastic Fmt.

Area covered by unit

The Buck Pike Tuff and Clastic Fmt. (BPTC) displays a sinuous band of outcrops in the SW lower elevated areas around Furness. As elevation increases to 700m northwards, outcrops alternate with the BPV below in a repetitive manner and in the NE outcrops return to a lower elevation of 300m. Small footpath outcrops no wider than 2m are present at all elevations, however large cliff outcrops with dips up to 85° are present only at high elevations along Dow Crag. The unit typically shows moderate-good exposure with minimal weathering and as a result produces the highest proportion of outcrops in the mapped area, 23% of outcrops belong to the BPTC out of a total of 13 units.

Contact with the unit below

The BPTC forms a gradational contact with the BPV below. This is best seen along Walna Scar Road (GR: 26130, 96340) where medium grained volcaniclastic sandstone of the BPV becomes interbedded with lapilli tuff, marking the base of the BPTC.

Approximate thickness

280m, deduced form unit's surface exposure and dip at Furness (GR:26250, 96350).

Large scale features and subdivisions

Outcrops can be subdivided into four members. The lapilli tuff member is of the highest abundance (46% of formation exposure) with outcrops ranging from a minimum width of 4m to a maximum of 10m and bedding planes commonly in the form of ash layers 6cm thick. A medium-coarse volcaniclastic sandstone represents 20% of formation outcrops, these are well exposed and commonly well weathered, with widths up to 50m across Buck and Brown Pike. 18% of formation outcrops hold a very fine volcaniclastic sandstone member, they are moderately exposed showing massive rounded morphologies with beds ranging from 510mm of thickness. The final, least abundant member is ignimbritic, comprising 16% of exposures. These outcrops are concentrated in NE regions around the Bell and Dixon Scrow (GR: 29000, 97850), showing 7m wide outcrops with moderate weathering containing beds 15-20cm thick.

Outcrop scale features

The outcrops of the most abundant member commonly show heights of 3m and widths of 5m. SW outcrops around Torver High Common (GR: 26150,94850) show tinges of light and dark green whereas outcrops at Dixon Scrow in the NE are light-moderate grey in colour. Ash layers (Figure 3.4) are present at 18% of member outcrops, all of which are located at Torver High Common. The med-coarse volcaniclastic sandstone member forms very long outcrops up to 10m in height. Its shows a cleavage but has poorly developed beds of light grey colour. The fine grained volcaniclastic member shows taller and thinner outcrops commonly 5m in height and are light green-light grey colour. Outcrops from this member are often observed to grade into the med-coarse member, this is especially prominent on Buck Pike (GR: 26130,97110). The ignimbrite member displays short wide outcrops holding long voids of weathered out fiamme up to 6cm in length (Figure 3.5).

Sedimentary features

The lapilli tuff member shows normal grading of lithic fragments 2cm in diameter surrounded by inversely graded pumice fragments, in turn overlain by ash deposits 1cm thick (Figure 3.4). These are best seen at High Pike Haw (GR:26140,94850). In the same area chute and pool structures (Figure 3.6) can be found within the lapilli tuff member. The structures are surrounded by inversely graded lithics of 0.5cm diameter and show a palaeocurrent of 185°. The lapilli tuff member also displays a truncation of cross-lamination at The Bell (GR: 28790, 97790) with a height of 50cm (Figure 3.7) and representing a palaeocurrent of 130°. Fiamme (Figure 3.8-Figure 3.10) show widths of up to 6cm with 3cm of height and rheomorphic flow structures (Figure 3.11) are readily abundant within the ignimbrite member.

Lithology

The lapilli tuff member shows a rough external appearance made up of lithic fragments and lapilli, lithic fragments range from 10-30mm in diameter and the latter can be up to 105mm (Figure 3.12), as seen at Dixon Scrow. Internal mineralogies consist of subhedral, 12mm phenocrysts of biotite, 1mm quartz crystals and 1-2mm crystals of feldspar all surrounded by an aphanitic green matrix and representing a dacitic composition. The medium grained volcaniclastic sandstone member shows sub angular to angular, moderately sorted grains of quartz, feldspar and mica. Quartz is most abundant ranging from 20-50% at 1-2mm, with feldspar grains approximately 1.5mm commonly making up 30% and 1mm mica grains equating to 20%.

Interpretation

Large lithic fragments found within the lapilli tuff member suggest origination from the lateral blast of a large explosive eruption. The fragments are poorly bedded, and the surrounding matrix holds current structures (Figure 3.7) indicating deposition from a sub aerial pyroclastic density current. Fiamme with a bow tie morphology (Figure 3.10) were observed at Flask Brow (GR: 27095, 95914), however, wispy ended morphologies typically showed a more systematic occurrence (Figure 3.9). Rheomorphic flow structures (Figure 3.11) found at High Pike Haw cannot have formed subaqueously due to the prolonged heat required for production. Therefore, evidence holds to suggest this unit was deposited predominantly subaerially.

Correlation and age

This formation can be correlated with the Lincomb Tarns Formation of the Ordovician.

Type locality

High Pike Haw (GR:26153,94862) due to its abundancy of outcrops displaying typical lithologies and holding significant sedimentary structures (Figure 3.4).

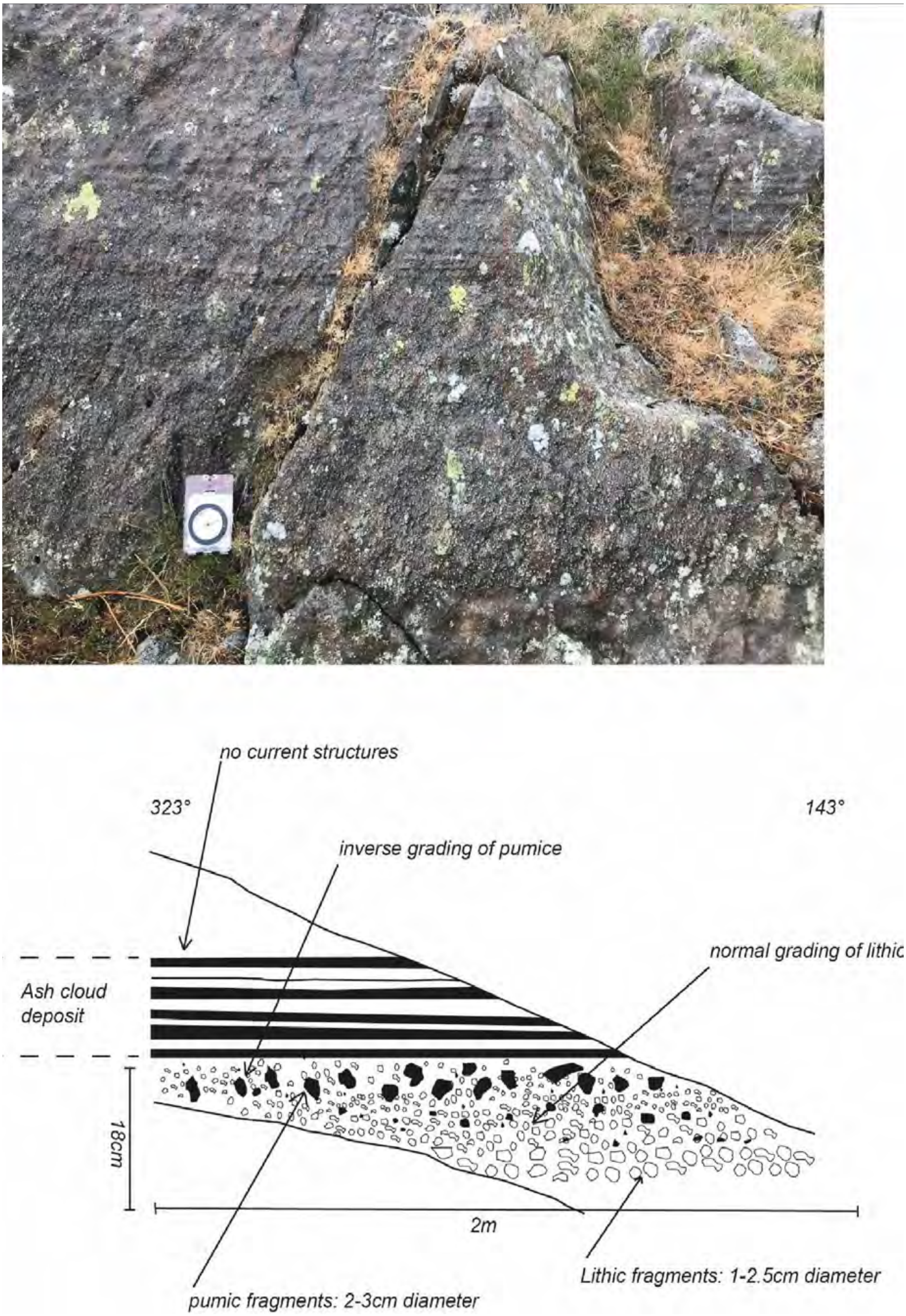

Figure 3.4 *Buck Pike Tuff and Clastic Fmt. GR: 26114, 94863.* A geological sketch accompanying a field photo of an ignimbrite flow unit recorded at High Pike Haw (GR: 26123,94849). Chosen as the type locality for the BPTC.

Figure 3.5 *Buck Pike Tuff and Clastic Fmt. GR: 25749, 95925.* Moulds of weathered out fiamme present in the ignimbrite member, the largest being 6cm in width.

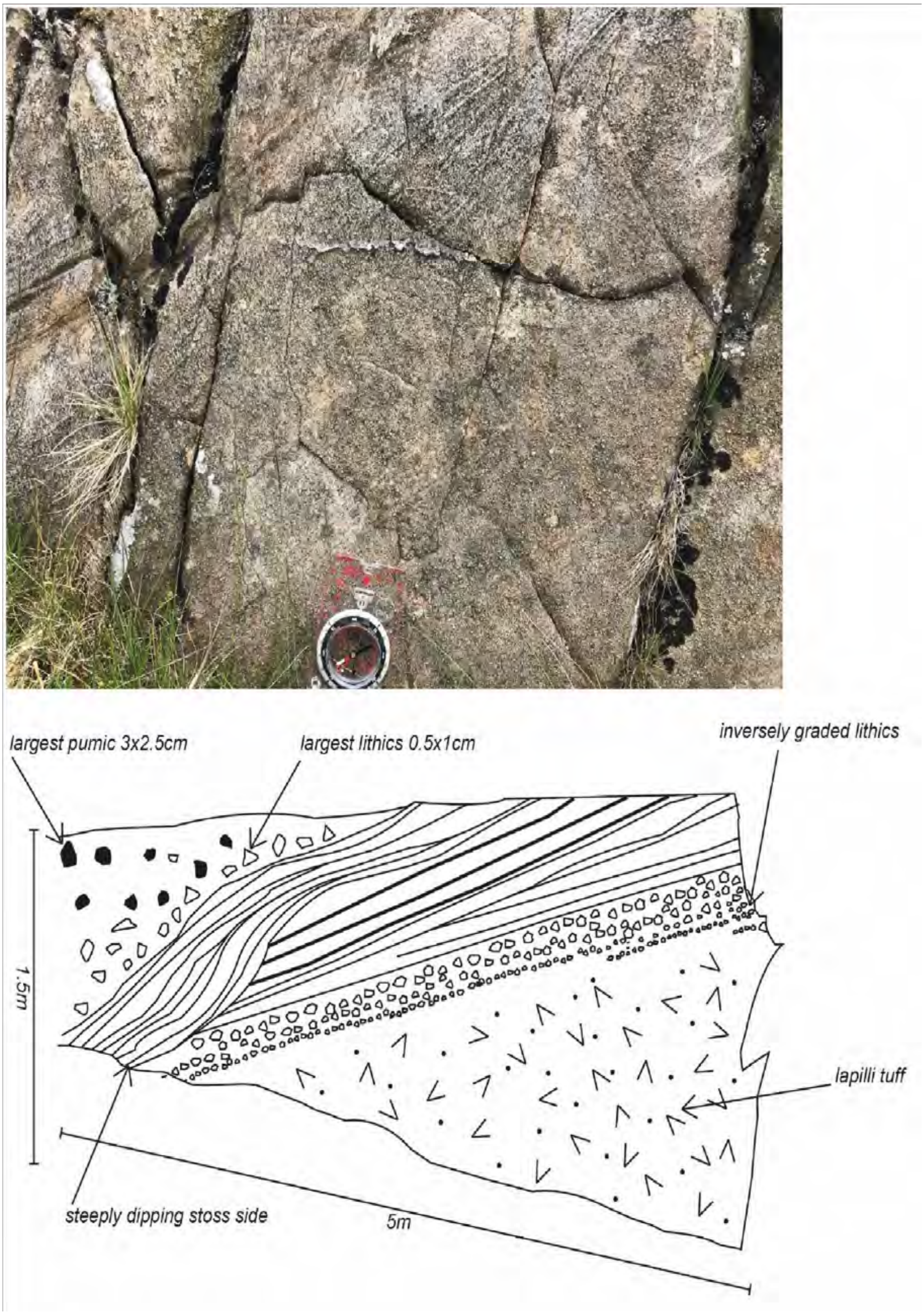

Figure 3.6 *Buck Pike Tuff and Clastic Fmt. GR: 26214, 94863.* Geological sketch accompanying a field photo of a chute and pool structure with a palaeocurrent of 185° observed in the lapilli tuff member.

Figure 3.7 *Buck Pike Tuff and Clastic Fmt. GR: 28909, 979903.* A field photo showing a truncation of cross -lamination, representing a palaeocurrent of 130°.

Figure 3.8 *Buck Pike Tuff and Clastic Fmt. GR: 29085, 97953*. A field photo of the internal lithology of the ignimbrite member. Lense shaped fiamme describing eutaxitic textures are abundant, commonly 1cm in width.

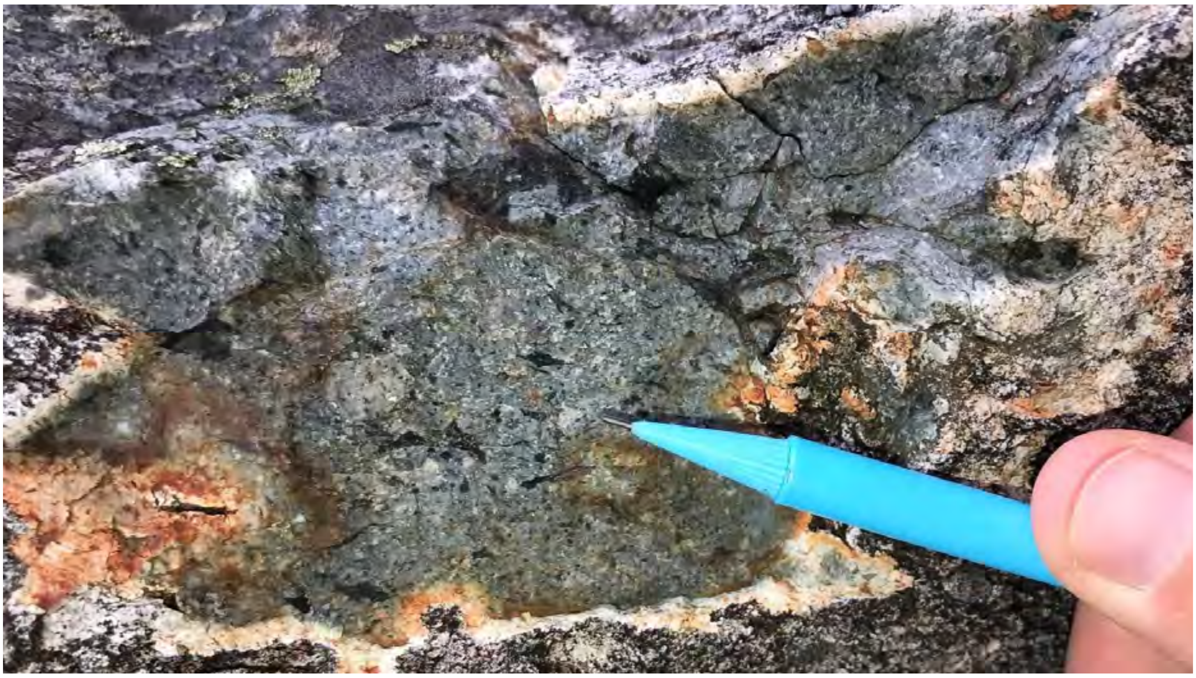

Figure 3.9 *Buck Pike Tuff and Clastic Fmt. GR: 29075, 97984.* A field photo showing the mineralogy of the ignimbrite member. Fiamme are present and range from 0.5-1cm in length.

Figure 3.10 *Buck Pike Tuff and Clastic Fmt. GR: 27053, 95925*. An ignimbrite hand sample holding fiamme structures of which some display a *bowtie* morphology.

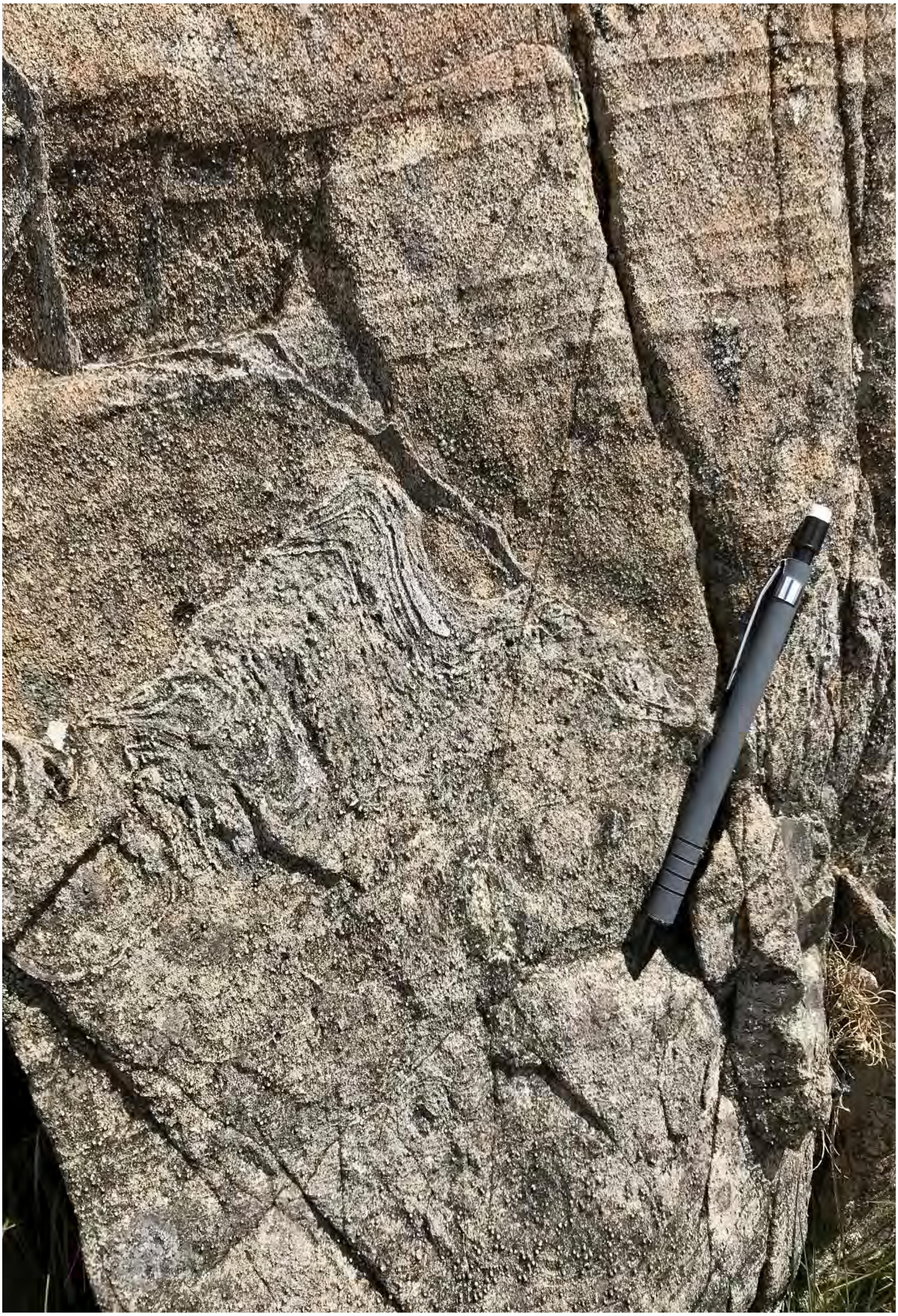

Figure 3.11 *Buck Pike Tuff and Clastic Fmt. GR: 26091,94895.* A rheomorphic flow structure shown as a band of small scale folds within the ignimbrite member.

Figure 3.12 *Buck Pike Tuff and Clastic Fmt. GR: 28734, 97845.* The lapilli tuff member shows outcrops with very large lithic fragment inclusions, up to 105mm in diameter.

Figure 3.13 *Buck Pike Tuff and Clastic Fmt. GR: 28903, 97897.* The lapilli tuff member shows outcrops with easily identifiable bedding planes.

Goat Crag Tuff Fmt.

Area covered by unit
The Goat Crag Tuff Fmt. (GCT) is dispersed thoroughly throughout the northern regions of the mapped area. Its speckled presence occurs predominantly at the lower elevated areas including Low Long Crag (GR:26750,95090) and the saddle of Dow Crag (GR: 33610,97750) both of which do not exceed an elevation of 550m. The lowest elevated occurrence is Timley Knot (GR: 28300, 97000) where it is exposed at only 350m. Outcrop widths commonly range from a minimum of 1m, exposed along the footpaths of Crowberry Haws (GR: 28370, 97700), to a maximum of 15m wide cliff sections at Coniston Fells (GR:28250,98750), typical widths however, are around 5m.

Contact with the unit below
The GCT forms a gradational boundary with the BPTC below. A walking transverse through Low Long Crag from GR: 26750, 96000 to GR: 26250, 96300 reveals the occurrence of volcaniclastic sandstone at GR: 26340, 96280 to mark the diffuse boundary. However, at Limestone Haws (GR: 27300, 9650) the GCT appears to lie directly on top of the BPV. This is due to combination of the unit pinching out towards the SE and faulting activity recorded at GR: 27940,96690.

Approximate thickness
170m, deduced from the formations surface exposure and dip at Furness.

Large scale features and subdivisions
The formation contains two members, lapilli tuff and ignimbrite. Ignimbrite members have the highest abundance in the NE regions of the mapped area, including Subthwaite Crag (GR:28450, 97920) and Boulder Valley (GR: 28050, 98600). This member produces very high outcrops of up to 15-20m in Crowberry Haws (GR:38360,98190). Bedding is poorly developed throughout the member and the only measurable planes are in the form of eutaxitic fiamme (Figure 3.14). The ignimbrite is the least abundant of the two members, only representing 22% of formation outcrops and lays stratigraphically beneath the lapilli tuff. The lapilli tuff member is present throughout most northern regions including Furness (GR:26450, 95710), Subthwaite Crag (GR: 28460,98000) and Goat Crag (GR: 26750, 97550), it commonly shows shorter outcrops than the member below, although they still exceed 6m in width. Bedding is poorly developed, however, cross bedding and lamination structures (Figure 3.15) observed at Torver High Common (GR: 26100, 95240) allow for reliable bed thickness's to be measured at 15cm.

Outcrop scale features
The ignimbrite members typically form tall cliff outcrops, show moderate weathering and are dark grey-black in colour. Fiamme are often 5-10mm in length (Figure 3.14) and offer the only reliable bedding indicator, cleavage however, is very prominent. Lapilli tuff shows much wider outcrops which are typically tabular and well fractured, as seen at Goat Crag, but can also take oval shaped morphologies more typical in Timley Knott (GR: 28380, 97090). This member commonly shows a very dark grey-black colour with a distinctively rough texture, in Subthwaite Crag green and blue tinges have also been recorded. The outside appearance is littered with lapilli fragments, lithic fragments and clast moulds. Lapilli sizes average around 15x17mm but blocks and bombs of up to 104mm (Fig. 3.16) can be found at Goat Crag.

Lithic fragments are commonly present at most outcrops and are commonly no larger than 35mm in width, although fragments up to 65mm where found at the Old Man Breast. Moulds of clasts although minimally abundant, can be up to 60mm as seen at Low Long Crag.

Sedimentary features
Cross laminated beds (Figure 3.15) are minimally present within the lapilli member. They can be seen at Low Long Crag, where they have a height of 75mm and show a palaeocurrent of 159°.

Mineralogy
In hand specimen the ignimbrite member shows well developed 5-10mm length fiamme (Figure 3.14) surrounded by a very fine grained matrix. Lapilli tuff commonly displays dacitic-rhyolitic composition (Table 3.1), dependable on the abundance of quartz present, with a phenocryst:martrix ratio of 25:75. Phenocrysts are typically euhedral, although subhedral has been recorded in some outcrops.

Table 3.1 Size and abundances of all phenocrysts recorded in hand specimen in the lapilli tuff member of the GCT.

	Min. abundance/%	**Av. abundance/%**	**Max. abundance/%**	**Min. size/mm**	**Av. size/mm**	**Max size/mm**
Qtz	10	25	40	0.5x1	2x2	3x3
Bt	25	27	30	9x4	5x7	2x4
Fspr	40	47	60	1x1.5	8x7	15x9
Hbl	15	20	30	1x2	2x2	2x3

Interpretation
The poorly bedded and very poorly sorted nature of the lapilli tuff and ignimbrite, in combination with the large variation of clast size is typical of a sub aerial deposition from an explosive volcanic eruption.

Correlation and age
This formation correlates with the Tarn Haws Fmt. of Ordovician age.

Type locality
Goat Crag (GR:26877, 97286) due to the very good exposure, minimal weathering and variety a grain sizes present typical of the formation (Figure 3.16).

Figure 3.14 *Goat Crag Tuff Fmt. GR: 28486, 97654*. Lenticular fiamme of approximately 5mm width forming a eutaxitic texture and allowing for bedding measurements to be taken, pencil lead 5mm long.

Figure 3.15 *Goat Crag Tuff Fmt. GR: 26143, 95118.* Small scale cross lamination within the lapilli member, showing a paleocurrent at 159°

Figure 3.16 *Goat Crag Tuff Fmt. GR: 26991, 97407*. Large lithic fragments and bombs can be found within the Lapilli member, this outcrop represents the type locality for the formation due the outcrops good exposure and presence of all clast sizes found within the formation.

High Pike Shelly Limestone Fmt.

Area covered by unit
The High Pike Shelly Limestone Fmt. (HPSL) strikes NE-SW to form a relatively straight outcrop pattern, tracing the border of the uplifted peaks from Low Pike Haw (GR: 26000, 494500) to Willy Scrow (GR: 29330, 97450). The base of the unit shows very good exposure, but the middle and top are less well exposed due to extensive vegetation. Surface exposure ranges from a minimum of 80m at Low Pike Haw resulting from steeper dips of 71° up to 160m where smaller dips and normal faulting are present at Torver Bottom (GR: 26940,95590).

Contact with the unit below
The HPSL forms an angular unconformity with the GCT below (Figure 3.17 and Figure 3.18). This is best seen at Low Pike Haw (GR: 27091, 95891). Locally the HPSL rests at 71° SE on top of the GCT, dipping 31° S. The shallow dip of the GCT is the product of an open antiform of which the HPSL is emplaced on the south eastern limb. SE trending normal faults displace the contact at Flask Brow (GR:

27091, 95891) and Limestone Haws (GR: 28032,96739) with 25-35m lateral offsets and a 50° anticlockwise rotation of strike.

Approximate thickness
180m, deduced from the unit's surface exposure and dip at Torver High Common (GR: 26550, 95150).

Large scale features and subdivisions
The HPSL can be split into two members defined by the degree of weathering. The two members are interbedded with each other at a ratio of 5:2, poorly weathered:well weathered and hold bed thickness of 22cm and 11cm respectively (Figure 3.19). Outcrops are typically large, well weathered and hold moderate-good exposure with 6m of height and 12m wide, but outcrops can reach 50m in width around Timley Knott (GR: 328850, 97120).

Outcrop scale features
The poorly weathered member commonly shows a dark navy blue-black colour with individual beds recognisable from selective weathering taking place within the member (Figure 3.20). Beds range from laminations of 2mm thick (Figure 3.21) to well defined beds 4.5cm thick. Large pock marks and eroded nodules can be observed within the member, and represent discrete zones of increased mica contents ranging from diameters of 1-15cm (Figure 3.22). Where mica content is high enough, discrete zones may be completely weathered out, forming the new well weathered member. The well weathered member is light-moderate grey with a high vitreosity produced by a mica content of 25% (Figure 3.23) and is well vegetated as a result of its high concentration of calcium carbonate (Figure 3.24).

Sedimentary features
The poorly weathered member holds fine, planar lamination 1-3mm thick (Fig. 3.21) best seen at Limestone Haws (GR: 28158,96888). Scoop shaped cross bedding (7cm thick) with a tangential base showing a palaeocurrent of 195° can be observed at Timley Knott (GR:
28853, 97123).

Lithology
The well weathered member shows moderately rounded and well sorted fine sand sized grains (Figure 3.23) of 80% quartz and feldspar, and 20% mica. It is very calcareous, fizzing vigorously with HCL. Larger, medium-coarse grains rarely coat the outside (Figure 3.25), which give a metallic lustre with a cuboidal shape and bare resemblance to chalcopyrite. The poorly weathered member shows a similar grain size and composition but does not hold as much calcium carbonate, indicated by the less intense fizzing of HCL.

Fossil content
The well weathered member exposes various sizes of brachiopods and shelly fossils (Figure 3.26- Figure 3.28) at Limestone Haws (GR: 28158, 96888), in the same bed a death assemblage of shelly fossils and other marine organisms has been observed.

Interpretation
The shelly fossils and lamination suggest deposition took place in a low energy lagoonal environment of a carbonate atoll. The deposit may be classified as a fossiliferous biomicrite and indicates a high terrigenous clastic supply.

Correlation and age
Dent Group of Ordovician age.

Type locality
Limestone Haws (GR: 28158, 96888) due to very good exposure and presence of fossils and sedimentary structures (Figure 3.29).

Figure 3.17 *Buck Pike Tuff and Clastic Fmt. GR: 26042, 94572.* The last exposed beds of the BPTC. A small synform hinge is located 1m to the right of the hammer, 5m south east of the hammer the beds form an anticline before shallowly dipping beneath the marine strata.

Figure 3.18 *The High Pike Shelly Limestone Fmt. GR: 26042, 94572* The valley marks the angular unconformity. 5m SE of the valley, marine strata dip steeply to the south east and 5m NW of the valley sits a shallowly dipping, SE limb of an open anticline.

Figure 3.19 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* The pencil marks the extent of beds from the well weathered member.

Figure 3.20 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* Weathering can also bring out individual beds of the poorly weathered member.

Figure 3.21 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* Laminations 2mm thick are abundant in poorly weathered member

Figure 3.22 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* The poorly weathered member holds large eroded nodules from discrete zones of increased weathering.

Figure 3.23 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* The well weathered member shows sand sized grains with high mica contents up to 20%.

Figure 3.24 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* The well weathered member holds substantially more vegetation than its poorly weathered counterpart, the vegetation allows the member to be traced laterally across the outcrop.

Figure 3.25 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* Cuboidal grains with a metallic lustre can be observed coating the outside of the well weathered member.

Figure 3.26 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* A convex up 1.5cm length bivalve shell within the well weathered member.

Figure 3.27 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* A shelly fossil with a diameter of 6mm contained within the well weathered member.

Figure 3.28 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* A very small shelly fossil with a diameter of 3x1mm found within the well weathered member

Figure 3.29 *The High Pike Shelly Limestone Fmt. GR: 28154, 96905.* The type locality for the HPSL, located at Limestone Haws and chosen for its presence of sedimentary structures, fossils and both members.

Willy Scrow Trilobitic Mudstone Fmt

Area covered by unit
The Willy Scrow Trilobitic Mudstone Fmt. (WSTM) lies in low marshlands at an elevation of 270-300m. It forms a NE-SW striking band approximately 100m wide, stretching from Low Pike Haw (GR: 261000, 9445) in the SW to Willy Scrow (GR: 29090, 97250) in the NE. The band shows a minimum width of 90m at Low Pike Haw, a product of a locally steeper dip of 71°. It shows a maximum width of 140m at Torver Bottom where a shallower dip of 46° has occurred locally by fault block rotation of normal faulting. The unit shows poor exposure throughout the mapped area, except for 4-8m high river sections present at Eddy Scale (GR:27750, 96000) and Ash Gill Beck (GR: 26910,95350).

Contact with the unit below
The WSTM forms an unconformable, transgressive contact with the underlying HPSL, deduced from the discrete increase in grainsize and lithology, stratigraphic relationship with overlying formations, and lack of evidence for appropriate faulting. This is best seen at Eddy Scale (GR: 27554, 96185) where the inferred contact has the smallest margin of error due only to 4m of grassy vegetation striking with the contact (Figure 3.30).

Approximate thickness
80m, based on the unit's surface exposure and dip at Eddy Scale (GR: 27754, 96185).

Large scale features and subdivisions
No subdivisions of the WSTM can be made as the unit appears homogenous throughout, the only exception being the interbedded deposits of the unit above at the contact. Low levels of weathering are present throughout the formation, making it particularly identifiable from the unit below.

Outcrop scale features
Outcrop localities are mostly confined to river channels transecting SE through the unit. These produce outcrops commonly exceeding 100m in length and providing at least 75m of stratigraphic thickness. Other localities include disused quarries, which provide exposures exceeding 10m in height with very low weathering. Outcrops show a dark grey-black colour (Figure 3.31) and hold well defined, sharp bedding contacts, resistant to weathering. Bed thickness is typically 40cm, but ranges from 26-90cm.

Sedimentary structures
Lamination is present throughout the unit and is best seen at The Rigg (GR:28144, 96641) where alternating grey-dark grey bands of 2mm are displayed (Figure 3.32).

Lithology
The unit is not calcareous, and beds are made up of well sorted fine silt-mud. The clay minerals show a dark grey-black colour when weathered but unweathered surfaces are more commonly moderate-dark grey.

Fossil content
WSTM is moderately fossiliferous, with the highest abundance of fossils found in scree deposits at Torver Bottom (GR:27113, 95284). All fossils found were disarticulated, many were unidentifiable but a fragment of a trilobite's pygidium (Figure 3.33) was recorded and correlated to be the suborder *Phacops.*

Correlation and age
Skelgill formation, Stockdale group of Ordovician age.

Interpretation
The dark grey-black colour indicates conditions with poor oxygen circulation, and the fine grain size is a product of very low energy conditions. The fragmented fossil suggests reworking from deposits of originally shallower depths. The formation therefore represents the offshore neritic zone of 150-200m water depth.

Type locality
The river channel at Eddy Scale (GR: 27605, 96175) due to very good exposure through the whole unit and presence of lamination and contact with unit above (Figure 3.34).

Figure 3.30 Willy Scrow Trilobitic Mudstone. GR: 27554, 96185. The hill outcrop in the left side of picture holds the HPSL at the rear of the hill, and the WSTM at the front (towards the photographer), the contact hidden only by 5m of vegetation. The valley running down to the right of the hill outcrop is the product of a fault, and to the right of this fault lays another hill outcrop (right side of picture). This outcrop holds only WSTM.

Figure 3.31 *Willy Scrow Trilobitic Mudstone. GR: 28144, 96641.* Two hand samples, HPSL in the left and WSTM in the right. WSTM holds a dark grey-black colour, one of the properties making it distinguishable from HPSL's light-moderate grey colour.

Figure 3.32 *Willy Scrow Trilobitic Mudstone. GR: 27620, 96104.* Typical lamination observed throughout the formation. Alternating dark grey and grey bands with 2mm of thickness.

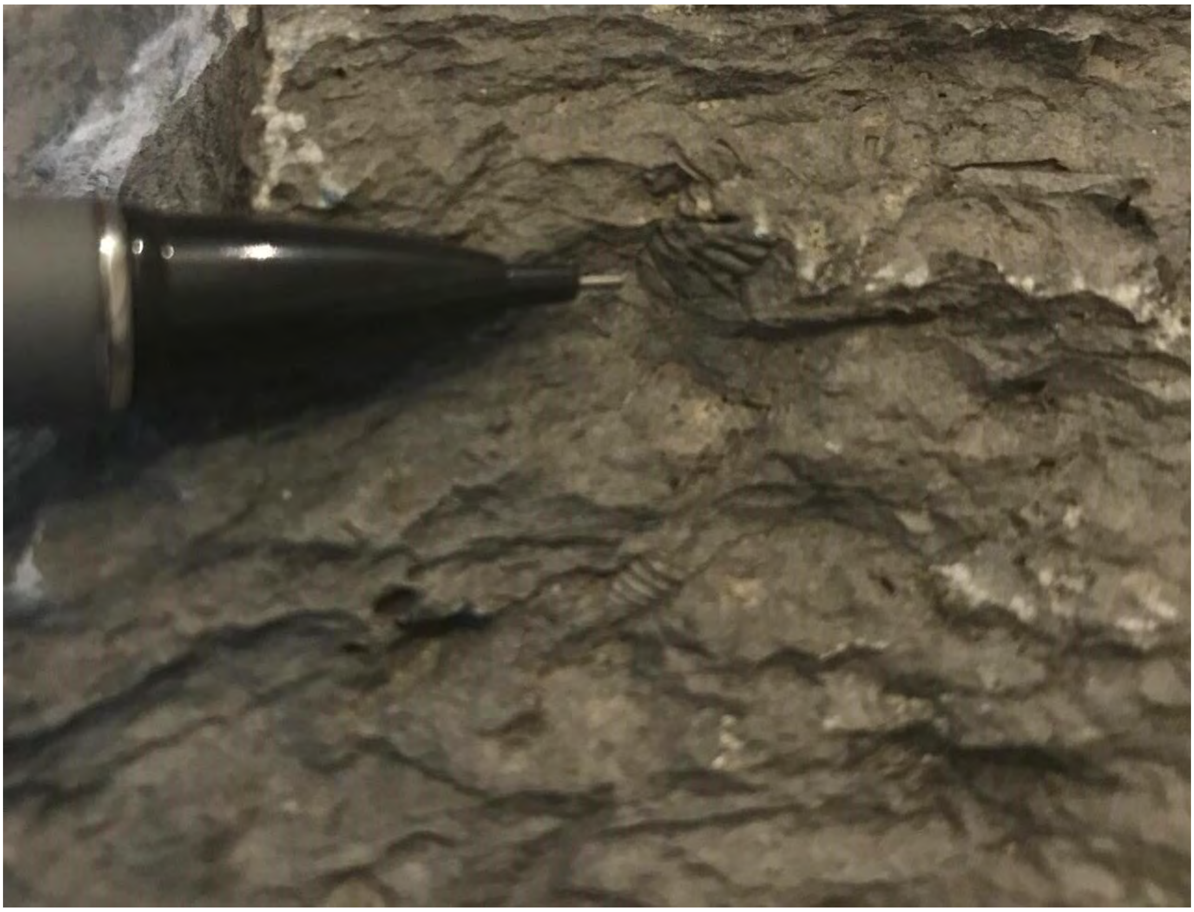

Figure 3.33 *Willy Scrow Trilobitic Mudstone. GR: 27183, 95673.* Disarticulated trilobites contained within scree deposits of the WSTM. The most recognisable being a pygidium fragment placed in the middle of the picture, directly below the pencil lead.

Figure 3.34 *Willy Scrow Trilobitic Mudstone. GR: 27596, 96124.* A river section representing the type locality for the WSTM. Chosen due to very good exposure and minimum weathering, with the full formation being visible along the river.

Bleaberry Siltstones Fmt.

Area covered by unit
The Bleaberry Siltstones outcrop in a NE widening band in the wet marshlands from Torver Plattocks (GR:26632, 94245) to Banishead (GR:28456, 96492). The unit strikes NE-SW and runs parallel with the unit below. The unit's surface exposure varies from a minimum of 170m in the SW as it pinches out between the units above and below, to a maximum of 440m in Banishead, where it dips at a shallower angle of 48°. The well cleaved morphology (Figure 3.36) and resulting low competence of the rock dictate its sensitive susceptibility to weathering. This in partnership with the well vegetated land surrounding the unit allows for poor exposure inside the mapping area. The unit therefore, is best displayed at river cross sections.

The contact with the unit below
The unit progressively fines towards the base until it becomes interbedded for 50m with WSTM below (Figure 3.35), this is best seen in the Torver river channel (GR: 27670, 96110). However, faulting observed at Eddy Scale (GR: 27554, 96185) has bought down the Bleaberry Siltstones to such a depth that it is in contact with the HPSL. This is also met with a locally eastward swing of strike.

Approximate thickness
260m, deduced from the unit's surface exposure at Banishead (GR: 28480, 96450).

Large scale features and subdivisions
A coarsening up cycle from fine-med silt at the base of the unit observed at Banishead (GR: 28150, 96500) and Summers Cove Beck (GR: 27737, 95993) to coarse silt-fine sand at the top of the succession, visible at Bleaberry Haws (GR:

26734, 94932) and Banishead (GR: 28383, 96392), is the dominant feature of the unit. The BS is the second largest siliciclastic unit mapped. It seldom shows outcrops taller than 1.5m except for river sections where they can reach 4m tall, with bed thickness ranging from 30-47cm with an average of 40cm.

Outcrop scale features

The outcrops have poor-very poor exposure with widths rarely exceeding 2m. The outcrops are generally well weathered and enclosed by grassland to give a patchy and inconsistent scattering parallel to strike (Figure 3.37). However, dried river channels allow much greater widths, commonly 10s of meters with two cross section views being provided. Bedding contacts are poorly defined and show ambiguity with fracturing or water erosion is commonly encountered, but where identifiable they are sharp and straight. The prevalent weathered colour of the unit is of smoky grey, but fresh surfaces reveal a dark, denim blue.

Sedimentary features

The formation lacks bioturbation but holds prominent 2-3mm, grey and dark grey bands of lamination (Figure 3.38 and Figure 3.39). Ash layers are present throughout the succession and lay parallel to bedding with 20-30mm thickness (Figure 3.40).

Lithology

The formation consists of moderate to well rounded grains ranging from fine silt to coarse silt. They are well sorted and typically grey-blue in colour. The unit holds a very low mica content at 2% and is calcareous only in the top 35m of the succession. In some areas such as Banishead, the unit is not calcareous at all.

Interpretation

The dark colour of bedding, a result of low oxygen circulation, and the lack of carbonate material derived from shells, in combination with a lack of body fossils concludes an environment with poor life conditions. Suspension settling of the silts to form laminations represents that of a low energy, offshore environment, but with a shallower depth than the WSTM. Ash deposits suggest ongoing volcanic activity. Therefore, the depositional environment may be interpreted to that of the continental shelf of an active plate margin, offshore neritic zone of 75-150m water depth.

Correlation and age

This formation correlates with the Brathay Fmt. of Silurian age.

Type locality

Eddy Scale (GR:27894, 95936), due to its excellent exposure, minimum weathering and lamination structures present (Figure 3.41)

Figure 3.35 *The Bleaberry Siltstone Fmt. GR: 27596, 96124.* The compass marks a contact between the WSTM and the overlying BS. In this instance the WSTM is overlying the BS due to the interbedded nature of the contact.

Figure 3.36 *The Bleaberry Siltstone Fmt. GR: 28153, 96533.* The prominent cleavage and thinly bedded nature of the BS outcrops increase its susceptibility to weathering, resulting in very small, vegetated outcrops

Figure 3.37 *The Bleaberry Siltstone Fmt. GR: 26653, 94742.* The intense vegetation surrounding outcrops produces a disjointed, patchy outcrop pattern running parallel to strike.

Figure 3.38 *The Bleaberry Siltstone Fmt. GR: 28383, 96392.* Laminated bands are prominent throughout the formation. At the top of the formation however, lamination is only selectively present in finer grained beds.

Figure 3.39 *The Bleaberry Siltstone Fmt. GR: 27712, 95985.* Towards the base of the formation, lamination is much more abundant due to the fine grained nature of the deposits.

Figure 3.40 *The Bleaberry Siltstone Fmt. GR: 27613, 96021.* Ash beds are not common in the succession, but where present are 10-20mm thick. In this picture, the ash bed is running down diagonally right above the pencil lead.

Figure 3.41 *The Bleaberry Siltstone Fmt. GR: 2784, 95983.* The type locality for the BS. The section displays excellent exposure with minimum weathering with good cleavage and bedding surfaces.

Bleaberry Heterolithic Fmt.

Area covered by unit
The Bleaberry Heterolithic Fmt. (BH) displays a thin band of outcrops 80m wide laying at a low elevation of 200m and stretching from Bleaberry Haws (GR:26450, 9451) to Banishead (GR:28500, 96450) in the NW. Outcrop heights rarely exceed 1m except at river sections where exposures can reach 3m. High levels of weathering and erosion are present at most outcrops and are the primary reasons for a lack of vertical height at outcrops.

Contact with the unit below
The BH forms a gradational contact with the BS. The coarse silt of the unit below grades into discrete bodies of fine sand and fine-med silt, best seen at Torver river (GR: 27700, 96090).

Approximate thickness
120m, deduced from the unit's surface exposure at Long Haws (GR: 28730, 96440).

Large scale features and subdivisions
Sandstone and siltstone members are present at all localities in ratios of approximately 3:1 respectively, however, the stratigraphically lower outcrops have a higher abundance of siltstone. Bedding rarely exceeds 15cm, except at Bleaberry Haws (GR: 26410, 9440) where it can reach 65cm. Bed thickness ratios between the two members are commonly 5:1 and show gradational contacts. Well rounded and smooth morphologies of the sandstone member contrast with the siltstones sharp and angular exposures.

Outcrop scale features
Outcrops are consistently light grey in colour with individual beds of the same member showing straight and sharp boundaries. Bedding is also commonly weathered out, especially at outcrops around Bleaberry Haws (GR: 26140, 94140). Siltstone members commonly grade up to sandstone, resulting in difficulty for identification of individual beds, although slight colour deviations of grey-dark blue can make sandstone beds discernible from light grey siltstone beds.

Sedimentary features
Flame structures and ash beds (Figure 3.42) can be observed at Matthew Tranearth (GR:27220, 95000).

Lithology
Siltstone members are moderately calcareous throughout the succession and have mica contents ranging from 2% in the NE to 10% around Matthew Tranearth. Hand specimens show clay minerals make up the remaining +90% of the composition and rarely exceed medium silt. Sandstone members also show a moderate calcium carbonate content, which is at a maximum around Bleaberry Haws and shows less calcium carbonate at Matthew Tranearth and further NE. Grain size remains consistent at coarse silt-fine sand, composed of 20% mica and 80% quartz and feldspar, but in Bleaberry Haws grains up to 1mm are present. Lithologies represent that of a Greywacke.

Interpretation
The heterolithic formation represents an offshore transition environment, 50-75m water depth subjected to ongoing volcanic activity.

Correlation and age
This formation correlates with the Birk Riggs Formation of Silurian age.

Type locality
Matthew Tranearth (GR: 327232, 495012) due to the moderate exposure, with both members and sedimentary structures present (Figure 3.43).

Figure 3.42 *Bleaberry Heterolithic Fmt. GR: 27213, 95013*. An ash bed 22mm thick interbedded between siltstone beds.

Figure 3.43 *Bleaberry Heterolithic Fmt. GR: 27213, 95013.* This outcrop has been chosen as the type locality due to the moderate exposure and presence of ash beds and both members.

Bleaberry Cross-bedded sandstone Fmt.

Area covered by unit
The Bleaberry Cross-bedded Sandstone Fmt. (BCS) strikes NE-SW displaying a 3km wide band stretching from Torver Plattocks (GR: 26250, 94000) to Long Haws (GR: 29000, 96350) at an elevation no greater than 200m.Minimum outcrop widths occur in the SW (GR: 26293, 94013) at 5m, and is met with steeper dips of 45°. Greater exposure in the NE allows for larger outcrops with minimal weathering, compared to poorer exposure and moderate weathering in the SW.

Contact with the unit below
The BCS forms a gradational, conformable contact with the BH below. Long Haws (GR: 28670, 96390) best shows this, where fine-med silt and fine sand grades into fine-med sand, representing the BCS.

Approximate thickness
240m deduced from the unit's surface exposure at Little Arrow Intake (GR: 2830, 95940).

Large scale features and subdivisions
The BCS remains largely homogenous in both grain size and lithology, except for a 4m thick mudstone bed (Figure 3.44), best seen at Bleaberry Haws (GR: 26790,94520), transecting the formation almost equally in half. At the top of the formation, individual mudstone beds are interbedded with the prevalent sandstone member, showing a bed thickness of 8cm and commonly being the host of extensive weathering recesses. This member is only present for the top 5% of total stratigraphic thickness of the unit. The remaining 95% is represented by a thickly bedded sandstone, reaching up to 1.3m in SE regions.

Outcrop scale features
Sandstone members present the largest outcrops of the marine succession, with a maximum of 20m height and 35m width at Long Haws (GR: 28898,96132). They commonly show a massive, rounded morphology and are rough to the touch (Figure 3.45). A moderate-dark grey colour is characteristic of the member but tinges of blue and brown can be found at New Intake (GR: 28950, 96350). Bedding contacts are commonly eroded, to form both straight and disjointed lineations of a few centimetres thick. The mudstone member located at the centre of the formation also displays sharp bedding with minimal weathering. Towards the top of the BCS, the interbedded mudstone beds are light-moderate grey and single bedded with 8cm thickness.

Sedimentary features
Hummocky Cross Stratification (Figure 3.46 and Figure 3.47) is the most abundant structure in the formation. Located towards the base of the unit, it is best seen at Long Haws (GR: 28640, 96310), but poorer examples are also present at Bleaberry Haws (GR: 26750, 94600). Asymmetrical cross bedding is also present at Bleaberry Haws (GR: 26320, 94050), towards the centre of the unit (Figure 3.48), where current ripples show a palaeocurrent of 155° and young southwards. The top of the unit contains ash layers (Figure 3.49) and flame structures (Figure 3.50) at Long Haws (GR: 29000,28980) and at the very top of the unit symmetrical wave ripples are also present (Figure 3.51) within the mud member.

Lithology
The BCS is moderately sorted with a grain size ranging from very fine sand in the SW (GR: 26280, 94050) to medium-coarse in the NE (GR: 28898, 96132). It represents an immature sandstone with mica contents reaching 20%, quartz and feldspar grains equate for the remaining 80%. It is minimally carbonaceous in NE and SW extremities, but calcium carbonate concentrations are high in the centre of the mapped area, around Matthew Tranearth. The mudstone member located halfway through the succession is not micaceous but is carbonaceous with a grain size of mud-fine silt. The top of the succession holds highly micaceous (25%) mudstone beds that are not carbonaceous with a grain size of mud.

Interpretation
HCS, derived from storm and current reworking, at the base of the unit characterises an offshore transition environment, which then becomes the lower shoreface as wave and current action create cross bedding above the fair weather wave base. High mica contents suggest glacial transport produced the immature deposits. Very immature mud deposits at the top resemble turbidites. Volcanic activity ongoing.

Correlation and age
This formation correlates with Coldwell Formation of Silurian age.

Type locality
Bleaberry Haws (GR: 28898, 96132) contains the type locality (Figure 3.52) due to excellent exposure and abundance of sedimentary structures.

Figure 3.44 *Bleaberry Cross-bedded Sandstone Fmt. GR: 26850, 94567.* well cleaved, 4m thick mudstone member holding thin mudstone beds 10cm thick.

Figure 3.45 *Bleaberry Cross-bedded Sandstone Fmt. GR: 28977, 96422.* Sandstone members of the BCS show massive, rounded outcrops making them discernible from smooth, angular outcrops of the Wide Close Calcareous Sandstone Fmt.

Figure 3.46 *Bleaberry Cross-bedded Sandstone Fmt. GR: 28543, 96321.* Long Haws holds the best example of HCS. The structures hold a wavelength of 40cm with hummocks reaching 31cm in height.

Figure 3.47 *Bleaberry Cross-bedded Sandstone Fmt. GR: 26753, 94598.* Bleaberry Haws holds a poorer example of HCS, although hummocks and swales can be identified in the top right of the outcrop.

Figure 3.48 *Bleaberry Cross-bedded Sandstone Fmt. GR: 26213, 93952.* Undulatory ripples are best seen at Bleaberry Haws, here they show a wavelength of 15cm with a ripple index of 10, therefore representing current ripples aligned towards 155° and younging south.

Figure 3.49 *Bleaberry Cross-bedded Sandstone Fmt. GR: 28380,95980*. An ash layer 30mm in width embedded between two sandstone beds, recorded at Little Arrow Intake.

Figure 3.50 *Bleaberry Cross-bedded Sandstone Fmt. GR: 28898, 96132.* Flame structures and load casts between mudstone and sandstone members observed at Long Haws. They are well developed with 3cm of height t and 5cm of width, younging south.

Figure 3.51*Bleaberry Cross-bedded Sandstone Fmt. GR: 28898, 96132.* Symmetrical wave ripples with a linguoid morphology, observed at New Intake. They show a ripple width of 12cm and a height of 2.3cm, therefore containing a ripple index of 5.2.

Figure 3.52 *Bleaberry Cross-bedded Sandstone Fmt. GR: 28898, 96132.* On the left of the picture, the type locality for the BCS. To the right of the picture, the first outcrops of the overlying formation and the contact between the two running perpendicular down the middle of the picture. A3 mapping board for scale, on top of inferred contact.

Banks Laminated Siltstone Fmt.

Area covered by unit
The Banks Laminated Siltstone (BLS) begins in SW Torver (26500, 93250) and runs NE in a 330m wide band at an elevation between 230 and 300m towards New Intake (GR:29000,96000). Outcrop heights range from 1m in the SW up to 20m at New Intake in the north. Smaller outcrops in the SW correspond with dips of approximately 60°, which become shallower towards the NW to 45-50°. Poor exposure and extensive weathering is common in Torver but this gradually improves towards New Intake where exposure is very good and weathering minimal.

Contact with the unit below
An unconformable contact exists between the BLS and the BCS in the form of a transgressive surface (Fig. 3.52). Medium-coarse sand exists at the top of the BCS, which discretely drops to a fine-medium silt over a distance of 20m. Faulting was disregarded as no slickenfibres or strike alterations were present between the two formations.

Approximate thickness
265m based of the unit’s surface exposure and dip at New Intake (GR:28810, 95910)

Large scale features and subdivisions
The BLS shows no stratigraphic variations or counterparts to the unit, and represents one, well cleaved uniform body of fine-med silt. At the base of the succession around New Intake, larger outcrops up to 30m wide correspond with an increased bed thickness of up to 45cm (Figure 3.53), whereas smaller outcrops show a bed thickness of just 5cm. Outcrops through the middle of the succession are commonly

small, never higher than 1m with bed thickness ranging from 5-15cm thick. Towards the top of the succession outcrop widths can be as wide as 10m at Wide Close (GR:27650, 94640), but are commonly no greater than 3m and hold beds with 39cm of thickness.

Sedimentary features
Lamination (Figure 3.54) is abundant throughout the formation, and is best seen at Torver Banks (GR: 32740,94250) where alternating 6mm bands of dark, clay rich layers and light silty layers are coated with an orange band weathering.

Lithology
At the base of the formation the BLS holds a grain size of medium silt with high levels of calcium carbonate. The grain size increases minimally to coarse silt at the top of the succession and calcium carbonate levels fluctuate from low to moderate throughout the formation. Mica content shows a decrease from 10% at the base to 4% at the top with grains being well sorted throughout the formation

Interpretation
The BLS shows a higher calcium carbonate level than the BS below, suggesting a more productive ocean setting. Grain size and mica content indicate a less mature sediment than the WSTB. If the WSTB holds more mature sediment from a less productive ocean, then a more major transgression may be hypothesised between the WSTB and the HPSL. No ash deposits were found in this formation due either to a lack of exposure or cessation of volcanic activity.

Correlation and age
This formation correlates with The Wray Castle Fmt. of Silurian age.

Type locality
Torver Banks (GR: 32740,94250) due to moderate exposure, minimum weathering and lamination present (Figure 3.55).

Figure 3.53 *Banks Laminated Siltstone GR: 28898, 96132*. A very tall and wide outcrop of the BLS, characteristically showing and increased bed thickness with the greater outcrop width and height.

Figure 3.54 *Banks Laminated Siltstone GR: 28989, 96044*. Thin bands of lamination present within the BLS, an orange halo of weathering surrounds the darker, clay rich layers.

Figure 3.55 *Banks Laminated Siltstone GR: 28691, 95915*. The type locality for the BLS, the outcrop shows moderate exposure with minimum weathering and contains laminated beds, typical of the formation.

Wide Close Calcareous Sandstone Fmt.

Area covered by unit
The Wide Close Calcareous Sandstone Fmt. (WCCS) forms the widest NE striking band in the area with a width of 850m and laying at an elevation between 150 and 280m. Lateral extent covers SW Torver (GR: 27000,94000) through to Bleathwaite Pasture (GR: 29000, 95500) where it has the units minimum outcrop width of 3m and steeper dips of 63°. However, Bleathwaite Pasture also holds the largest outcrop at 10m wide with a finger like geometry stretching 200m along the flanks of a river valley (GR: 29000, 95400).

Contact with the unit below
The WCCS forms a gradational, interbedded contact with the formation below. The BLS coarsens from a medium to coarse silt whilst also becoming interbedded with medium sand of the WCCS, best seen at Bleathwaite Pasture (GR: 29000, 96500).

Approximate thickness
640m deduced from the unit's surface exposure and dip at Wide Close (GR: 27500, 94250).

Large scale features and subdivisions
The unit shows an overall coarsening up trend from fine sand at its base to medium-coarse sand at the top and contains two members. The first, stratigraphically lowest and most consistent member forms smaller outcrops 3-5m in width but holds the unit's largest bedding up to 105cm of medium sand at Bleaberry Pasture (GR: 29050, 95410). The second member becomes interbedded with the first in the top 400m of the unit. These outcrops can be the largest with widths up to 10m and holding sandstone beds 1m thick. However, bedding of the second member is much smaller with just 6cm of fine silt-mud and interbedded at a ratio of 2:11 mud:sand. The unit is poorly exposed throughout the area and holds moderate weathering with smooth, angular well fractured outcrops, but good exposure can be found SE of Bleaberry Pasture (GR:2900,95400).

Outcrop scale features
Lower sandstone members produce short, wide outcrops rarely higher than 2m and up to 10m in width (Figure 3.56). Typically, they are light-moderate grey but some outcrops show tinges of navy blue. Bedding contacts are commonly eroded out and replaced with streaks of vegetation 5cm thick, with the exception of Wide Close (GR:27580, 94270) where they are straight, sharp and minimally eroded. Bed thicknesses show a lack of variation at individual outcrops and rarely exceed a thickness range greater than 20% of the thickest bed present. However, in the SW corner of Bleaberry Pasture (GR:29010, 95410) bed thicknesses show the greatest variation with the largest being 100cm and the smallest 20cm. Interbedded members have relatively short heights no greater than 2m. These are dark grey, show good cleavage and possess vegetated contacts holding mudstone beds rarely exceeding 15cm. The well cleaved nature of this member creates a high susceptibility to weathering which is characteristic of the exposures at Bleaberry Pasture and around Torver village.

Sedimentary features
No sedimentary structures recorded, despite good exposure.

Lithology
Calcium carbonate has lateral variations throughout the unit. It is not present at localities in the SW around Torver village, but outcrops become increasingly carbonate rich NE towards Bleathwaite. Mica contents vary vertically and laterally throughout the formation. In the NE mica contents at the base of the formation are around 8%, decreasing to 4% towards the top. However, in the SW mica contents increase from 15% at the base up to 20% towards the top of the formation. Quartz and feldspar grains constitute the remaining 80% of the lithology, grain sizes show fine-medium angular sand at the base, grading up to medium-coarse sand towards the top.

Interpretation
The lateral variation of calcium carbonate suggests a lateral variation of calcite cement and dissolved calcareous debris, therefore providing a deficit of preserved fossils. A different mode of transport deposited the WCCS to that of the BCS, with maturity levels of the sediment within the WCCS indicating river transportation as opposed to glacial.

Correlation and age
This formation correlates with the Garthwaite Fmt. of the Silurian.

Type locality
Bleathwaite Pasture (GR: 29011,95470) due to good exposure, minimum weathering and both members being present (Figure 3.57).

Figure 3.56 *Wide Close Calcareous Sandstone Fmt. GR: 29011, 95470*. The sandstone member of the WCCS displays short wide outcrops rarely exceeding 2m of height.

Figure 3.57 *Wide Close Calcareous Sandstone Fmt. GR: 28300, 93950.* The type locality for the WCCS located at Bleaberry Pasture. Both members are present with good exposure and minimal weathering.

Torver Black Mudstone Fmt.

Area covered by unit
The Torver Black Mudstone Fmt. (TBM) outcrops only once in the mapped area, this being SW of Torver (GR: 27760,937670).

Contact with unit below
The TBM holds an unconformable, transgressive contact with the WCCS deduced by the discrete change in depositional environment and stratigraphic relations with lower units.

Large scale features
The outcrop describes a 3m high and 9m wide road cutting through a cliff, showing good exposure and moderate weathering. It is well vegetated and dark grey to black in colour, the outcrop shows a good cleavage and shows bed thickness's ranging from 8-12cm.

Sedimentary features
The formation is very well laminated with alternating black and grey bands of 2-15cm thickness (Figure 3.58 and Figure 3.59).

Lithology
In hand sample it holds dark grey-black, very well sorted clay minerals and is not calcareous.

Interpretation
Low energy offshore environment, with poor oxygen circulation.

Correlation and age
This formation correlates with The Latrigg Fmt. of Silurian age.

Type locality
500m SW of Torver (GR: 27760,93700), the outcrop shows good exposure and is well laminated (Figure 3.60).

Figure 3.58 *Torver Black Mudstone GR:* 27*764, 93654.* The TBM displays the most prominent lamination out of the whole marine succession.

Figure 3.59 *Torver Black Mudstone GR:* 27*764, 93654.* Bands of lamination within the TBM can range between 1 and 20mm thickness.

Figure 3.60 *Torver Black Mudstone GR: 27764, 93654.* The type locality for the TBM is located 500m SW of Torver.

Buck Pike Dolerite Fmt.

Area covered by unit
The Buck Pike Dolerite Fmt. (BPD) outcrops on both high and low elevated ground. It is present at elevations between 650-700m at Buck Pike (GR:26170, 97210) and 300-500m at Limestone Haws (GR:27740, 97160). The formation generally strikes NE-N in multiple 5m wide bands which cut across topography and unit boundaries, producing outcrops of around 1m in width. It intrudes both the oldest and youngest igneous and pyroclastic formations and preferentially intrudes fold hinges along Buck Pike

Large scale features and subdivisions
Outcrops at lower elevations around Limestone Haws typically show a granodioritic composition (Table 3.2), whereas outcrops further NW around Buck Pike, at a higher elevation, contain a dioritic composition (Table 3.3).

Table 3.2 A description of phenocryst properties from hand samples collected in the BPD at Limestone Haws.

Mineral	Typical crystal shape	Size/mm	Abundance/%
Biotite	Euhedral	8	30
Alk. fldspr	Euhedral	3-7	20
Quartz	Subhedral	1-2	30
Amphibole	Subhedral	2-3	20

Table 3.3 Phenocrysts in the BPD at Buck Pike are of a smaller size in comparison to that observed at Limestone Haws, the composition is also less silicic at Buck Pike.

Mineral	Typical crystal shape	Size/mm	Abundance/%
Hornblende	Euhedral	2-3.5	30
Plagioclase	Euhedral	2-3	20
Pyroxene	Subhedral	1-3	30
Biotite	Anhedral	1-2	20

Age

The BPD has a relative age younger than the GCT but older than the Limestone Haws Andesite Formation.

Type Locality

Limestone Haws (GR: 27750, 97180) due to the large outcrop exposure containing many clean surfaces (Figure 3.61).

Figure 3.61 *Buck Pike Dolerite Fmt. GR: 2662, 97397.* The type locality for the BPD, here the unit cross cuts through the volcaniclastic sandstone country rock, the contact being underneath the hammer.

Limestone Haws Andesite Fmt.

Area covered by unit
The Limestone Haws Andesite Fmt. (LHA) shows a scattered distribution of outcrops predominantly focused at lower elevations of 350m around Booth How (GR: 28180, 9694). However, larger outcrops up to 6m in width are also present along the ridge of Dow Crag (GR: 26240, 97600).

Contact with the unit below
The LHA has been observed to be emplaced on top of the lapilli tuff member of the BPTC at Dow Crag (GR: 26223), 97534). Further SE, at lower elevations, it is also laying over the BPV at Limestone Haws (GR: 27774, 97159).

Approximate thickness
40m based on the surface exposure and dip of a single flow observed at Limestone Haws (GR: 27756, 97168).

Large scale features
An Andesitic composition is consistent throughout the LHA, but variations of grain sizes have been observed. These range from aphanitic matrix dominated exposures, to outcrops with coarse phenocrysts up to 3mm (table 4). The LHA holds a rough, unshaped morphology and commonly displays good exposure with moderate weathering, showing the best exposure at Booth Howe (GR:28260, 97150).

Mineralogy
Across most outcrops, a vitreous aphanitic matrix makes up 60% of the composition, with the remaining 40% being made up of silicic phenocrysts (Table 3.4).

Table 3.4 Phenocrysts of the LHA range from a size of 1 to 9mm and define an overall silicic composition.

Phenocryst	Minimum size/mm	Maximum size/mm	Abundance/%
Biotite	1	5	20
Quartz	1	2	20
Plagioclase	3	9	30
Muscovite	2	2	10
Hornblende	1	2	20

Interpretation
The LHA represents multiple intermediate eruption episodes.

Age
The LHA has a relative age younger than the BPD and BPTC, but older than GCT, therefore many eruptions were present.

Type Locality
Nettle Crag (GR: 27576, 96479), due to very good exposure of cross section through unit with minimum weathering.

Structural data and analysis

Stereonet analysis

Four fold structures have been recorded inside the mapped area. Stereonet analysis (Figure 4.1-Figure 4.5) has been conducted for the two larger and two smaller styles present. Both large and small scale folds strike approximately E-W within a margin of 40°. They hold either steeply inclined or upright axial surfaces with varying interlimb angles from 24° to 134°. Bedding and cleavage dips of marine strata around Torver were also analysed, 20 bedding and 10 cleavage dips were used.

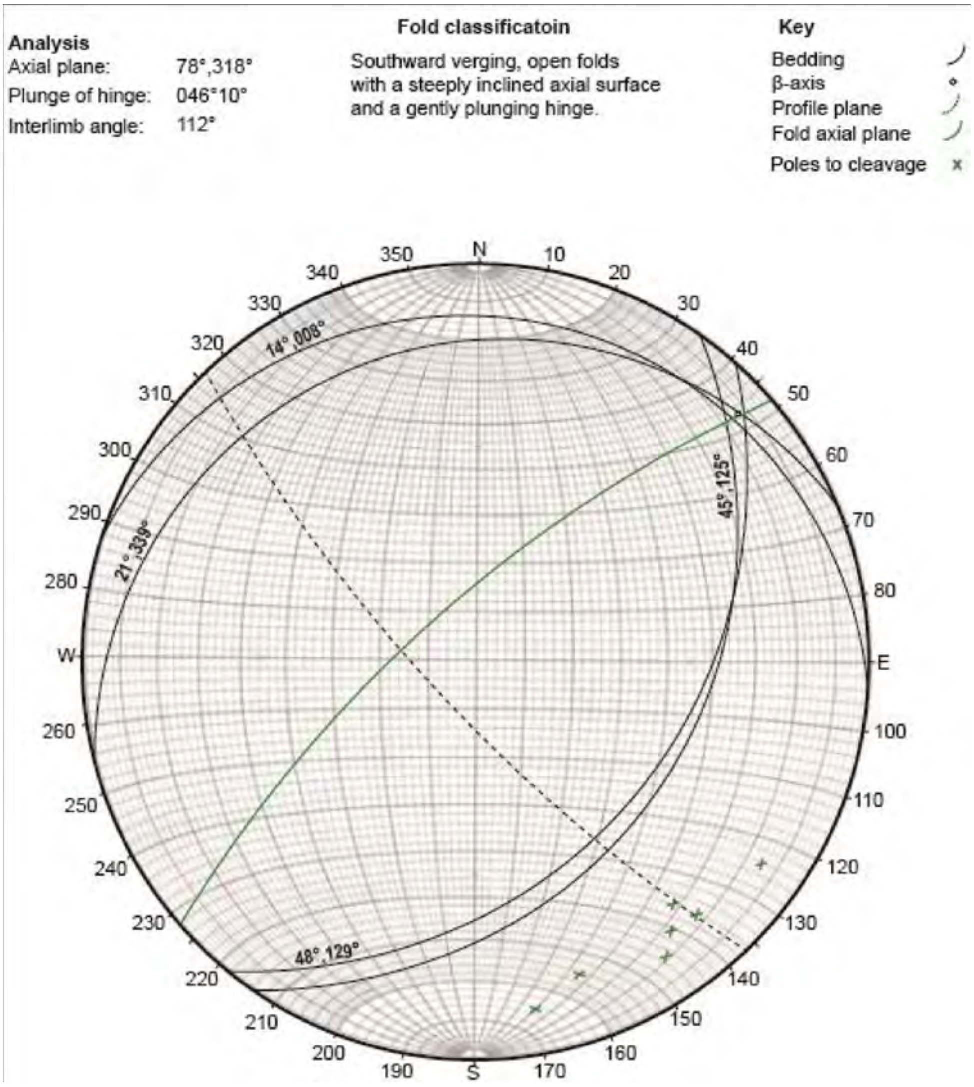

Figure 4.1 Stereonet analysis of D1 folds located at Torver Bottom (GR:26710, 95640).

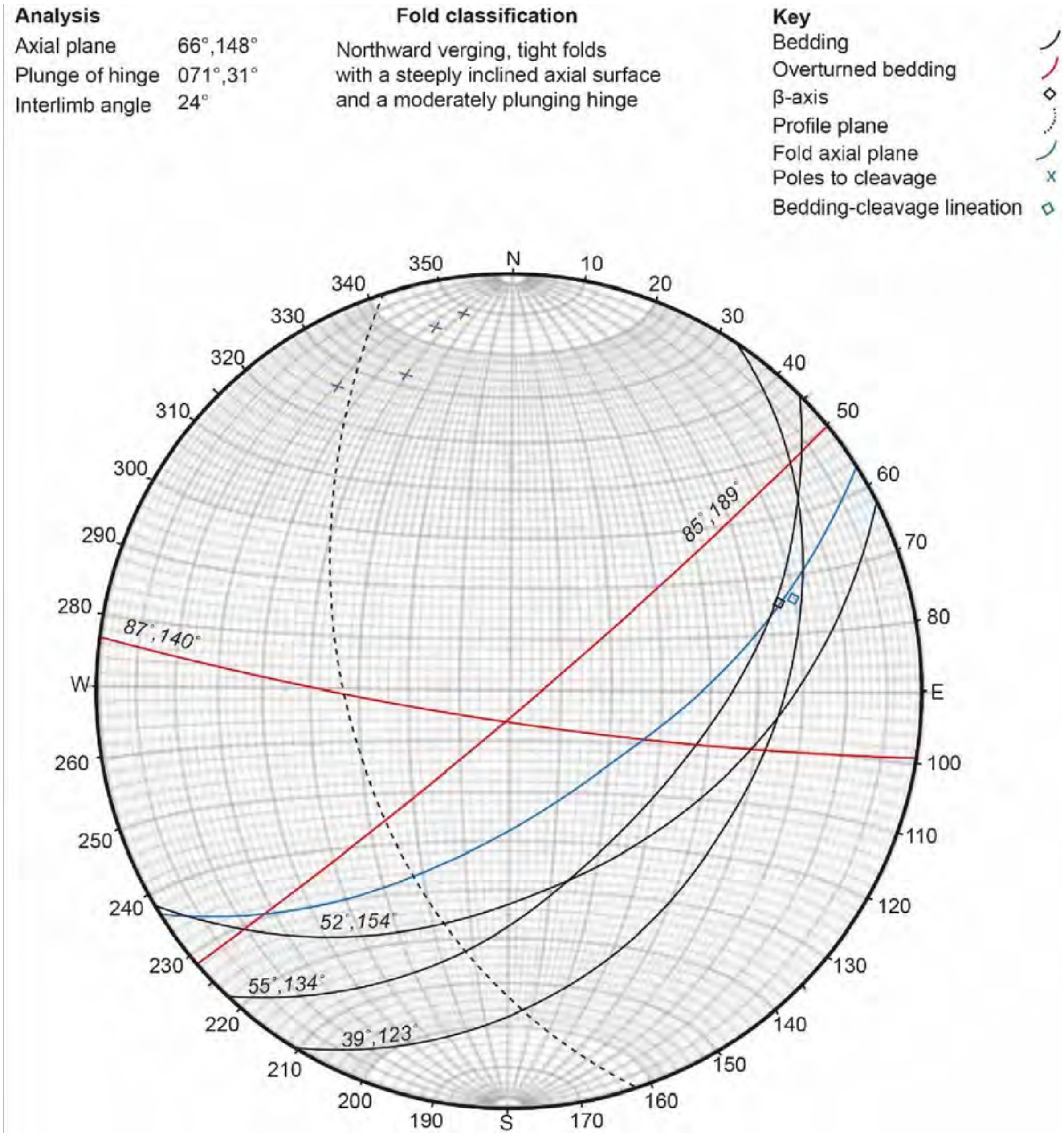

Figure 4.2 Stereonet analysis of D2 folds located at Dow Crag (GR: 26240, 96610).

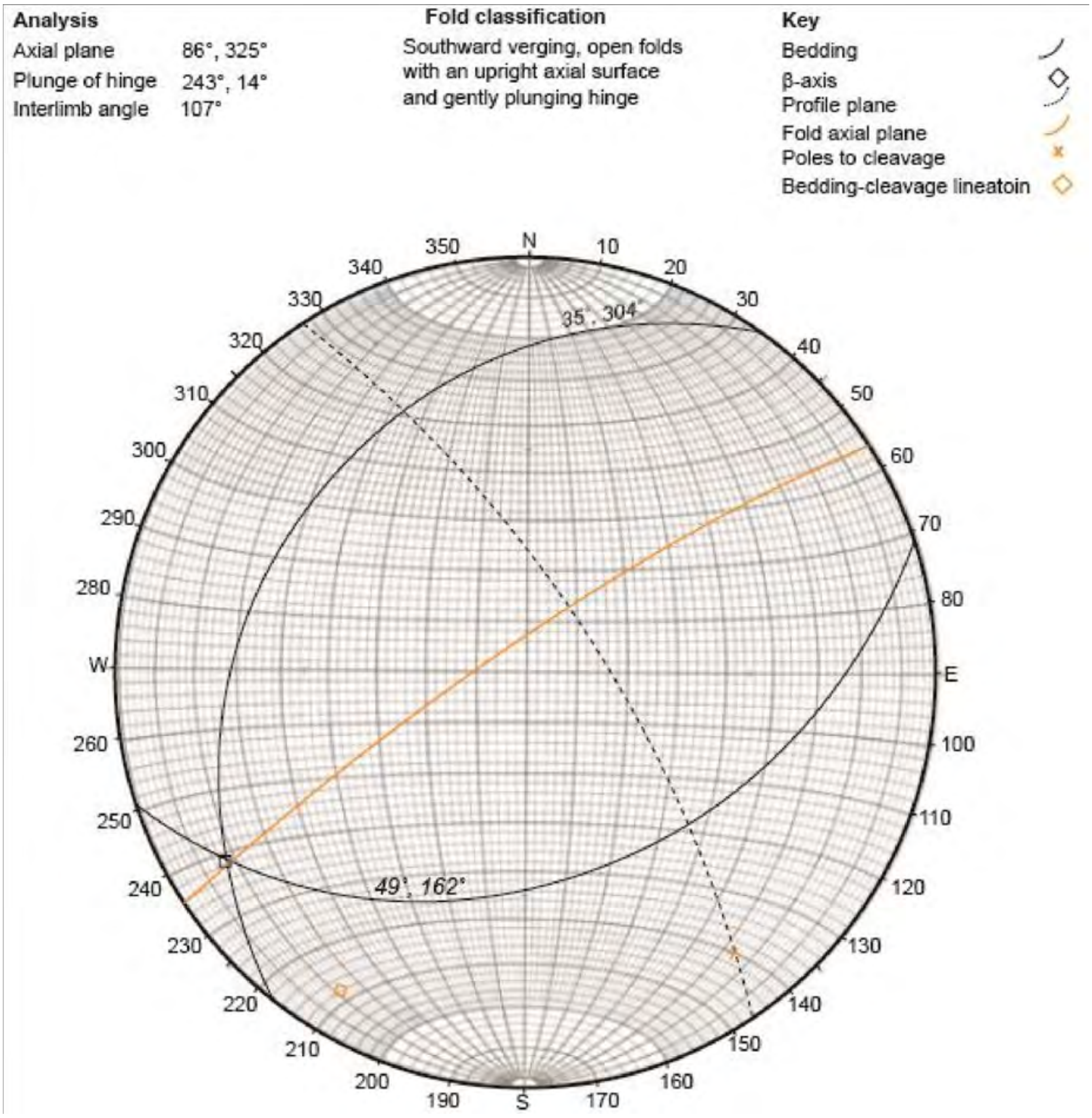

Figure 4.3 Stereonet analysis of small scale folding located at Banishead (GR: 28610, 96290).

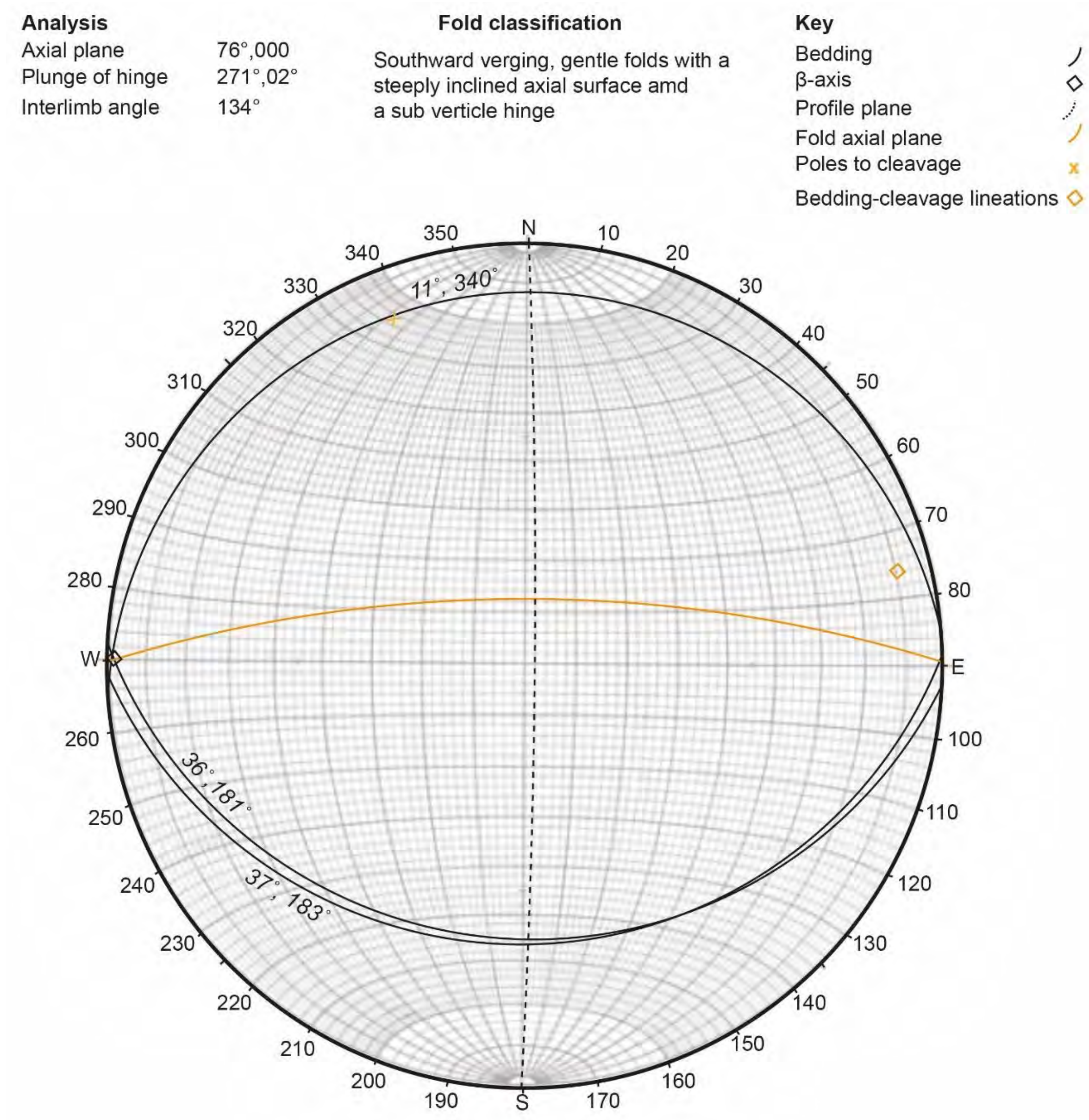

Figure 4.4 Stereonet analysis of minor folding located at Low Pike Haw (GR:25240, 94580).

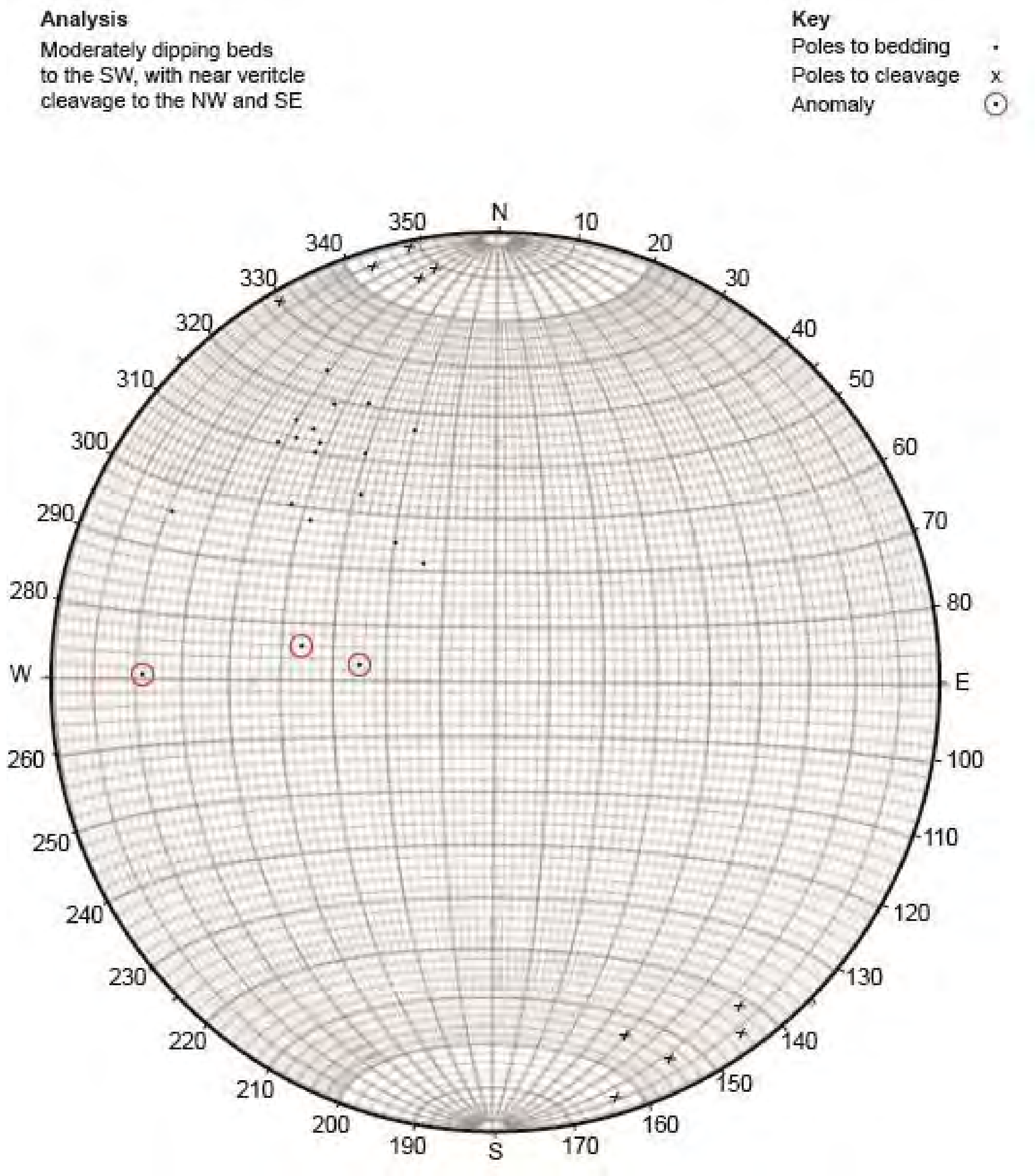

Figure 4.5 Stereonet analysis of marine strata located at Torver from GR: 26000,94000-GR:28000, 96000. The significance of the three bedding anomalies is discussed in the following chapter.

Cross Section analysis

Stereonet data has been utilised with mapped outcrops to produce three cross sections, and one 3D diagram, analysis was applied to three areas. A large cross section through Dow Crag and Bleaberry Haws (Figure 4.7) has been produced. The contact between the marine strata and pyroclastics has also been analysed at High Pike Haw (Figure 4.6), and a smaller scale cross section displaying an overturned fold at Dow Crag (Figure 4.8) was constructed. A 3D diagram of the marine strata in Torver (Figure 4.9) was produced to illustrate the lateral thickness variation of the units and a key has been provided (Figure 4.10) with reference to all cross sections.

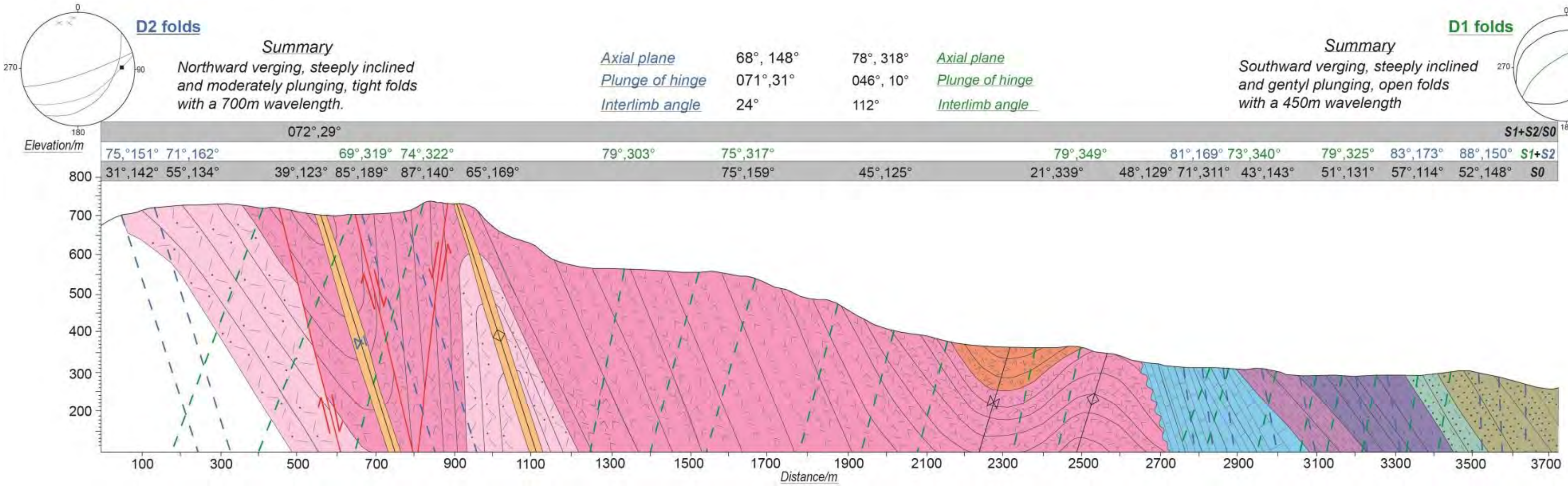

Figure 4.7 A NW-SE structural cross section from Dow Crag (GR: 26031, 98067) to Bleaberry Haws (GR: 26734, 94302).

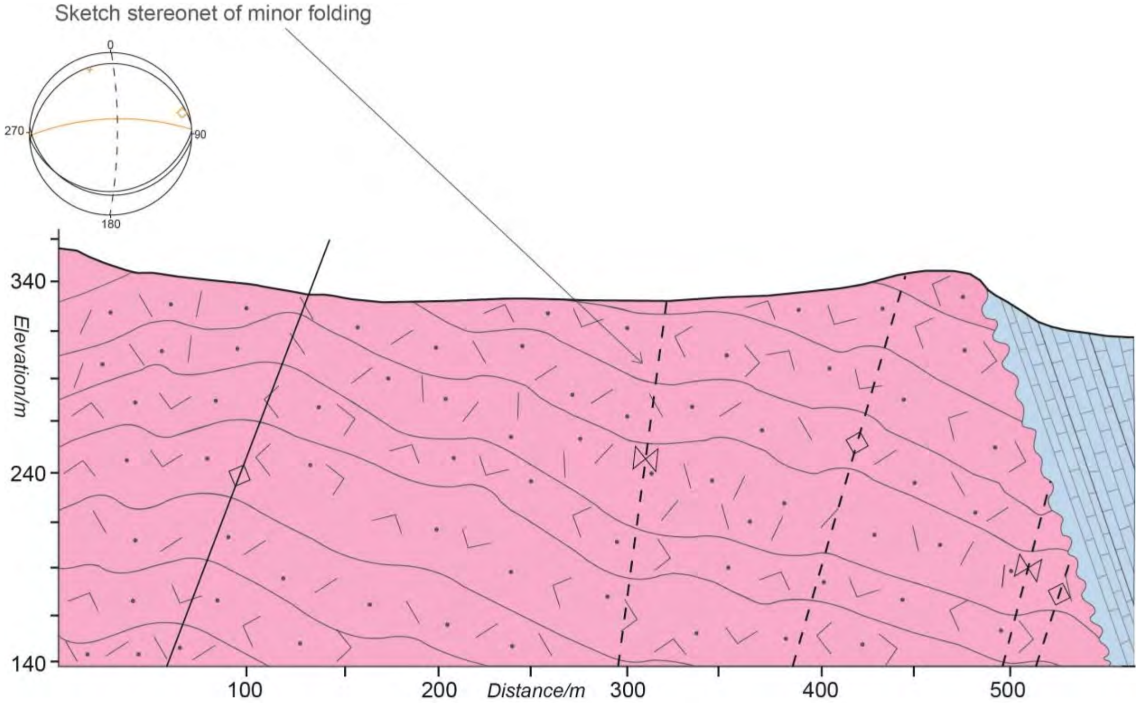

Figure 4.6
A structural cross section through the contact at High Pike Haw GR: 26205, 95098-GR: 26112, 94615.

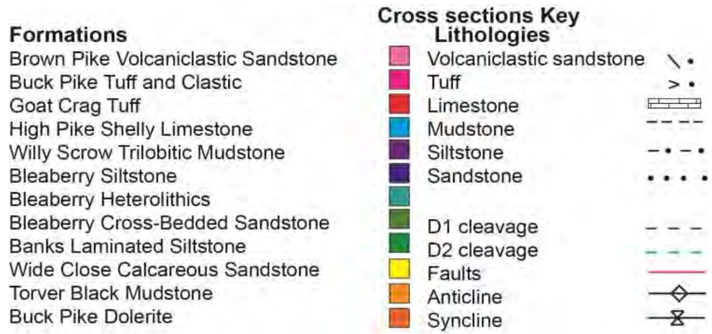

Figure 4.8 A key for all cross sections and diagrams.

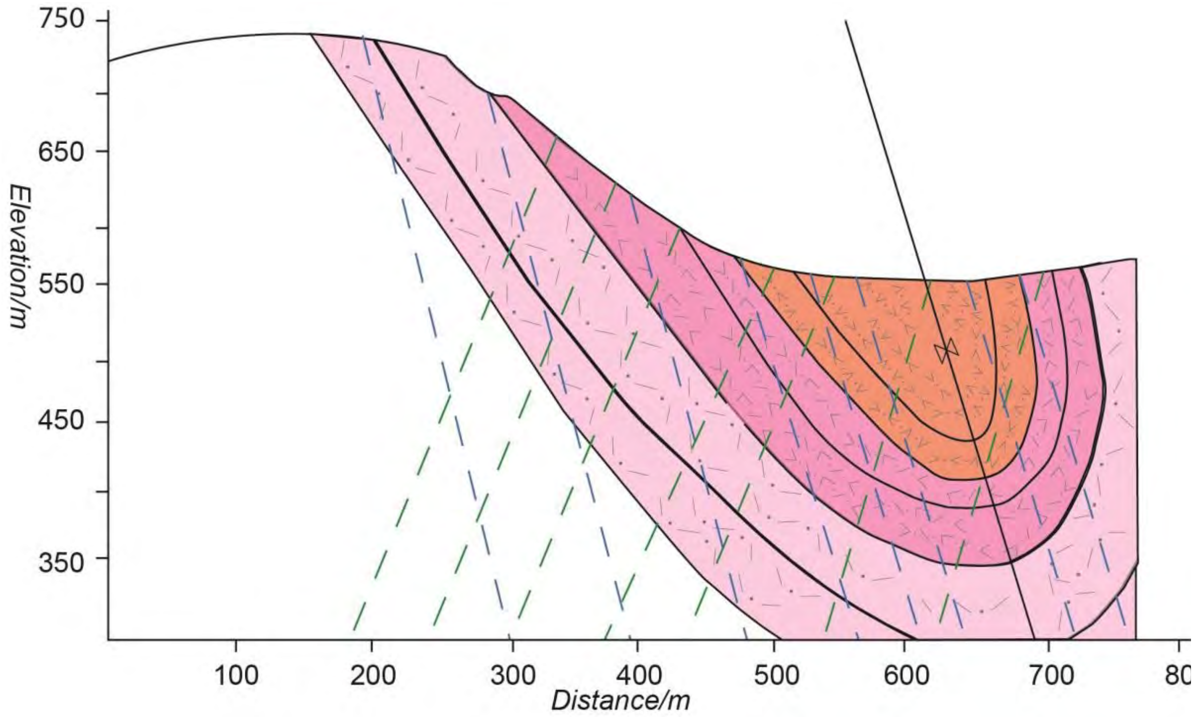

Figure 4.9 A structural cross section through Dow Crag (GR: 26095, 97989 – GR:26698, 97587) displaying an overturned fold with geometries obtained from a stereonet analysis (Fig**.** 4.2).

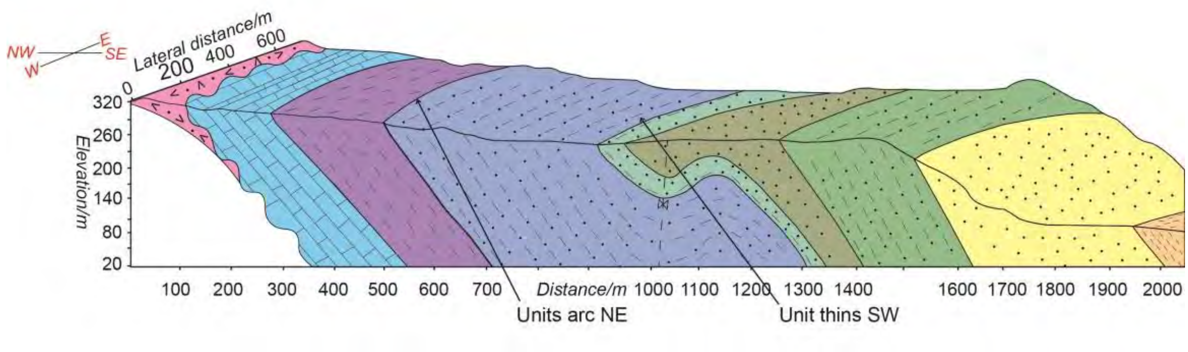

Figure 4.10 A 3D annotated diagram displaying the full marine succession present in the mapping area.

Thin section analysis

Thin sections have been produced from five field samples and analysed under a microscope (Figure 4.11-Figure 4.14). TOR 1, collected from Flask Brow (GR: 26997,95790), shows numerous feldspar and calcite twins defining a coarse microgranitic composition. This surrounds eutaxitic volcanic glass, of which a *bow tie* morphology can be observed (Figure 4.11). JPR CSS also shows numerous polysynthetic and pericline twinning within feldspar and calcite grains (Figure 4.12). Quartz grains commonly show subgrain rotation as the dominant deformation mechanism and are at the highest abundance of 60%. TOR 3 (Figure 4.13) displays a micrograniticcomposition of an intrusive igneous rock located at Booth How (GR:

28238, 97264). This sample holds the highest abundance of deformation structures, with grain boundary migration, subgrain rotation and fish structures all being observed. TOR 5 represents a foliated, coarse grained volcaniclastic rock (Figure 4.14) gathered from the BPTC at Crowberry Haws (GR: 28442, 98083). It shows an aligned calcite cleavage, responsible for the foliation observed in the field, with grains reaching up to 3mm in size. A very fine matrix surrounds it, composed of mica grains with similar orientation to that of the calcitic cleavage.

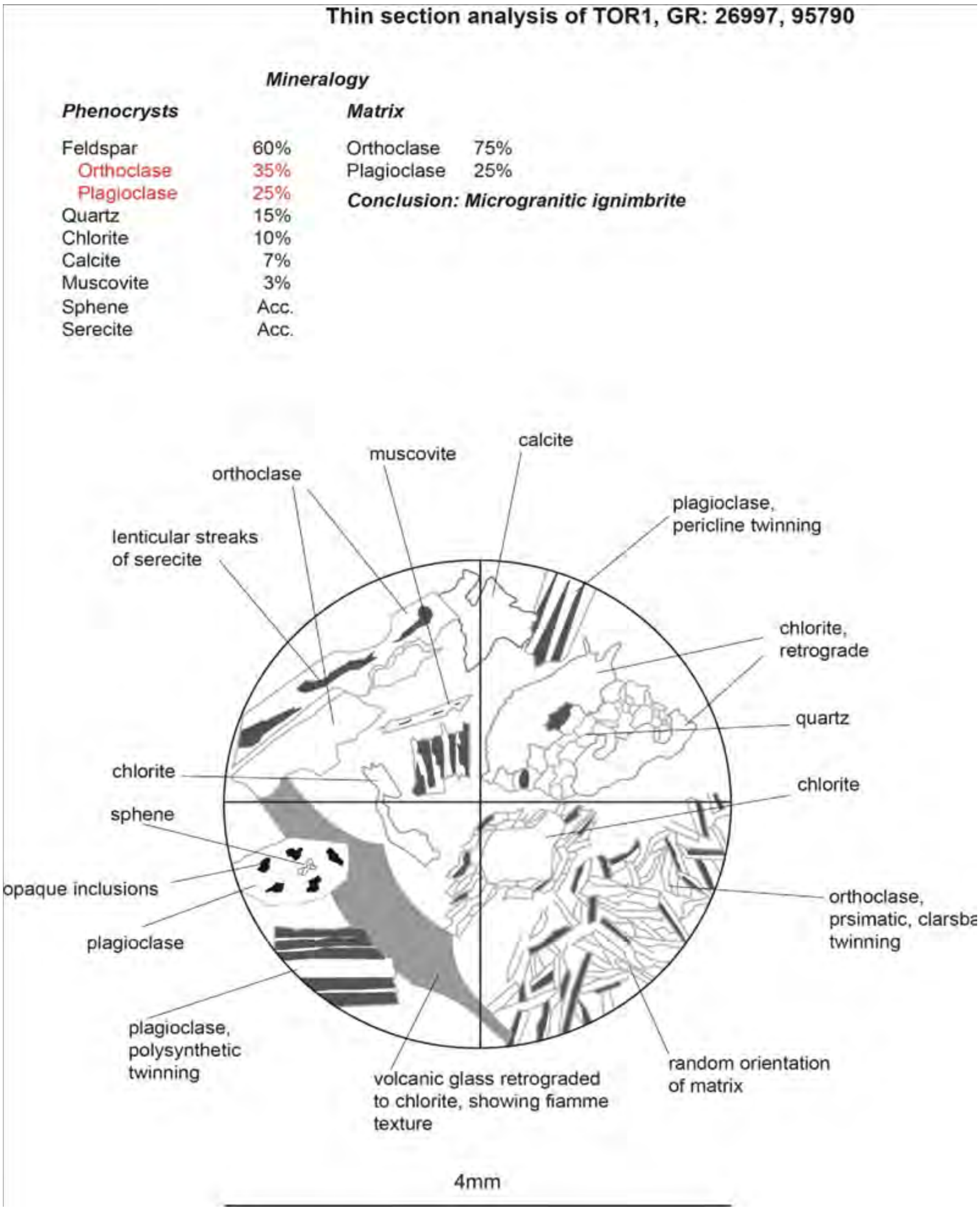

Figure 4.11 Thin section analysis of TOR 1, a sample collected from an ignimbrite member of the BPTC (GR: 26997,95790). The mineralogy constitutes that of a microgranite, with orthoclase feldspar holding the highest abundance. The field of view was chosen as an adequate representative due to the presence of a variety of phases and the discernible *bow tie* morphology of the volcanic glass.

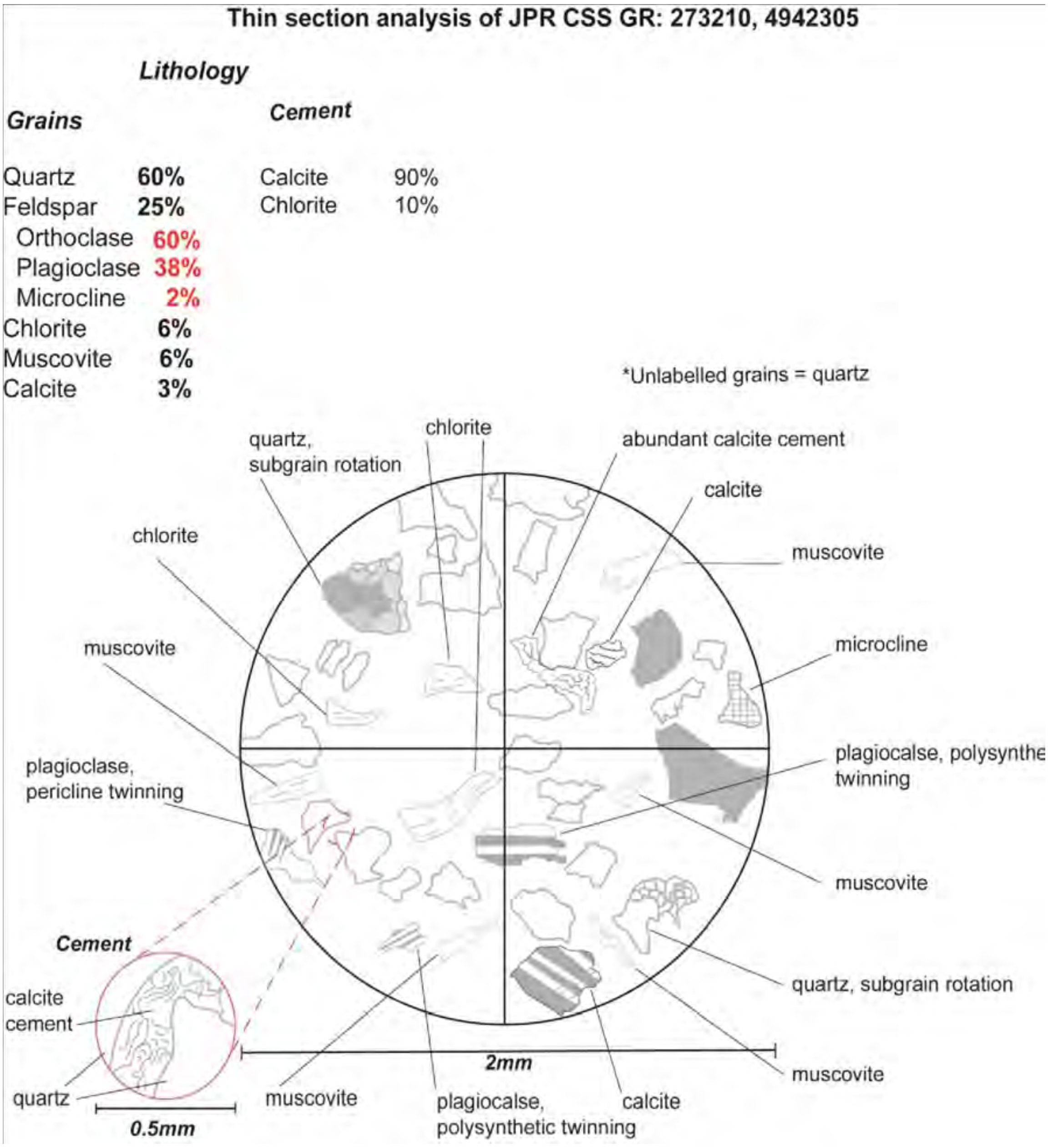

Figure 4.12 Thin section analysis of JPR CSS, a sample collected from the BLS at Torver (GR: 27231, 94230). A predominantly calcite cement encloses fine grains of quartz, feldspar, mica and calcite. Quartz grains show the highest abundance and many of which have deformed via sub grain rotation.

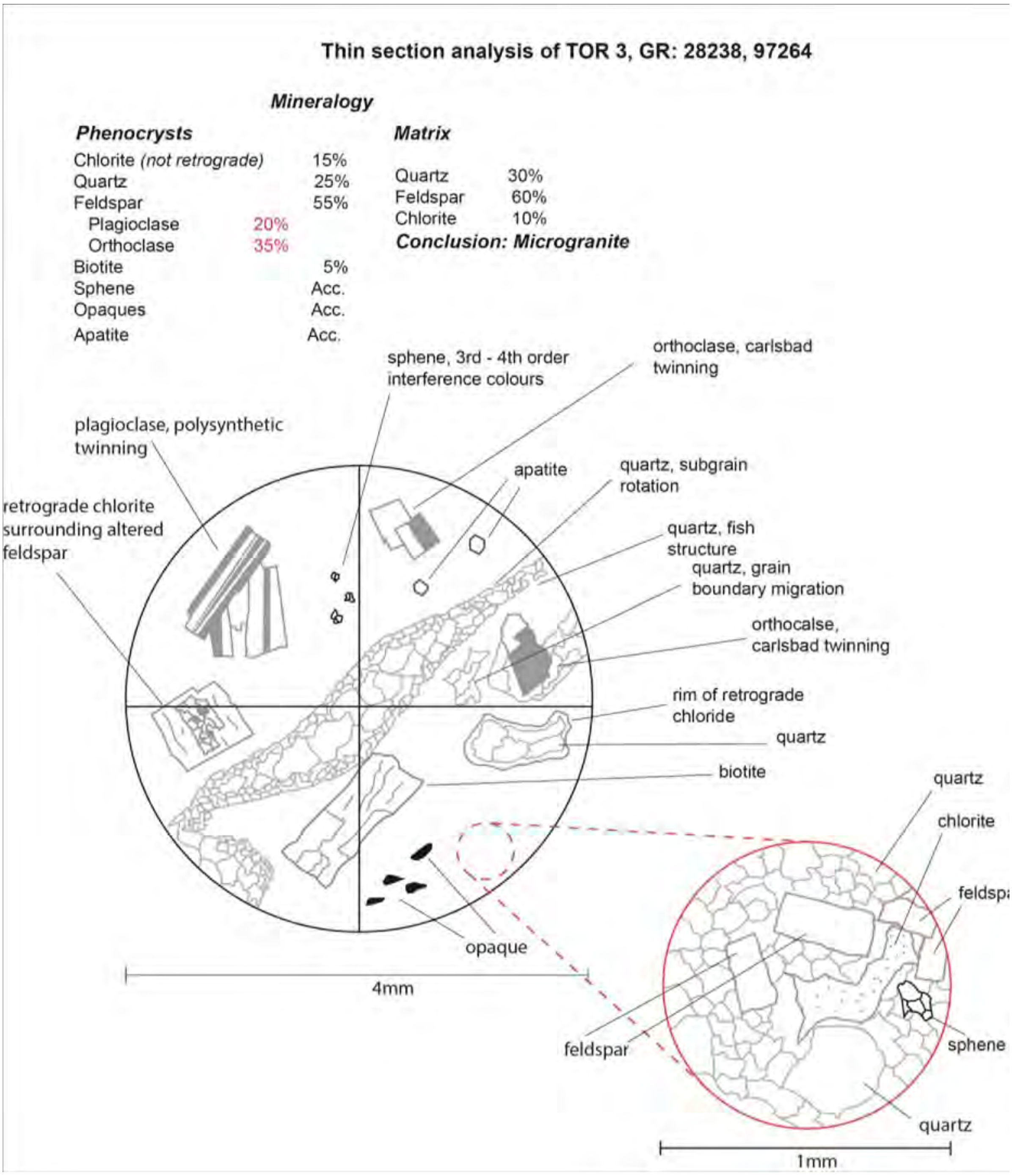

Figure 4.13 Thin section analysis of TOR 3, an intrusive igneous rock from the BPD located at Booth How (GR: 28238, 97264). The phases constitute a micrograniitic composition produced by coarse phenocrysts of feldspar, quartz and chlorite. Subgrain rotation is the most prevalent mechanism for deformation, however grain boundary migration is also present in a few grains, fish structures have also been observed in quartz assemblages.

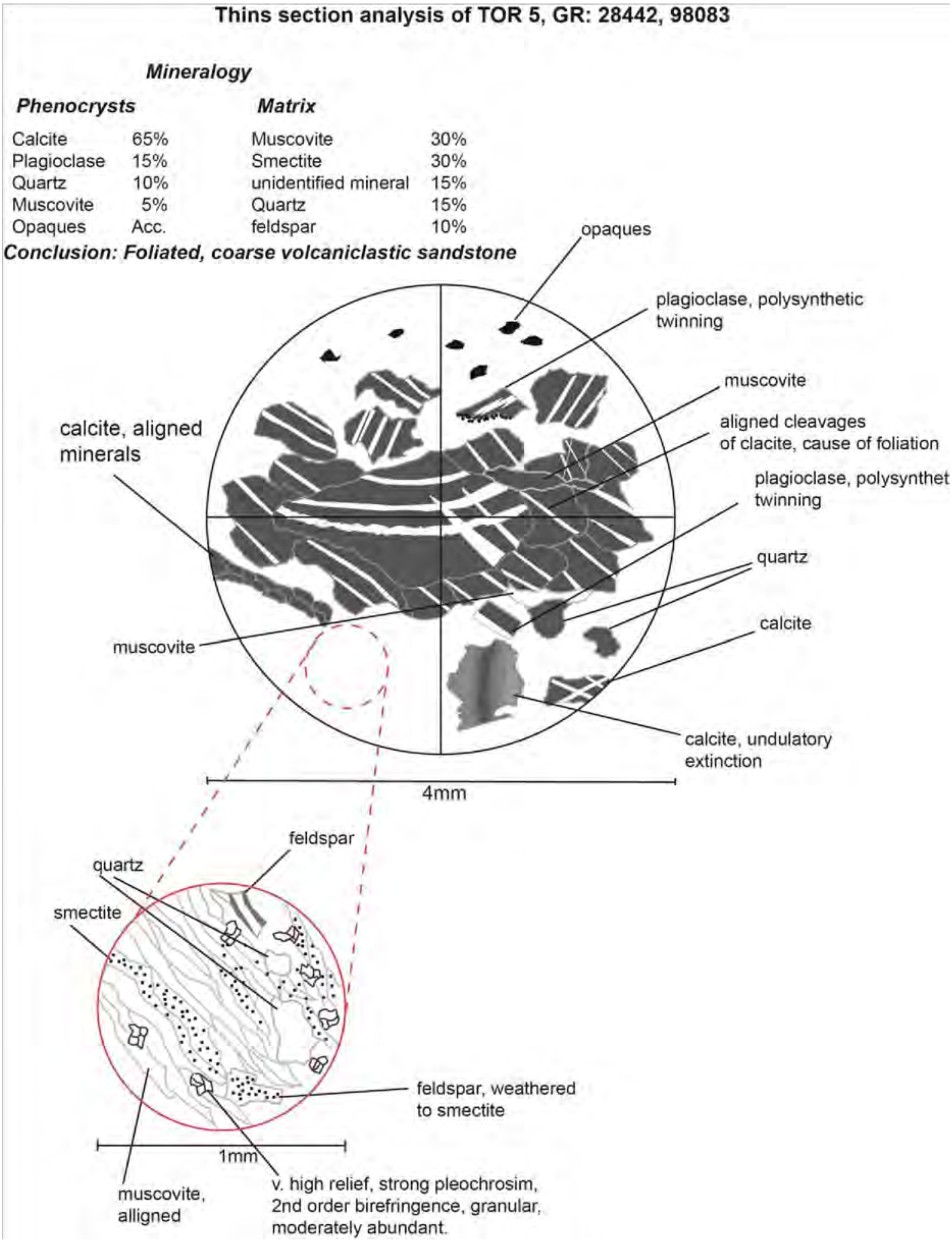

Figure 4.14 Thin section analysis of TOR 5, a foliated volcaniclastic sandstone from the BPTC at Crowberry Haws (GR:28442, 98083). The field of view has been displayed in cross polarised light to highlight alignment of calcite cleavage. Calcite grains hold the highest abundance at 65% and feldspar grains are commonly weathered to smectite.

Interpretation and discussion

The BVG

Evidence for sub aerial, lacustrine and fluvial depositional environments of the BVG, has been gathered throughout the mapped area. A paleogeographic map for the time of deposition in the late Ordovician has been constructed from recorded field evidence (Figure 5.1).

Asymmetrical ripples found within the BPV 100m south of Bursting Stone and number 6 on Figure 5.1.(6), formed in sediments below the fair weather wave base. Numerous other sedimentary features including current cross bedding, suncracked layers and bedding contortion, resulting from sub aqueous slumping, have been recorded at Seathwaite Fells (Oliver, 1954). However, fluvial deposits at Brown Pike (1 and Figure 3.2), SEE of Bursting Stone exclude the possibility of the asymmetric ripples representing wave propagation towards a northern shoreline. Furthermore, a fining up sequence 300m SE of Brown Pike (2) is the product of an environment with a decreasing energy supply and has therefore been interpreted to lay within the fluvial setting. Comparatively, nearly twenty marine, organic microfossil taxa have been identified at Holehouse Gill (Molyneaux, 1988) and fluvial facies have also been recorded at Thirlmere and Pike O'Blisco (Branney, 1988). Therefore, these observations hold more credibility to an environment containing multiple bodies of water and consequentially, wave propagation towards the northern shore of a lake is considered plausible at Bursting Stone (6). Furthermore, a smaller fetch in a lacustrine environment reduces wave size and water depth for the formation of ripples, which allows for a prediction of the lakes shoreline to be within a few 10s of meters north of the ripple's formation. This interpretation is complemented with trace fossils, lithologies and sedimentary structures suggestive of a shallowing lacustrine environment occurring at Sour Milk Gill, Borrowdale (Johnson *et al*., 1994). The writer argues that if a shallow marine environment was to be proposed, then a low energy sedimentary setting such that of a tidal lagoon would need to be maintained whilst significant volumes of strata were deposited. This would only be possible if subsidence rates could keep pace with high levels of sedimentation. However, if a non-marine setting such as an ephemeral lake was present then subsidence may not be required. Water depth would be maintained as heavy precipitation associated with phreatoplinian eruptions matched sedimentation rates.

However, *bow tie* shaped fiamme (Figure 4.11 and Figure 3.10) have been observed at Flask Brow (3). Welding from hot ignimbrite and pyroclastic fall deposits, have documented to be the cause of the discernible morphology (Smith, 1960; Sparks and Wright 1979) and are therefore strongly associated with subaerial eruptions. Non marine trace fossils have been found at multiple localities, including two sets of animal tracks of *Diplichnites* and *Diplopodichnus* ichnogenera crossing over one another displayed on bedding planes of rhyolitic tuff in the river Lickle, Lumpot (Mitchel, 1954). Although it is stated these tracks could also be the product of raindrops, this would not dismiss a subaerial setting. The brecciated tuff (7) observed at Goat Crag (Figure 3.16) contains very coarse phenocrysts up to 15mm in size and is poorly bedded and sorted. This opposes the delicately bedded and fine grained nature of marine deposition as described by Taylor *et al*. (1971). Evidence for a sub aerial setting also exists at Dixon Scrow where a pyroclastic surge deposit has been interpreted from truncation of bedding (Figure 3.7). This is found in close proximity to poorly bedded and sorted tuff deposits (Figure 3.12).

Fluvial erosion gulleys, stratification patterns and sparse sedimentary structures have allowed recognition between deposition within a lacustrine environment between Wasdale and Seathwaite and the more abundant subaerial emplacement (Branney, 1991). Both categories of deposit share identical compositions implying derivation from the same volcanic episode, yet desiccation cracks and cross stratification found in Seathwaite suggest shallow water submersion.

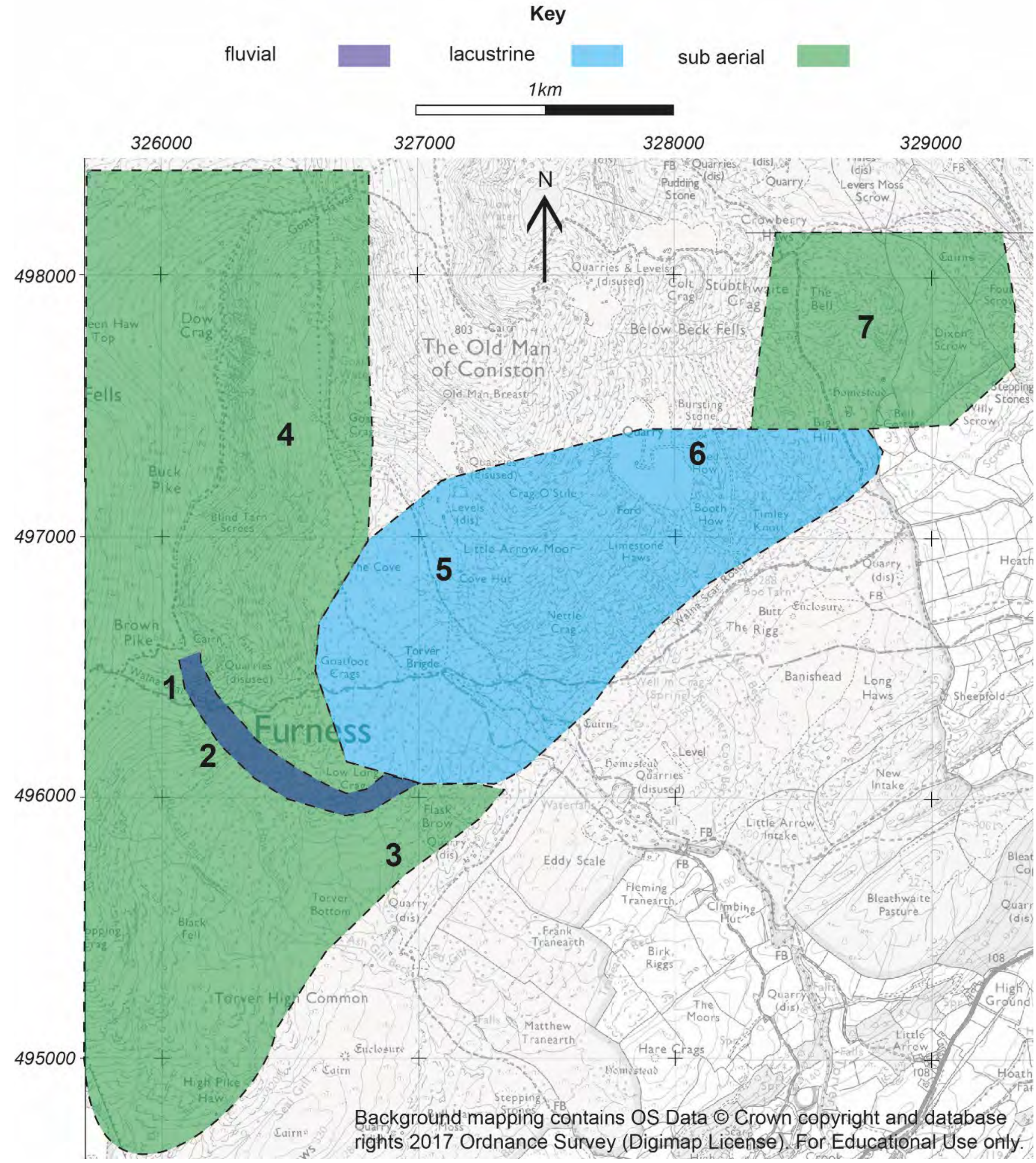

Figure 5.1. A paleogeographic map displaying the location of sub aerial, lacustrine and fluvial depositional environments. Purpose of numbering discussed in text.

The BVG and WS contact

The contact between the pyroclastic and sedimentary units has been interpreted to represent an angular unconformity. Stereonet analysis of marine bedding dips (Figure 4.5) highlights three anomalies, all of which are located near the contact and hold no anomalous cleavage dips. If the contact was conformable, one would expect no significant anomalies of bedding dip, unless for the product of faulting where both bedding and cleavage anomalies would be present. Folded structures have also been observed to descend below the contact at Low Pike Haw (Figure 3.17and Figure 3.18), and the highlighted dip anomalies are therefore argued the product of emplacement on top of gently folded and eroded strata.

The WS

An interpretative stratigraphic column (Figure 5.3) and key (Figure 5.2) of the marine succession has been produced from field measurements of grain size and carbonate concentration. Interpretations have then been deduced from fossil contents and stratigraphic relations between units compared with models of parasequences and transgressions. A vertical scale in metres with two independent ratios for both bed thickness and unit thickness. Directly adjacent to the column are two arrows, representing direction of increasing mica content in blue, and parasequences in red. A green scale has been developed to display calcium carbonate abundance throughout the sequence, with dark green representing vigorous fizzing from HCL and therefore a high calcium carbonate content. The stratigraphic column shows two parasequences separated by three transgressions and displays sedimentary and tectonic features through the units.

The marine succession is associated with four interpreted transgressions which occurred between the base of the succession and after deposition of WCCS. Deposition of HPSL has been calculated to occur at 457Ma (Thirlwall and Fitton, 1983), constituting the top of the Ashgill series. The early Katian Guttenburg excursion has been identified by a positive $\delta^{13}C$ shift (Young et al., 2010) and is interpreted as a cooling step preceding the Hirnantian glaciation, occurring in the late Caradoc, approximately 454Ma. it is therefore proposed that recovery from this cooling event and the resulting eustatic sea level rise is the cause of the transgressive episode prior to deposition of the HPSL. The cooling and resultant warming of this event is lesser than that of yet to come, hence the rise in eustatic sea level is not significant and allows formation of a shallow marine environment as opposed to a deep water setting.

The Hirnantian glaciation proceeded 9 million years later (Rickards and Woodcock, 2005). The glaciation finished with the termination of the Ashgill group and was met with a reduction of continental ice to rise eustatic sea level and initiate the transgression, depositing the WSTM.

Conodont δO^{18} compositions show cycles of cooling and warming throughout the Wenlock series (Trotter *et al*., 2016). A large negative shift in UK samples has been recorded from ~19.2‰ in the mid Homerian (correlating with the early Coldwell) to a minimum of 18.1‰ at the Wenlock-Ludlow boundary. The interpreted transgression to occur across the BCCS and BLS contact is proposed to be the result of the large negative and warming shift recorded at the end of the Wenlock series.

It has been proposed that bathymetry depth around Avalonia dramatically increased from the start of the Ludlow to the base of the Scanicus (Johnson, 1996). The author proposes this to be a direct cause of water depth and therefore displays a significant increase from Nilssoni to Scanicus. Although the transgression between WCCS and TBM does not occur until the base of the Scanicus, it is proposed this represents a phase of low stand normal regression, before transgression and the proceeding high stand normal regression to deposit the TBM.

The marine sequence holds consequential evidence of paleoclimate change and eustasy fluctuations. Recovery from a precursor to the Hirnantian glaciation caused the initial transgression to deposit the HPSL. This was shortly followed by the largest transgressive event resulting from post warming after glaciation. Throughout the Llandovery relative sea level increased minimally and consistently (Rickards and Woodcock, 2005), promoting normal regressive behaviour and parasequence development. Conodont δO^{18} values show a negative excursion at the Wenlock-Ludlow boundary, resulting from higher temperatures to cause a rise in sea level and deposit the BLS. The WCCS was then deposited through lowstand normal regression before the transgressive event prior to deposition of the TBM.

Figure 5.2 A key for the stratigraphic column on the following page.

Structures

Two dominant styles are present within the volcanics (Figure 4.8). The D1 folding event occurred prior to WS deposition, however the predominant cleavage present through both successions is that of the later D2 folds, occurring post deposition.

D1 folds have been identified by bedding dip relations through Low Long Crag and Torver High Common. Whilst they have not been observed directly, they are proposed as the cause of opposing dip directions throughout the area and show correlation with pre-Bala folding (Hartley, 1932). Hartley originally identified the structures through observation of multiple BVG subdivisions passing under the Coniston limestone, a trait presumed to be linked with the ENE pitch of the folds. The structures represent large scale folding with a half wavelength of 6-8km at Nan Bield Pass.

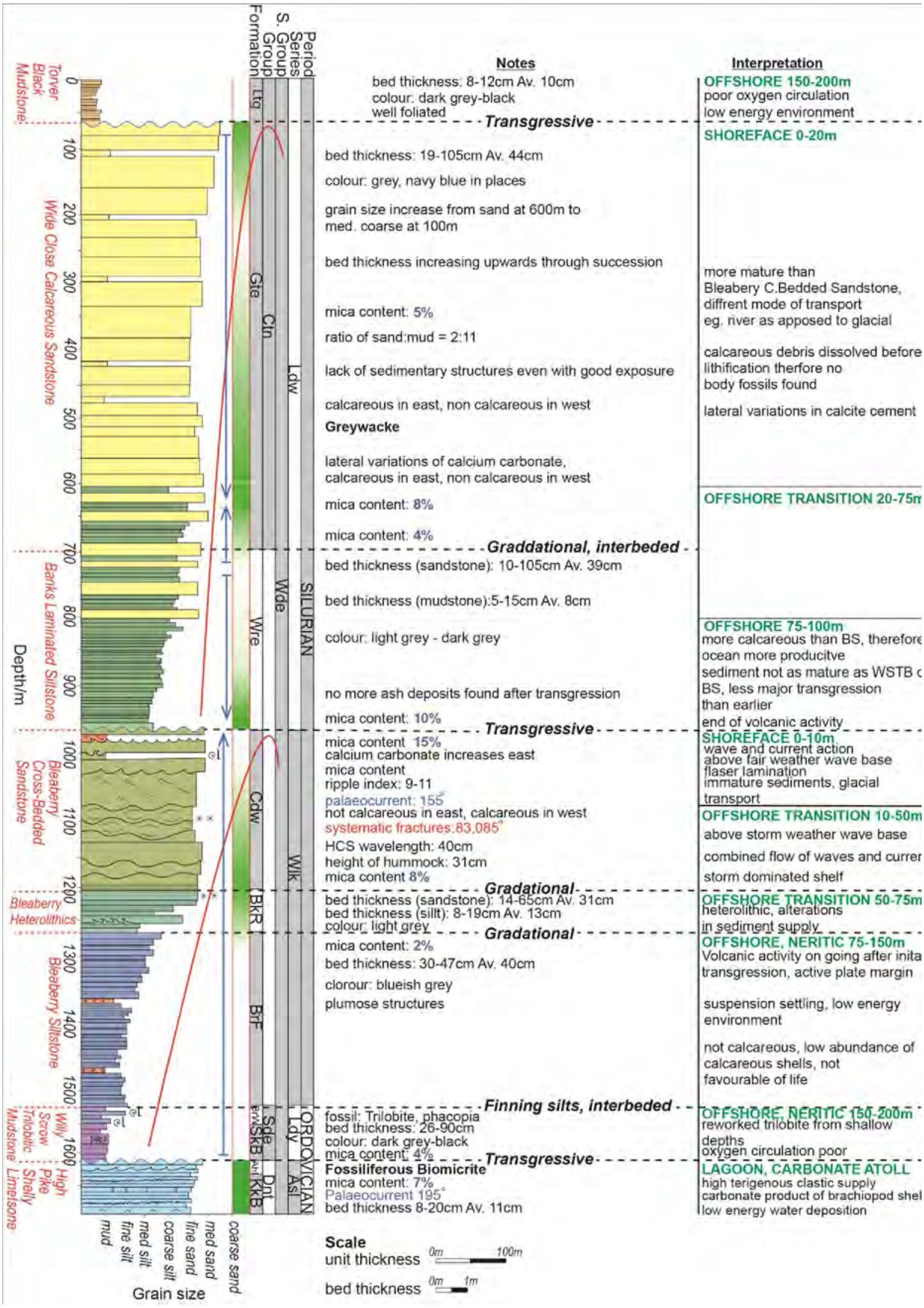

Figure 5.3 An interpretative stratigraphic column for the marine succession.

A common limb is shared with the Ordovician dated Ulpha syncline and continues to pass underneath the HPSL at Torver High Common (Soper and Neuman, 1974). Soper further proposes a difference of strike between the Nan Bield anticline and the unconformable BVG-WS contact is plausible evidence to suggest the Coniston Limestone truncated the anticline. The pre-Bala folding also alters the bedding strike of the BVG directly under the Coniston Limestone at High Pike Haw (Mitchell, 1954). The BVG strikes at near right angles to the Coniston Limestone with the only shared orientations being cleavage printed on both the Ordovician and Silurian strata. This is comparable to the similar phenomenon observed by stereonet analysis (Figure 4.5) in the HPSL. The small scale folding observed at High Pike Haw (Figure 3.17) is proposed to be the cause of the deviation of strike described by Mitchell and is therefore linked with the larger scale, D1 folding event. The author also proposes an overstep of 2500m between Kentmere and Broughton Mills, suggesting intense tectonic activity followed by extensive denudation was present before deposition of the WS.

In the BVG, the cleavage planes hold an ambiguous relation to the contained folds (Soper and Numan, 1974). Soper observes bedding-cleavage lineations held on the Nan Bield anticline's north limb are northeast plunging, contradicting south east plunges of the south limb. The strike, however, remains adequately constant, therefore implying the cleavage was applied obliquely across a pre-existing fold. This correlation contradicts the D1 cleavage presented within Silurian strata. However, the cleavage found in both the Silurian and Ordovician sequence are not easily related to folding (Mosley, 1968). Mosley documents that although mudstones and siltstones may possess a genuine slatey cleavage derived from preferred orientation of phyllosilicates, most rocks hold a fracture cleavage which is rarely axial planar. This suggests the potential for a misinterpretation between D1 and fracture cleavage. The author therefore proposes a synchronous development of folding, faulting and cleavage in Silurian sediments, proceeded by continuous development of cleavage under a stress direction which had rotated 5°. Stereonet analysis (Figure 4.5) shows further support to this proposal through the observed and unpresented bedding and cleavage anomalies respectively.

D2 structures have been interpreted through large scale outcrop relations and bedding-cleavage interactions. Between Brown Pike and Dow Crag outcrop repetition occurs at the scale of 500m. Whilst it may be argued this could be the product of faulting, direct observation and detailed mapping of a fault located at Buck Pike (GR: 26123, 97132) shows repetition being produced at a scale no greater than 10m. Furthermore, a common trait of overturned limbs has been observed at Goat Crag (GR: 26689, 97617), where bedding has been recorded at a steeper dip than its associated cleavage. Proceeding fault and igneous intrusions are then proposed to be isolated at the fold hinges due to their less resistive nature.

The interpreted D2 structures bare similarity to anticlinorian and synclinorian folds with isoclinal geometries, first proposed in earlier work (Green, 1920). Overturned anticlines have also been described between Adam Seat and Great Howe. The evidence of folding is based on a section exposed at Haweswater tunnel, and narrow boat shaped inliers of bedded tuffs produced by denudation of the original structure

(Mitchell, 1929). Mitchell also reports excellent examples of these folds around Brown How and Kentmere Pike, assigning these structures to products of Devonian earth movements. He further proposes, by the evidence of overfolds decreasing to the south, that forces responsible acted from a south-south easterly direction. Overturned structures with half wavelengths of 6m have also been reported in Wyrnose Valley, (Hartley, 1932) where dips change from 0° to 70° within a few meters.

However, Caledonoid isoclines were later widely rejected due to further developments of way-up indicators (Soper and Numan, 1974). It is stated recent field studies dismissed any overturning of strata, as younging evidence in bedded tuff consistently shows upright sedimentary structures. Furthermore, field studies conducted by Soper of the type area for Mitchell's pre-Bala folds conclude no evidence of NNE striking structures, and propose Mitchell's misinterpretation arose from interplay between topography, dip and faulting. Further criticism of Green's folds came through analysis of over 500 dips integrated with strike lines and geological horizons to create a diagram similar that of a structure-contour map (Mosley, 1960). The diagram portrayed NE-SW striking folds of only minor deviance from that described by other authors (Mitchel 1954; Soper and Numan, 1974) but of stark contrast to Greens proposed style. Although isoclinal folds are largely dismissed by recent field studies, the repetition of lithology observed along Dow Crag, presented with cleavage and bedding relations typical of overturning justify reasonable cause for further evaluation of structural style through the area.

Conclusions

The BVG was deposited sub aerially in both a lacustrine and terrestrial environment. Asymmetric ripples recorded at Bursting Stone are evident of water submergence south of the locality, however aligned clasts resulting from fluvial deposition to the SE of Bursting Stone dismiss the possibility of a large marine body of water. The morphology of fiamme has been used to decipher sub aerial welding, from depositional compaction. Sub aerial pyroclastic surges are the cause for truncated bedding at Dixon Scrow and the surrounding poorly sorted and bedded deposits.

Stereonet analysis has brought forward evidence of an unconformable contact between the BVG and WS. Bedding anomalies with no corresponding cleavage alterations are suggested to be the result of deposition on a previously folded and eroded surface. The overlying WS holds four transgressions which have been linked to global cooling and warming cycles including the Hirnantian glaciation. The strata have been subjected to two sperate folding events. Before deposition of the WS, a tectonic episode produced southward verging open D1 folds through Low Long Beck and the accompanying small scale folds observed to pass under the HPSL. Repetition of lithologies and bedding-cleavage relations underpin the interpretation of a post WS depositional folding event to create Isoclinal folds along Dow Crag, and a resulting cleavage through Ordovician and Silurian sediments.
This study has brought forward correlations between global events interpreted through isotopic data, and the local stratigraphy of the southern Lake District. Field evidence has also been provided for sub aerial emplacement and structural style of the BVG. Detailed mapping of the contact at Low Pike Haw and continued description of fluvial deposits around Brown Pike may provide further understanding towards the depositional environment of the two units.

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