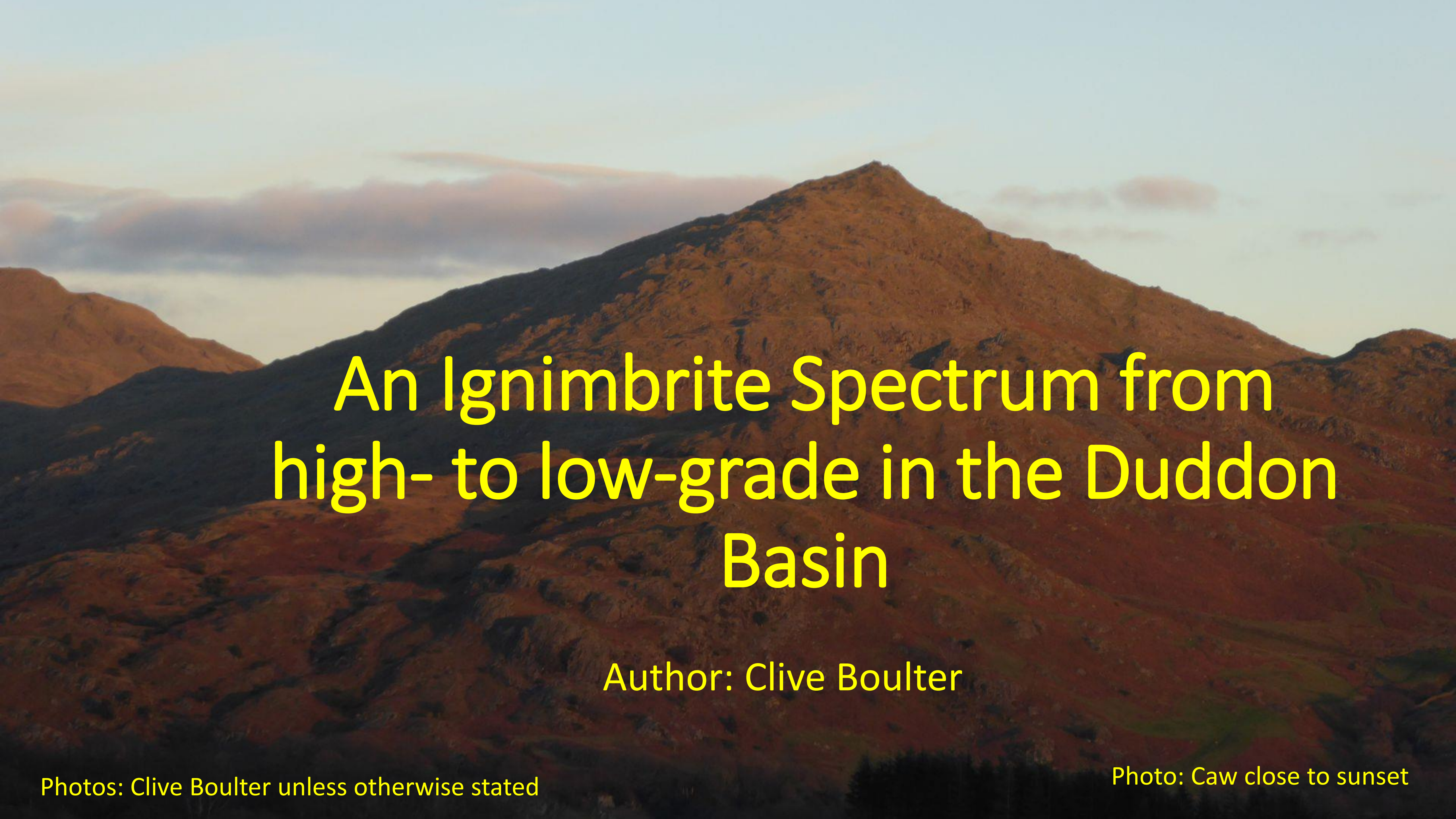


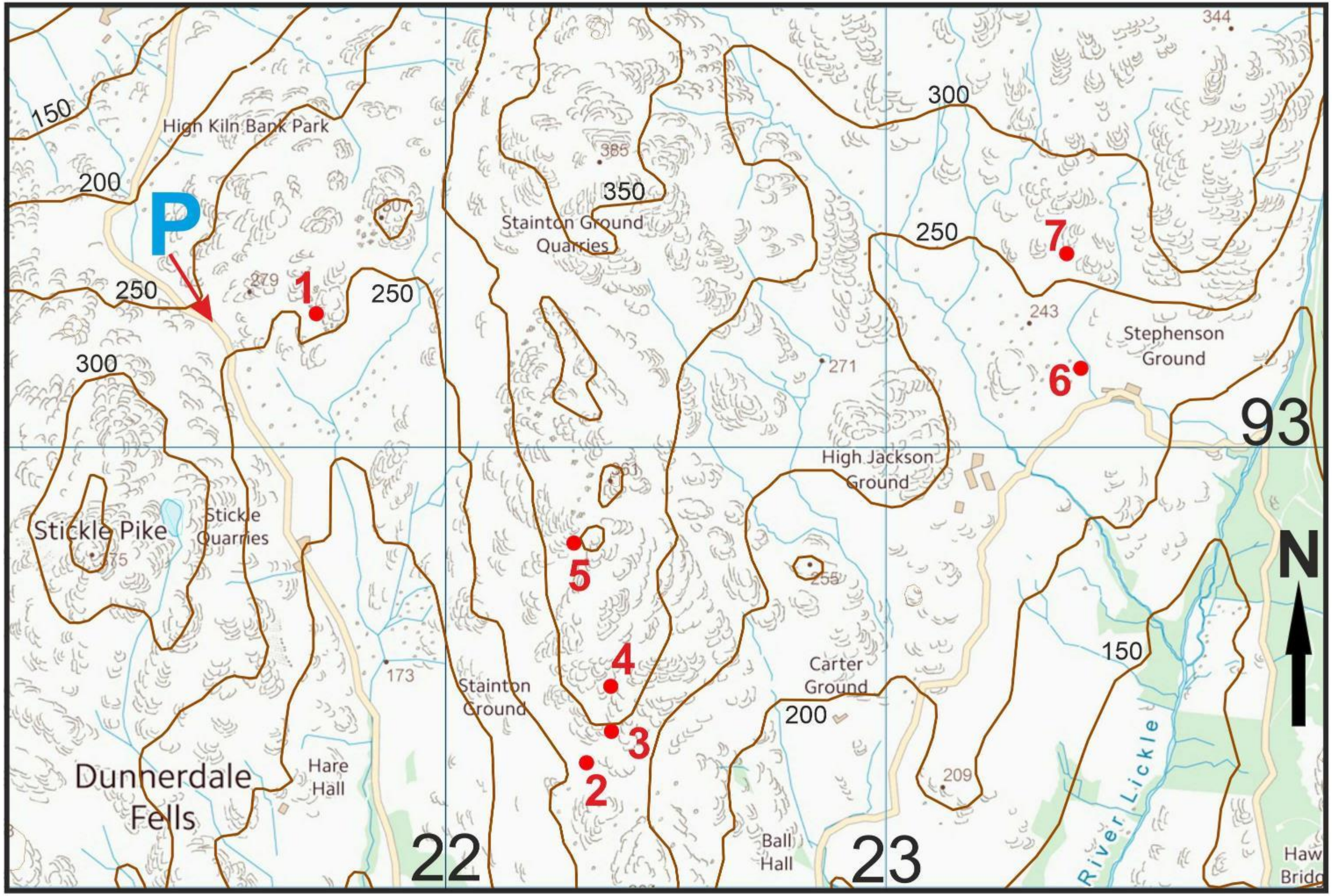
An Ignimbrite Spectrum from high- to low-grade in the Duddon Basin

Author: Clive Boulter

Photos: Clive Boulter unless otherwise stated

Photo: Caw close to sunset

Excursion Localities



LOGISTICS: Start at Kiln Bank Cross, SD 215933. Access to localities three to five is via pathless open fellside. The rest of the itinerary is on reasonably well defined paths. If car[s] can be parked at the eastern end of the traverse for drivers to return to Kiln Bank Cross this will save a return walk.

Ordnance Survey Open Data.

Kilometre grid, contours in metres.

IGNIMBRITES – hot sedimentation!

The main focus for the excursion is an ignimbrite at Raven's Crag in the Duddon Basin depocentre within the Borrowdale Volcanic Group. A subsidiary theme will consider the spectrum of ignimbrite types which is almost completely represented along the traverse from Kiln Bank Cross to Stephenson Ground. Ignimbrite is a bag term and is not a **rock type** name in the same way that turbidite is a genetic bag-term applied to a wide range of materials deposited from a turbidity current. In siliciclastic sequences **rock types** such as wacke, siltstone, and mudstone, are deposited from turbidity currents but the term is also applied to other compositions including clastic carbonate rocks, and rocks composed entirely of volcanic fragments, transported by the same processes. Much present-day usage defines ignimbrite as anything deposited from a pyroclastic density current [PDC], clearly a highly genetic approach but so is the use of the word turbidite. Away from scientific journals, and similar publications, the term PDC is often contracted to pyroclastic current but the density aspect is crucial to the concept because the pyroclast, lithics, and gas mixture [± liquid water], moves under gravity being denser than the surrounding atmosphere. To further set up conventions used on the excursion, a pyroclast is any fragment formed by volcanic activity which for a PDC would include any piece of the pre-eruption rocks ejected in the explosive event.

PDC Definition: eruption-derived particulate-gas density current that moves laterally along the ground [Brown & Andrews 2015 Encyclopedia of Volcanoes, Second Edition, Elsevier]. All the ignimbrites seen on the excursion were deposited on land which means we do not have to consider what happens when PDCs meet a body of water as was the case for the Pavey Ark Member of the Seathwaite Fell Formation.

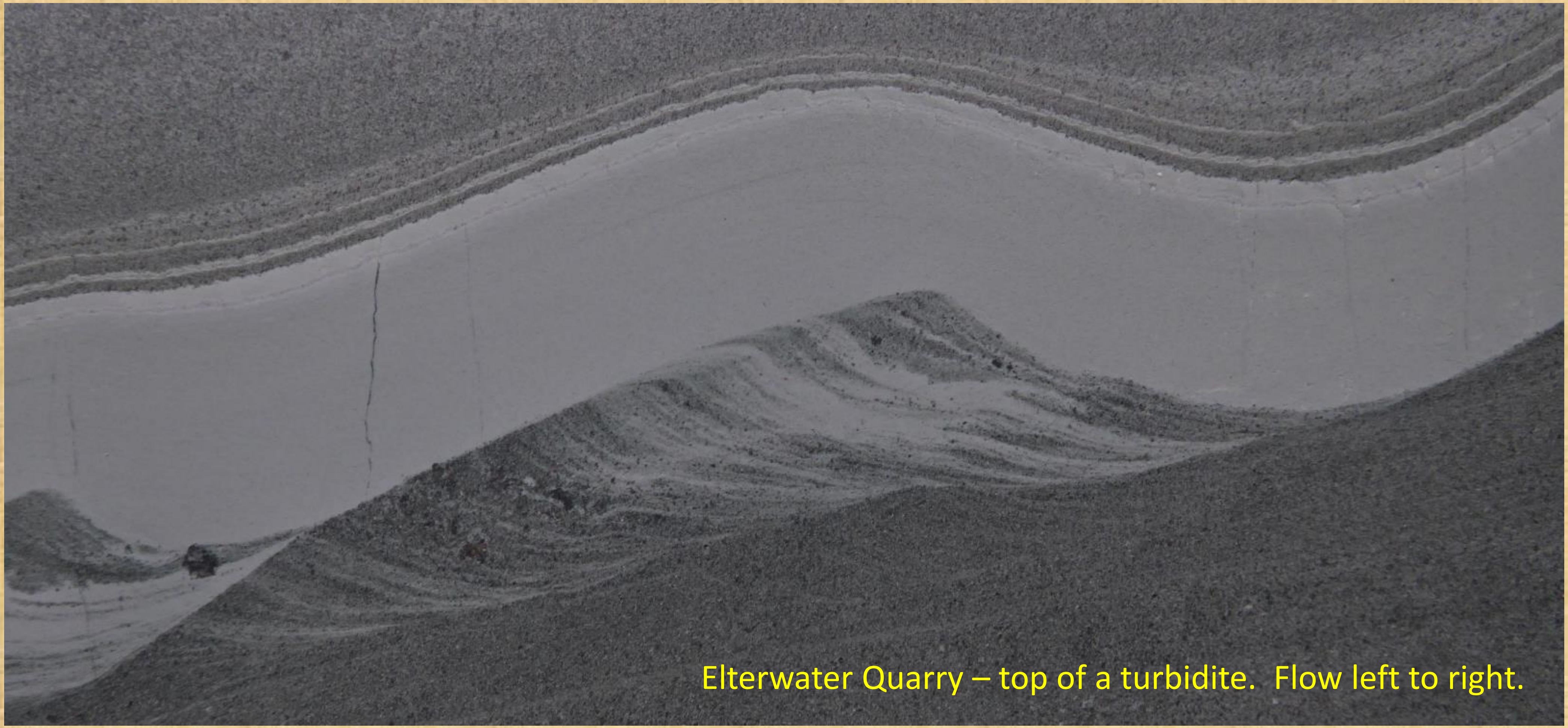
Stratified, cross-bedded, and unwelded, ignimbrite, Santorini [50 cent coin for scale]. This deposit is the product of a subaerial eruption that generated a very dilute PDC, perhaps with only one percent solids [see next page].

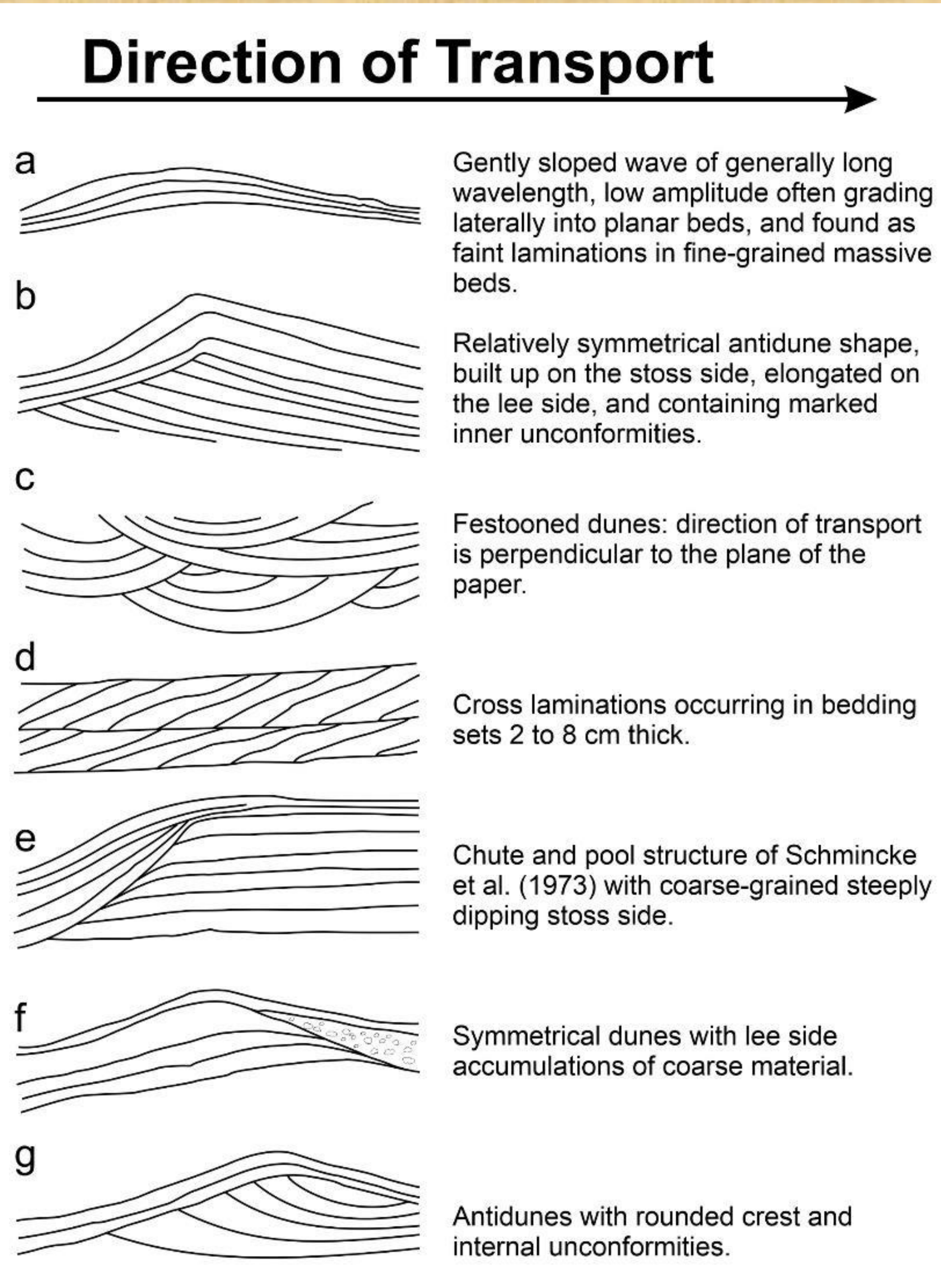
The classic **rock type** deposited from a PDC, and hence the classic ignimbrite, is a lapilli tuff. Remember these are grain-size terms, the tuff component refers to pyroclasts below 2mm and lapilli are in the size range 2 to 64mm. This mixture of grain sizes clearly indicates the defining characteristic of ignimbrites; they are poorly sorted which reflects their catastrophic explosive origin and the turbulent PDC transport process. There are however degrees of poor sorting in PDC/ignimbrite deposits mainly controlled by the density of the PDC. There is a continuum of PDC characteristics best expressed by the variation in particle concentration. Deposits from dilute PDCs are better sorted than those of high concentration PDCs and can be distinctly stratified with upper-flow regime sedimentary structures. Massive structureless ignimbrites, or those with subtle structure, are deposited from high concentration PDCs but, across the entire PDC spectrum, deposition is particle by particle hence this is a sedimentation process despite the high temperatures involved in some cases. Care has to be taken when inferring the characteristics of the PDC from the deposit because the nature of the ignimbrite is only directly controlled by processes at the base of the pyroclastic current.

The PDC continuum historically has been pigeonholed into a number of conceptual bins [pyroclastic flows, surges, ash flows, block and ash flows, glowing cloud, nuée ardente, etc.] and this approach has masked the true nature of the phenomenon being studied. As to origins, PDCs can be produced by a variety of eruption styles including collapse of Plinian columns/curtains, boiling-over/fountaining of eruption jets, directed/lateral blasts, and dome collapse.

A persistent, and widespread misconception, is that ignimbrites have to be welded [pumice flattened]; they do not and some PDCs cannot produce a welded deposit such as those generated when non-vesiculated magma meets external water. Some volcanoes have produced many voluminous ignimbrites with hardly any welded examples. A significant challenge in the Borrowdale volcanics is to recognise non-welded ignimbrites. In active volcanic regions it is normally easy to identify the origin of the vast majority of unwelded ignimbrites because they are created in magmatic eruptions which means that the explosivity is driven by volatiles within the magma. This mode of explosivity is expressed in all the pyroclasts of fragmented magma being frothy, either pumiceous or scoriaceous, depending on composition. If these fragments retained sufficient heat during transport in the pyroclastic current they become flattened, either during deposition or soon [hours] after, leading to the distinctive welding-fabric of aligned, highly-elliptical fiammé. Heat retention implies a high density PDC. If flattening does not happen in a recent ignimbrite formed by a magmatic eruption, the highly vesicular nature of the pumice/scoria will still be clearly evident forming an indellible marker of the eruption style and the transport history in a pyroclastic current. Unfortunately in ancient volcanic terrains that have gone through hydrothermal alteration, and the thermal and fabric changing processes of regional metamorphism, original pumice textures become unrecognisable; other evidence has to be sought to prove that an unwelded ignimbrite had such an origin. One such line of evidence is that dilute, low-concentration PDCs are typically low-temperature and do not retain enough heat to weld but their upper flow regime sedimentary structures are diagnostic of a pyroclastic origin. It was the recognition of this style of sedimentary structure that prompted the pyroclastic interpretation for all of the lower 20 metres of the Caw Formation on Raven’s Crag.

Much of the clastic sedimentology we normally see was deposited under low velocity conditions. The products of upper flow regimes are less common. During ripple formation at lower current speeds, grains are transported up the stoss sides and deposited on lee sides of the ripples [see photo below]. In contrast upper flow regime current velocities commonly produce dunes that accrete material on their stoss sides thus growing into the current direction. The next slide shows the array of distinctive internal structures associated with this growth behaviour. In shallow water the transition from the lower to upper flow regime is at a velocity of around 2 metres per second [~7 km/hr].


Elterwater Quarry – top of a turbidite. Flow left to right.



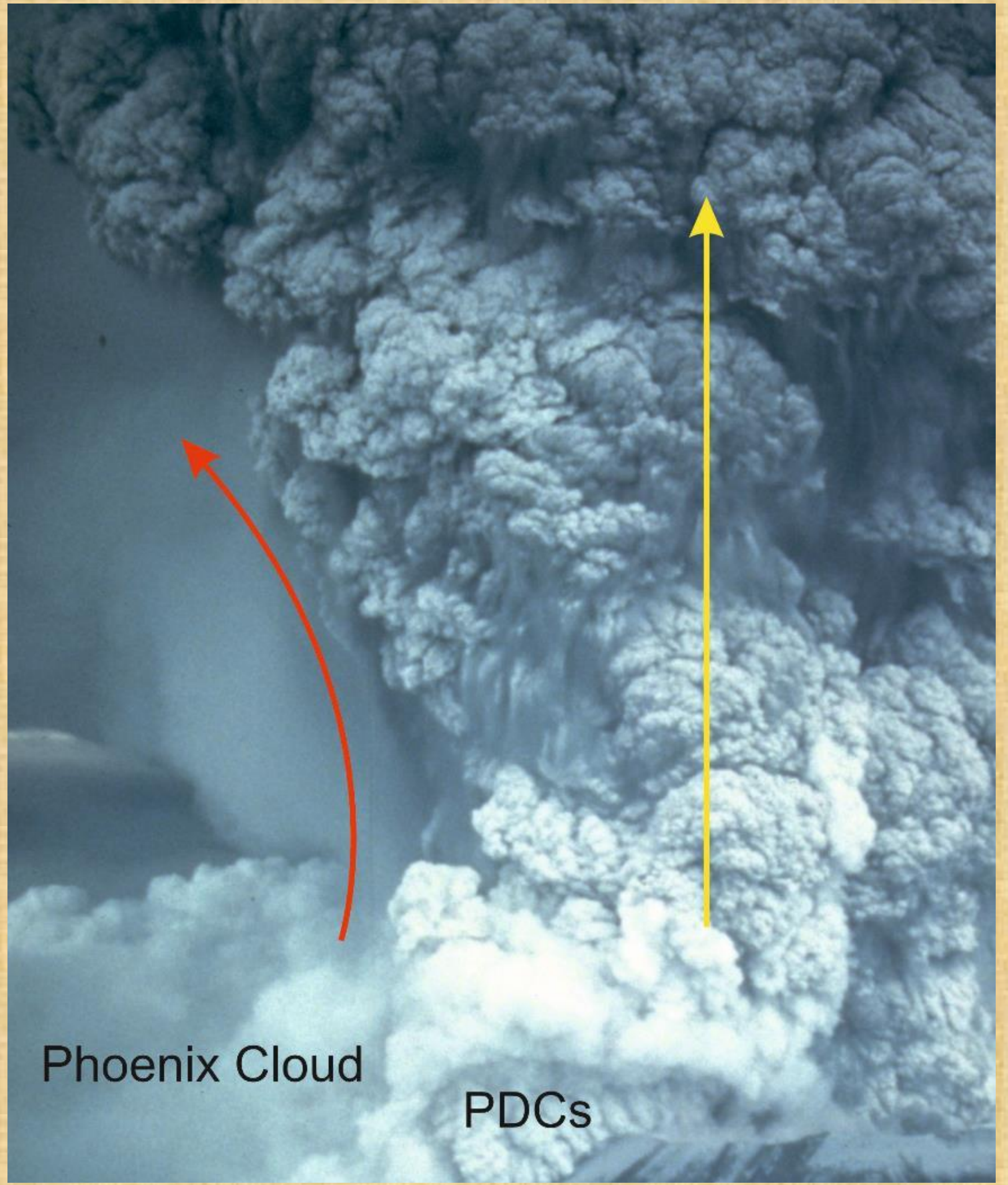
Morphologies of sand-waves seen in ignimbrites deposited from dilute PDCs are shown in this diagram [Wohletz & Sheridan 1979 Geological Society of America Special Paper 180].

These structures are typical of upper-flow regime conditions and are commonly found around tuff rings. Most volcanic edifices of this style form when rising magma meets groundwater. If this happens before the magma vesiculates, the magma fragments will be dense [not vesicular or amygdaloidal] and the explosivity is driven by the expansion of the groundwater. Such eruptions are known as phreatic and this style of eruption cannot produce a welding fabric. Because these events happen near the Earth’s surface it is likely that, in many cases, the magma will have started to vesiculate when it encounters groundwater such that expansion of magmatic volatiles might contribute to the explosive behaviour. Such eruptions are phreatomagmatic and, if the vesiculation of the magma is sufficient, the deposits might be welded. In both styles of behaviour the groundwater involvement ensures that the resultant PDC will be H_2O-rich either as liquid+gas+particulates [<100^{o}C] or gas+particulates [>100^{o}C]. All this moisture produces one of the most characteristic features of tuff ring deposits, accretionary lapilli which are aggregations of ash, a process enhanced by the sticky nature of the moist PDC. Usage of the term accretionary lapilli here is close to the traditional sense and follows Van Eaton & Wilson [2013 Jl. Volcanol. Geotherm. Res. vol. 250, pp. 129-154].

Mechanisms of accretionary lapilli formation have recently been much debated and the Glaramara Tuff in the Borrowdales has figured in this discussion. Brown et al. [2007, Sedimentology, vol. 54, pp. 1163-1189] have determined that the Glaramara Tuff is the product of an exceptionally large tuff ring. They applied knowledge, gained in studies of ignimbrite sheets associated with caldera-forming eruptions, to determine the origin of accretionary lapilli in tuff rings. In the latter settings explosive eruptions are episodic because groundwater needs time to recharge after each explosive event. The intervals between explosive events may be tens to a hundreds of years or they may be semi-continuous. In this account the formation mode for accretionary lapilli proposed by van Eaton & Wilson is adopted.

Mt St Helens 7th August 1980 showing ground hugging PDCs with ash lofted above the PDC forming a Phoenix cloud. United States Geological Survey

Formation of accretionary lapilli involves the interaction between processes in an eruption column/curtain, a PDC, and its overlying Phoenix cloud [coignimbrite plume]. PDCs are dense and hug the ground. The billowing clouds seen in the photo to the left are formed of ash lofted out of the PDC as ambient air entrained in the PDC is heated and becomes buoyant. Some recent publications [e.g. Brown et al. 2009 Geological Society of America Bulletin vol. 122 pp. 305-320] classify ash aggregates so as to restrict the use of the term accretionary lapilli and thus exclude much of what has been traditionally given this name in numerous publications. In this approach to be an accretionary lapillus requires an outer coating of very fine-grained ash with well developed concentric laminations surrounding a structureless core of coarser ash. A similar core but with an unlaminated coating of very fine-grained ash is a coated ash pellet. The deposits at Raven's Crag have only been studied in the field so detailed textural information is not available. Hand specimen examination shows weak lamination in some very fine-grained coatings so some of the ash aggregates might be accretionary lapilli in the Brown et al. classification. In these notes the classification Van Eaton & Wilson [2013 Jl. Volcanol. Geotherm. Res. vol. 250, pp. 129-154] will be used. These authors have massive ash pellets, layered accretionary lapilli, and ultrafine rim-type accretionary lapilli. Ash pellets are internally structureless and some have films of fine ash less than 0.2 mm thick. The layered variety are pellets that have one normally graded layer or multiple layers of similarly sized ash. The rim type have one to two layers of ultrafine ash around a coarser core and there is a distinct boundary between core and rim. This variety is found only in PDC deposits.



An indication of the basic dynamics involved in forming accretionary lapilli.

Massive ash pellets form in the eruption column/curtain and are dispersed downwind in the umbrella cloud. These pellets are internally structureless but some have films of fine ash less than 0.2 mm thick. If pyroclastic density currents are not created by the eruption, the pellets fall out of the umbrella cloud to form airfall deposits.

If the eruption column/curtain partially collapses or fountains, the interaction between PDCs, and the buoyant plume, creates an updraft of warm moist air. This in turn interacts with the umbrella region and results in a stratified and turbulent hybrid cloud dispersing downwind. Massive ash pellets falling out of the higher levels of the cloud now gain coatings by circulating between these different levels.

The ultrafine rim accretionary lapilli gain their rims when ultrafine ash is lofted from the PDCs [Phoenix clouds]. Layered accretionary lapilli falling into this extremely fine ash typically acquire multiple rims in a turbulent environment.

The scenario outlined here explains why the ultrafine rim-type accretionary lapilli are only found in PDC deposits [ignimbrites].

Photo: USGS image of an eruption at Mt St Helens.

Locality 1 Acadian Syncline in the Caw Formation SD 21702 93279

Small scale Acadian [tectonic] folds are not common in the Borrowdale volcanics. Almost all the rocks to be examined today are cleaved but the intensity is generally low and rarely gets in the way of recognising primary features. Locality one is more of a trial to test the quality of the slate but it is on the edge of the fairly extensive Stainton Ground quarries where the finest-grained lithologies were worth exploiting.

Within the Caw Formation there is a general coarsening upwards trend in a unit that is predominantly formed of pyroclastics reworked by rivers and lake processes. Debris flow events probably contributed significantly to the accumulation of the Caw Formation. The only definitive sedimentary structures in the lower part of this unit at Stainton Ground indicate a lacustrine origin.

Some of the worked faces have been split along the cleavage revealing the trace of bedding on the cleavage – the intersection lineation.

Weakly-defined graded bedding in a loose sample from Stainton Ground Quarry. Structures of this style indicate a lacustrine origin for these deposits.

Locality 2 High-grade ignimbrite, Paddy End Member, Lickle Formation. SD 22313 92279

This is a rhyolitic ignimbrite with a distinctive pink weathering rind. Highly flattened pumice fragments define a strong welding foliation parallel to the long adge of the GPS unit.

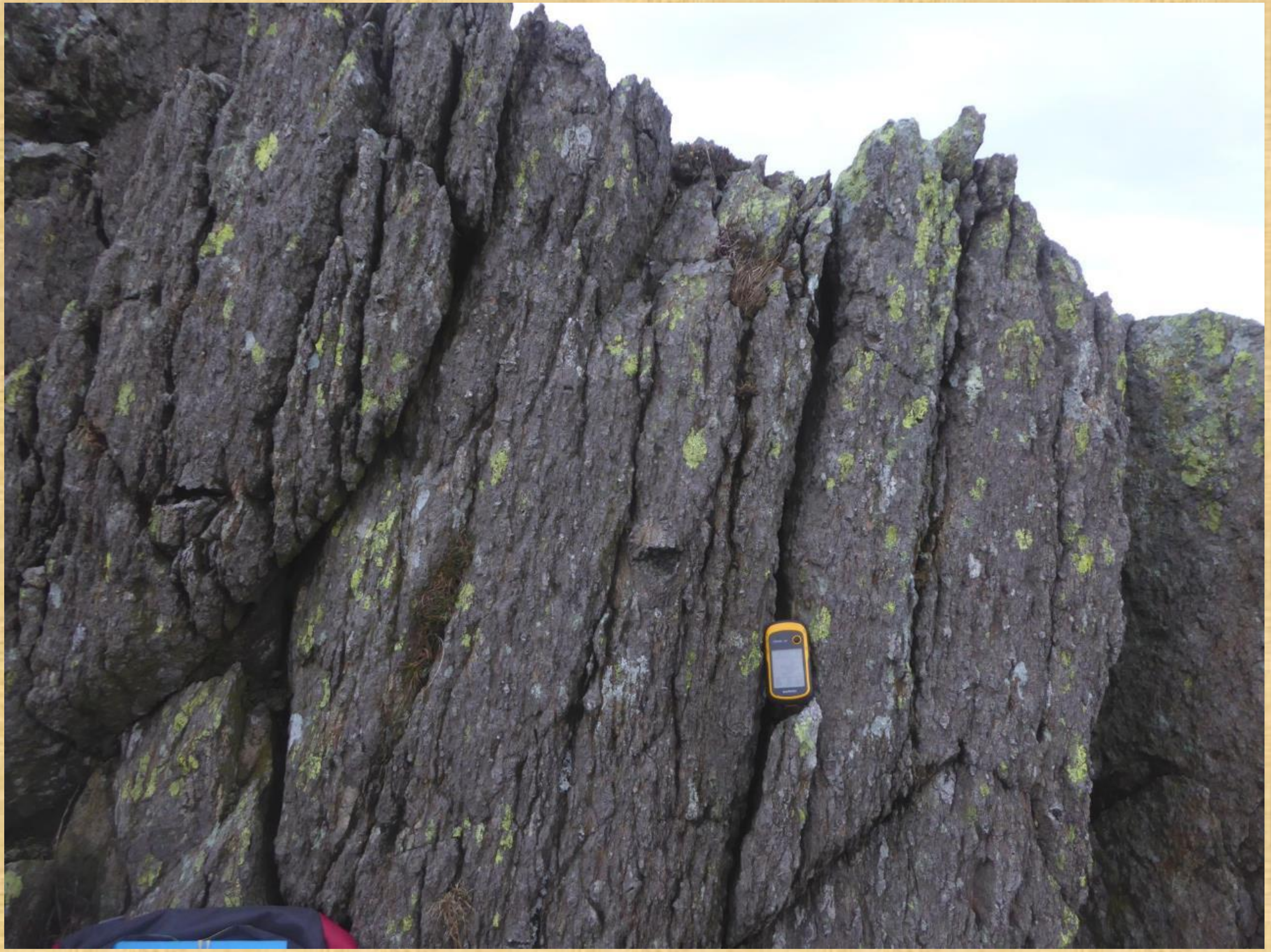
A parataxitic texture is a foliation created by extreme flattening of pumice fragments. A eutaxitic texture is a less intense version of the flattening foliation. The boundary between the two classes is not quantified.

The Paddy End Member is the lowest of the three stratigraphic units we are examining today. It is overlain by the Stickle Pike Member of the Lickle Formation which is followed by the Caw Formation.

Locality 2 is on the edge of a very fine example of a glacial meltwater channel which is best appreciated from a distance as in this photo from Stickle Pike.

Locality 3 Stickle Pike Member – rhyolitic lapilli-tuff. SD 22377 92357

There are better exposures of this unit but they are less convenient for our traverse.



At this locality there is a weak fabric defined by the alignment of slightly flattened pumice pyroclasts. On weathered surfaces small white fragments stand proud. According to the Ambleside Memoir these are non-vesiculated fragments of the magma that caused the explosive eruption.

The Stickle Pike Member varies from eutaxitic to parataxitic.

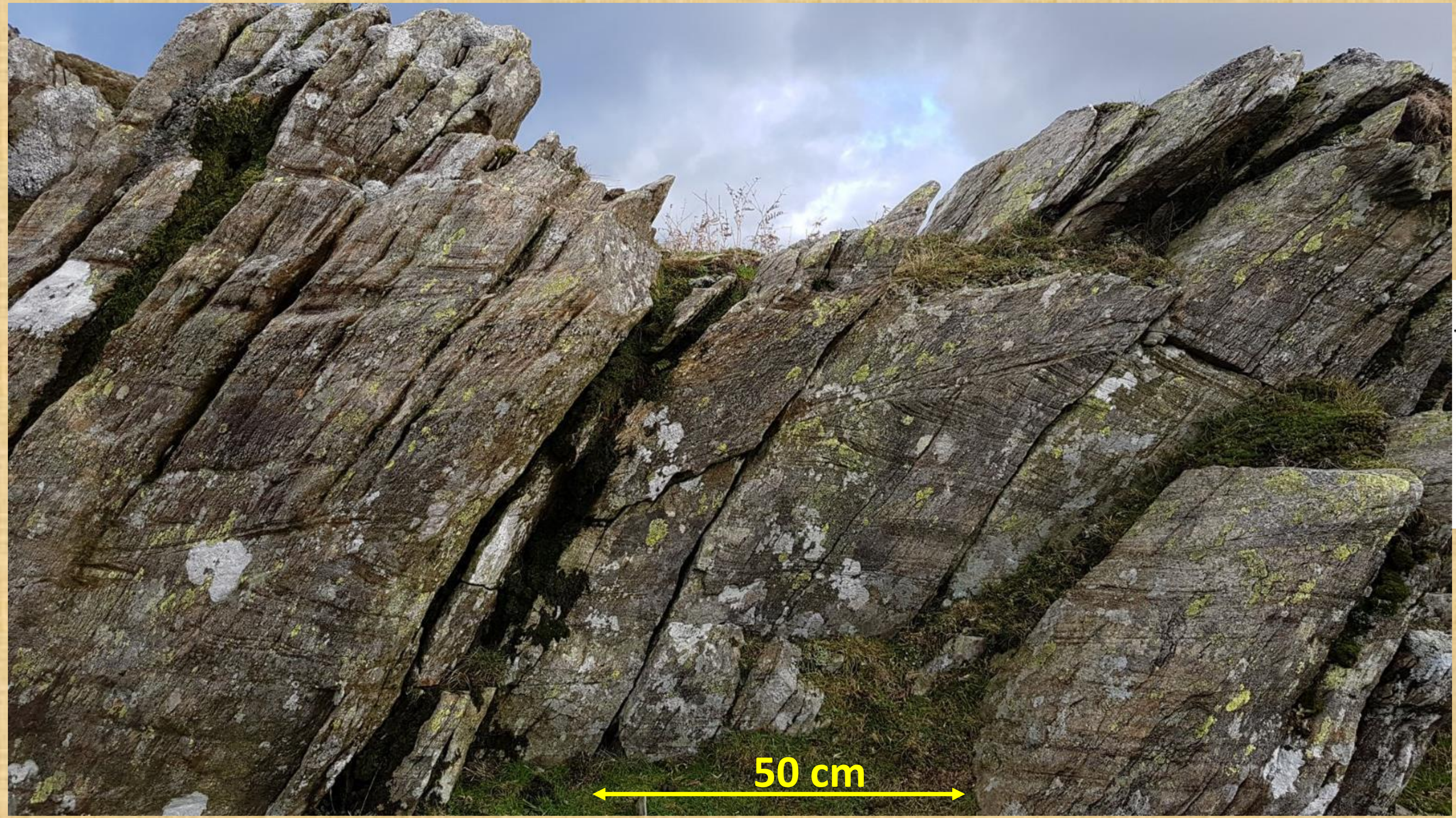
Locality 4A Raven’s Crag
Stickle Pike Member/Caw Formation contact. SD 22368 92454

In the lower unit [Stickle Pike ignimbrite] the weathered out [caries texture] pumice clasts show limited flattening but still define a weak eutaxitic fabric. The overlying stratified unit [basal Caw Formation] is the low density PDC deposit. Cross stratification and accretionary lapilli are common in this upper unit.

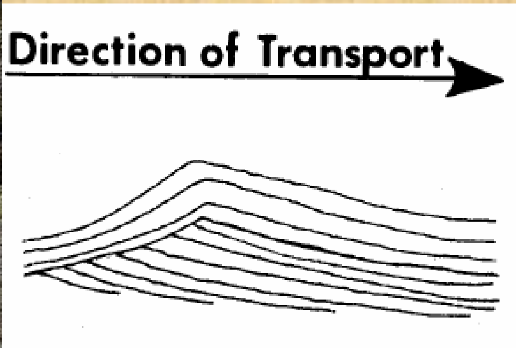
When defining mapping units [lithostratigraphy] a pragmatic approach has to be taken. Even though the two ignimbrites may be more closely related to each other than the stratified ignimbrite is to the rest of the overlying Caw Formation materials, the contrast between stratified and non-stratified rocks is easier to map.

Locality 4B Upper flow regime cross stratification in the low density PDC ignimbrite. SD 22405 92510

See the diagram on Slide six for comparable examples from tuff rings. Flow from left to right with accretion on the stoss side typical of upper flow regime environments. Slightly elliptical accretionary lapilli form layers, their shape is a result of weak Acadian strain.



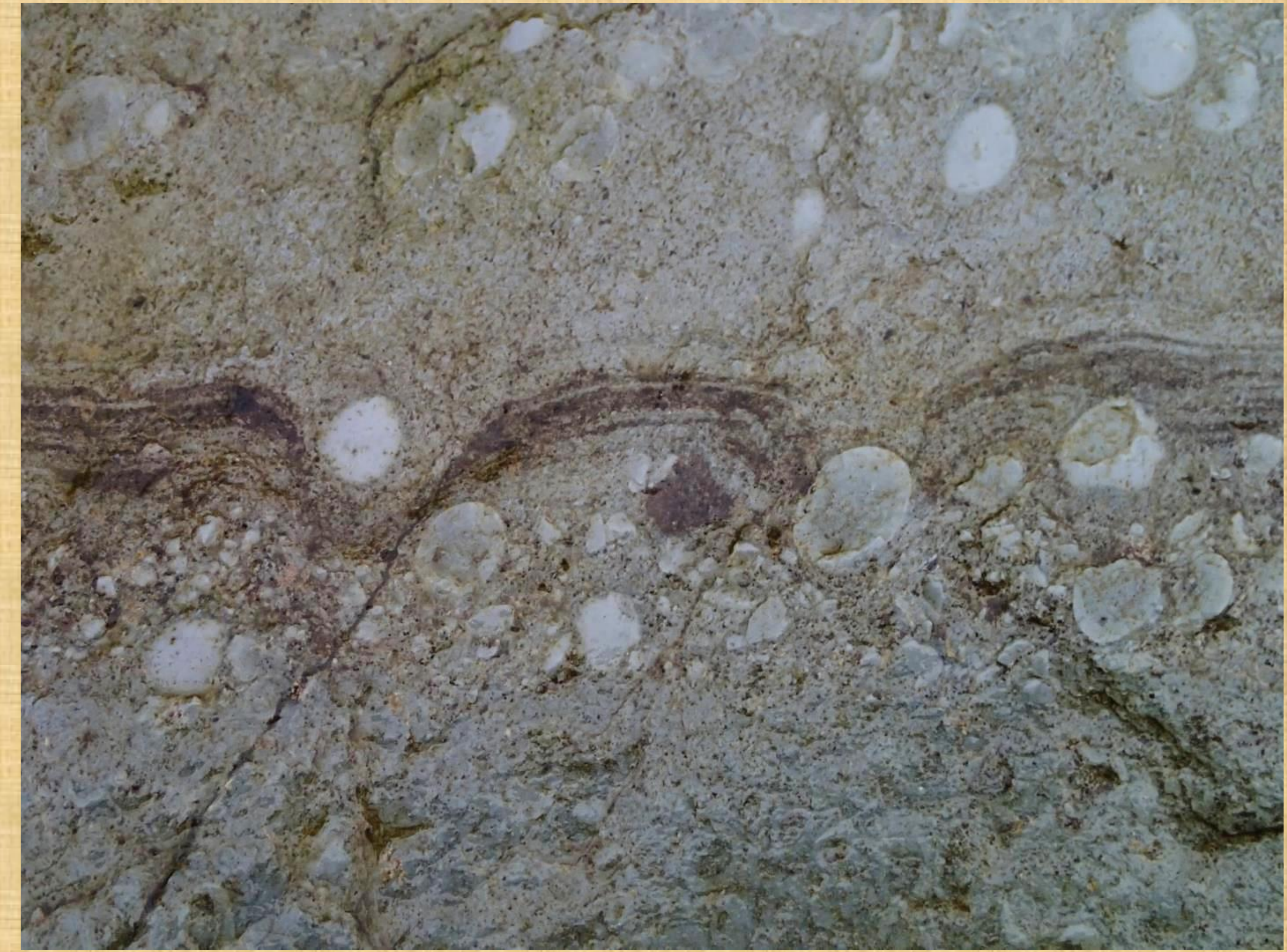
The layer above the internal unconformity on the stoss side is continuous over the crest and down the lee side.



Examples of accretionary lapilli from Locality 4.

The photo below shows rim fragments typical of ash aggregates sufficiently hard to fracture during collisions in a turbulent PDC. Is the weak concentric structure in some of the aggregates enough to classify them as accretionary lapilli in the Brown et al. scheme?

Most accretionary lapilli range from 5 to 10 mm.

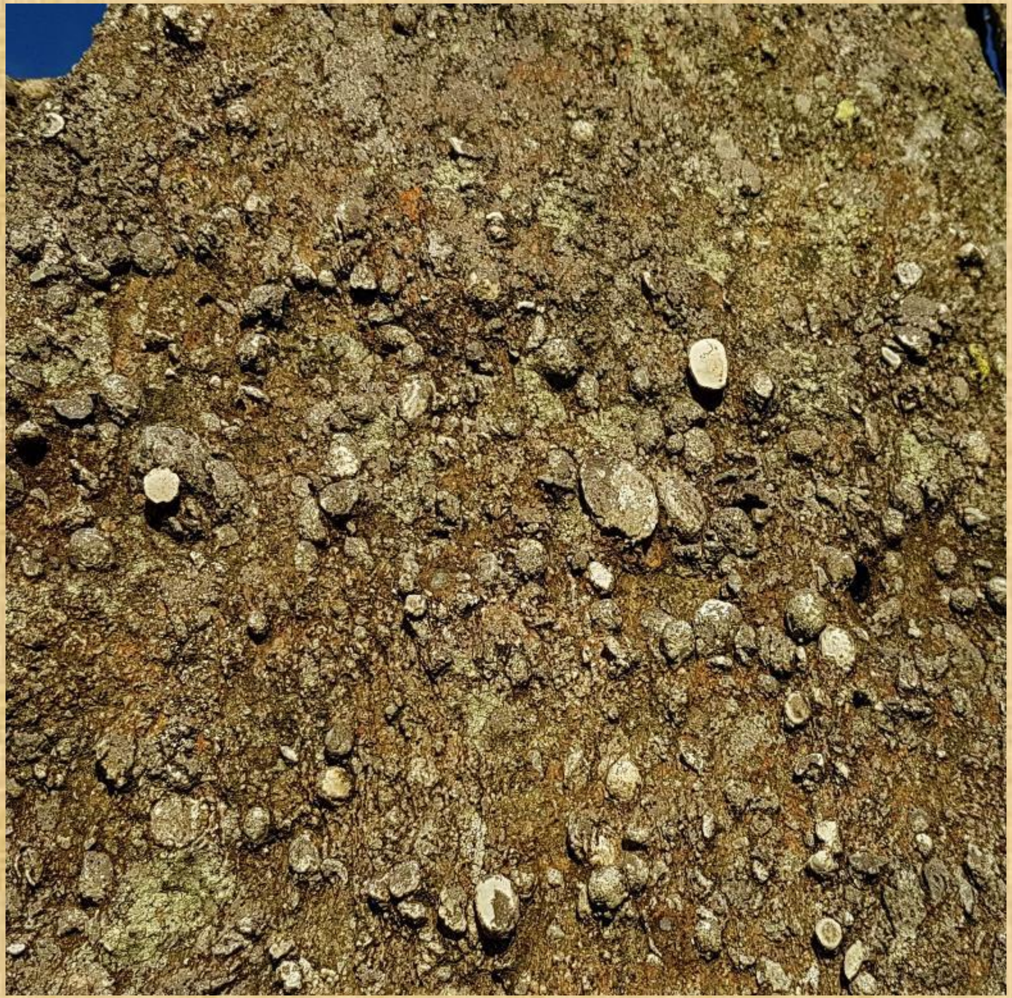


Impact sags created by clearly robust accretionary lapilli [Longsleddale].

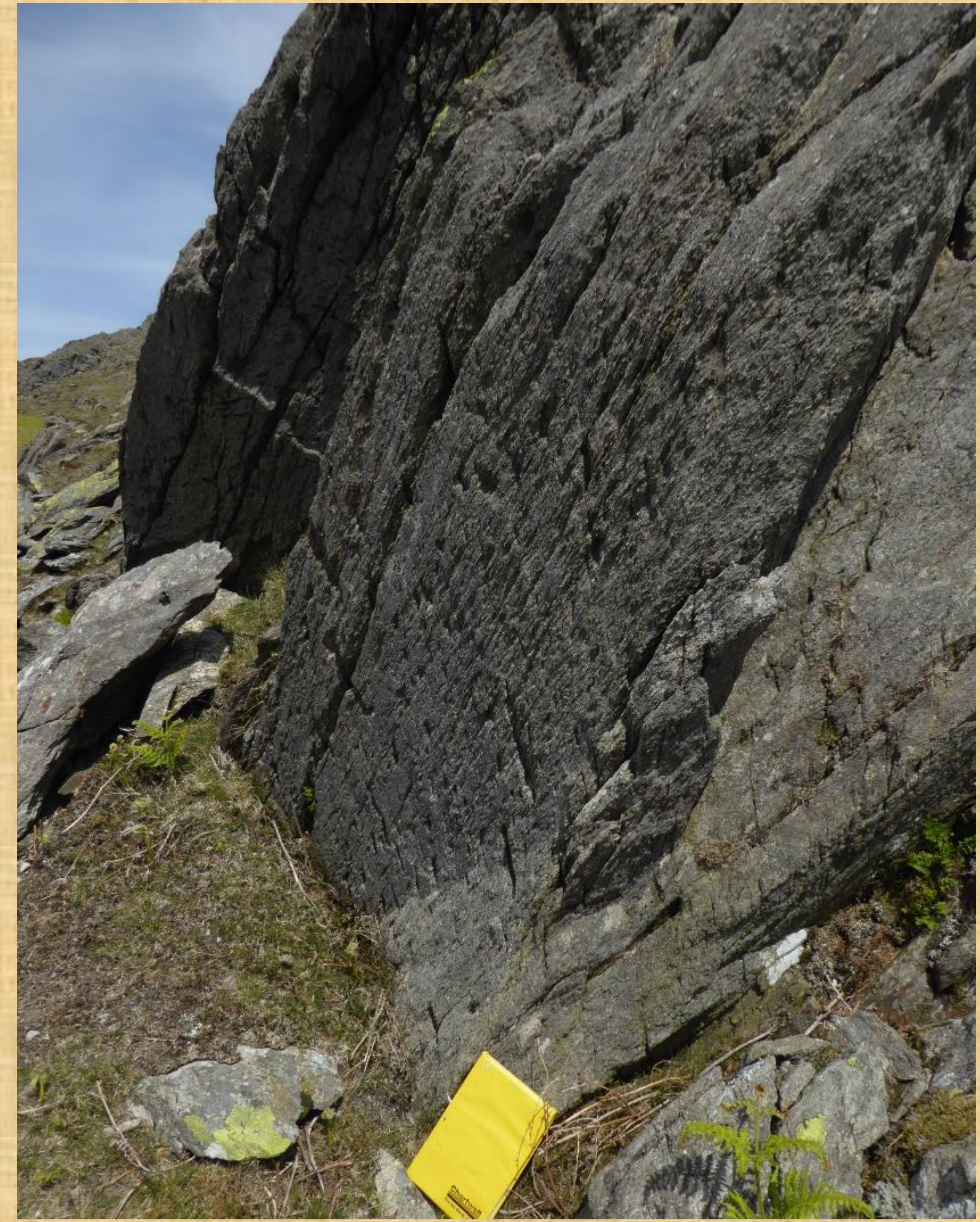
It is surprising how many volcanologists still believe that accretionary lapilli are weaklings that fall apart [disaggregate] at the slightest provocation. Rim fragments are one indication of how tough, but brittle, they are. Their presence in deposits from PDCs is another indication of a tough nature. Another sign of resilience is shown here where they have impacted an admittedly soft substrate and remained intact.

Locality 5 Debris flow deposit reworking the accretionary lapilli tuff.
SD 22299 92766

Two debris flows rework the ignimbrite at this locality. The far image shows most of the thickness of the upper debris flow deposit. The prominent circular to slightly elliptical white objects are 5 to 10 mm accretionary lapilli. The larger fragments are pieces of the pre-existing stratified deposits ripped up by the erosive debris flow. Clearly the accretionary lapilli are tough and do not readily disintegrate.



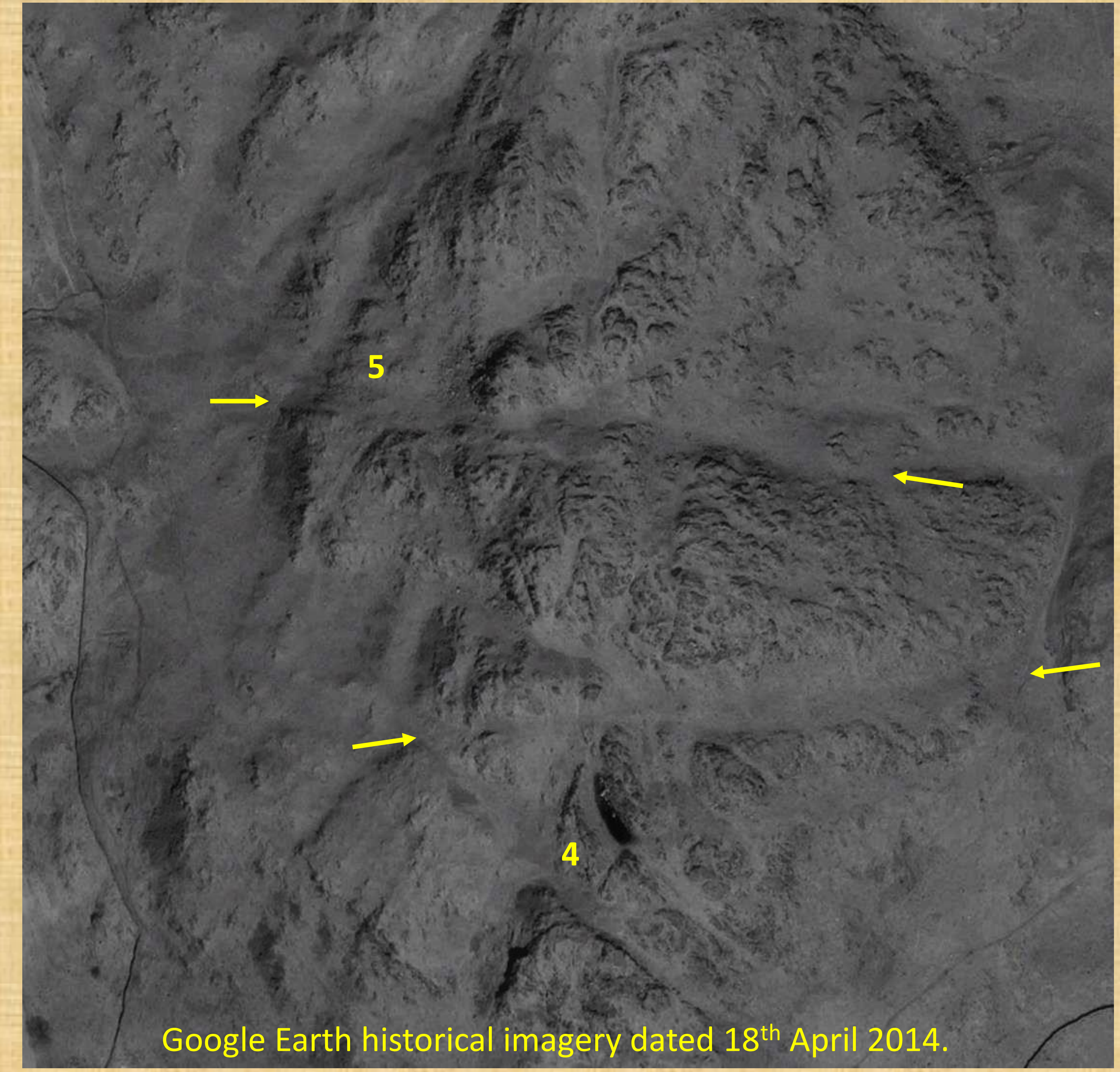
Closeup view of the upper part of the photo to the right.



Locality 5A SD 22225 92740

Welding fabric in the Stickle Pike Member steepening into the volcanotectonic fault that marks the boundary between primary pyroclastics to the south and reworked pyroclastics to the north. The likely position of the VTF is shown on the next slide.

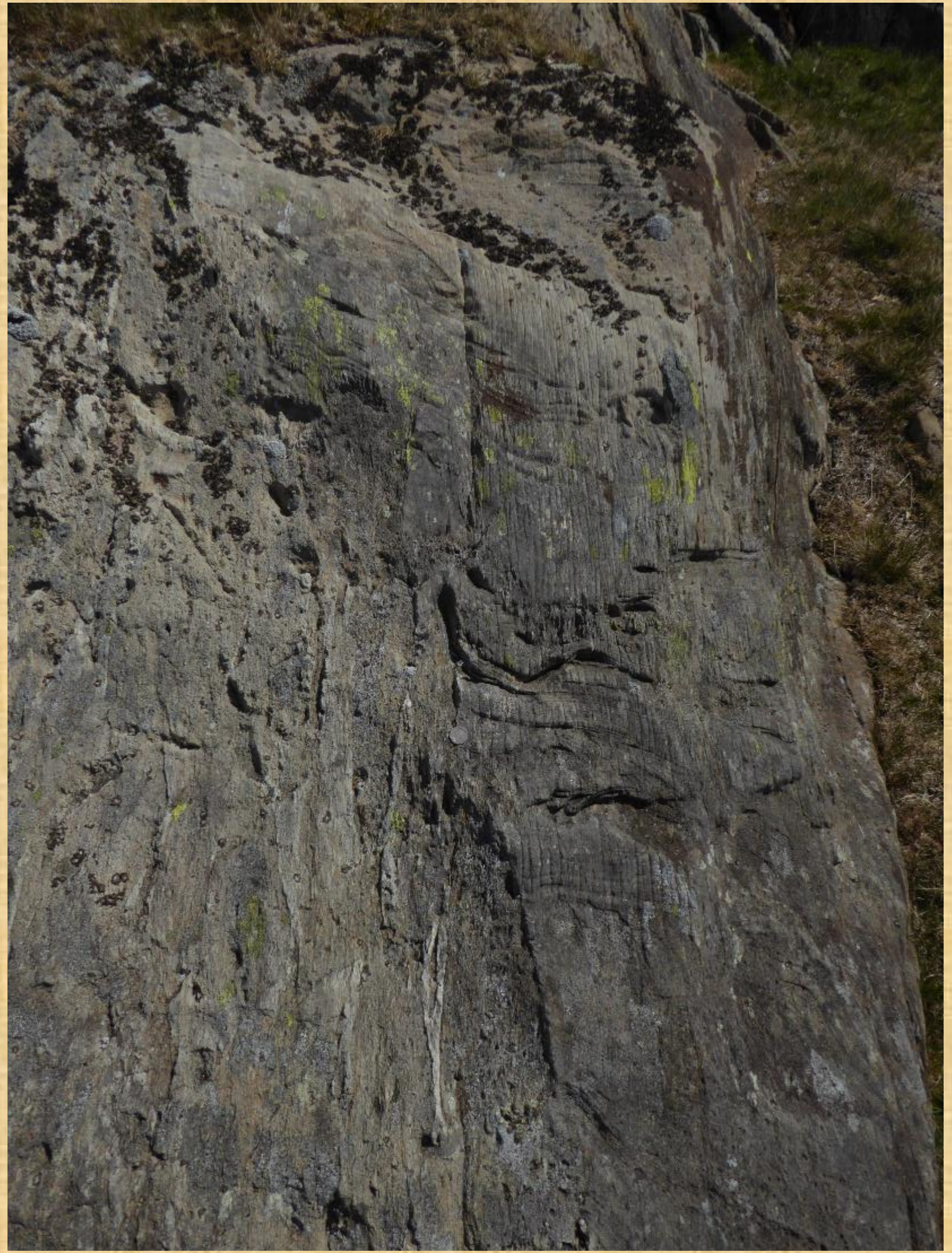
Another example of “pimple” rock – debris flow reworking of accretionary lapilli from Locality 5. Some people think accretionary lapilli are soft weaklings that cannot withstand reworking or transport in PDCs!



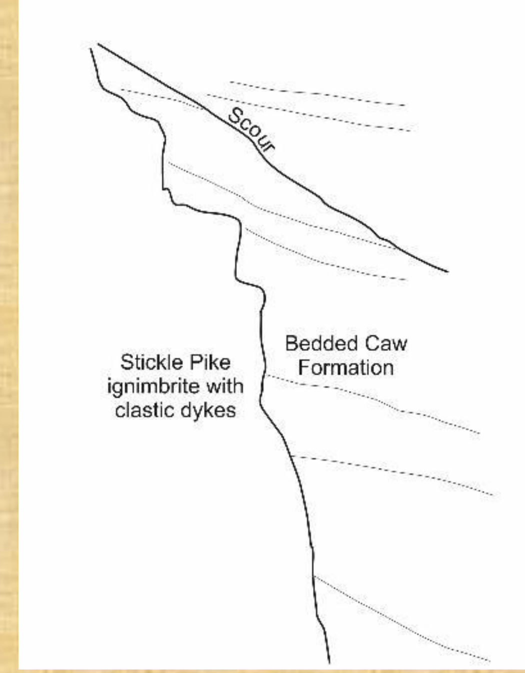
Google Earth historical imagery dated 18th April 2014.

Subtle east-west slacks are seen in some imagery but not all depending on vegetation growth, sun angle, and timing of capture. Two are shown here and the northern example marks the place where the lowermost Caw Formation changes from pyroclastic to debris flows. The east-west structures are volcanotectonic faults [VTFs] which were active during emplacement of the Stickle Pike Member and which must have been topographic features at the start of Caw deposition. To the south of the northern VTF the first 20 m of the Caw Formation are primary pyroclastics of a subaerial nature. To the north there are only reworked pyroclastics typified by debris flows. Further north are the slates of Stainton Ground Quarries which are lacustrine deposits.

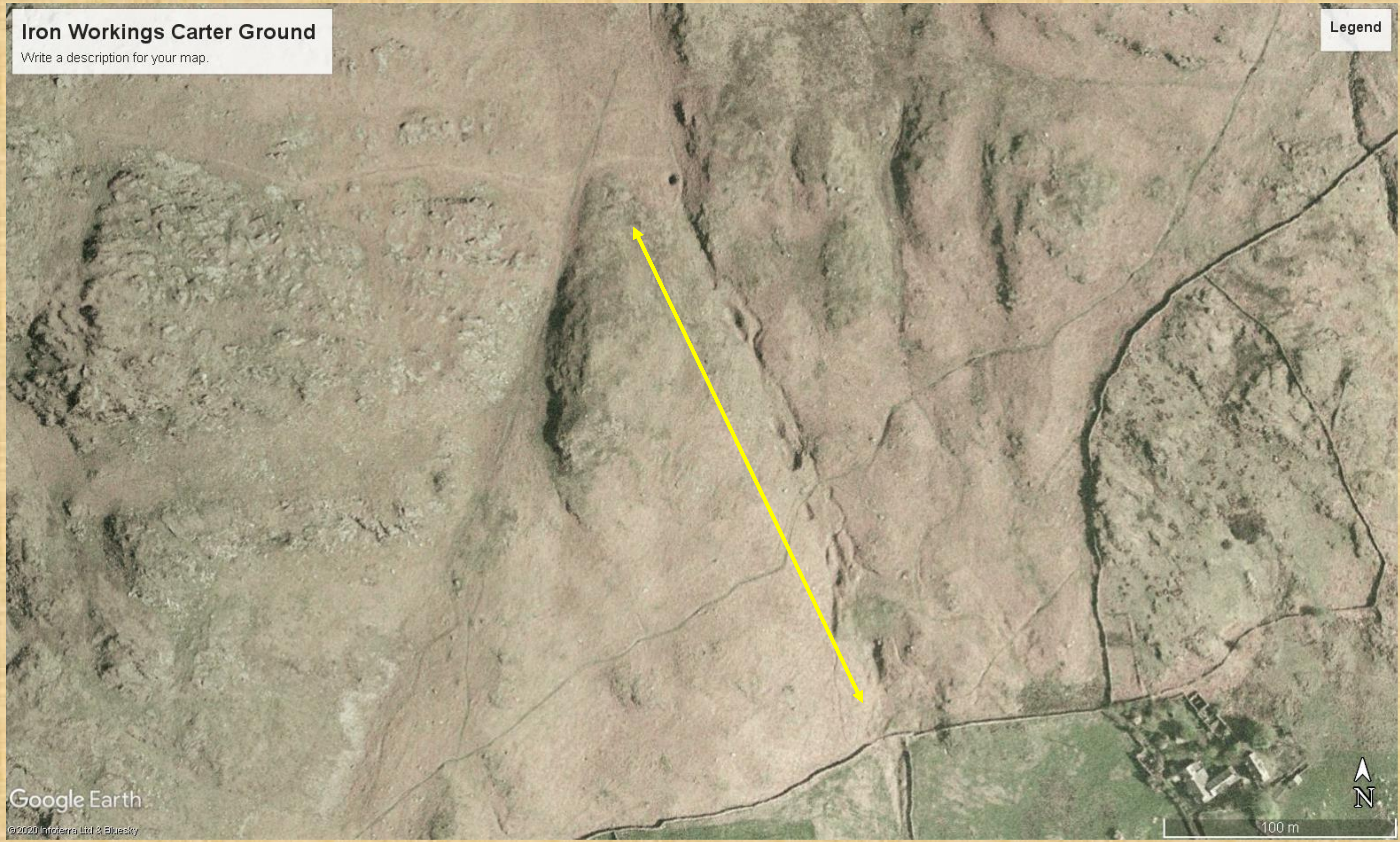
Conventional aerial photography of this area highlights NNE-SSW fractures of probable Acadian age. Typically for the Borrowdale volcanics the VTFs have a weak expression.



An example of the topography on the top of the Stickle Pike ignimbrite at the start of Caw Formation deposition. This exposure is from the next large fault block to the east and is close to the Tail Crag volcanotectonic fault. At this locality there is an approximately four metre step in the Stickle/Caw boundary which was present at the end of the Stickle ignimbrite event. There has been no subsequent reactivation as there are no signs of fault brecciation of any other expression of brittle failure.



Line drawing of the elements in the photograph. The abundant clastic dykes in the ignimbrite help to define the its contact with the overlying sedimentary deposits of the Caw Formation.



Having looked at Localities 4 & 5 drop down to the main Kiln Bank Cross to Stephenson Ground path and head east. At about SD 22720 92509 you cross a small valley which has an array of pits trending parallel to the yellow line on the photo. These are old iron workings now heavily overgrown and barely recognisable. This is the same event that created the haematite deposits on the west coast of Cumbria in the mid-Triassic.

“At Carter Ground there is the site of Dunnerdale iron mine. It was worked by the Carnforth Iron Co and produced 2100 tons of ore in 1872 and 2800 tons in 1874. All that remains is some subsidence along the line of a vein, a small spoil heap and a loading platform.” Cumbria Amenity Trust Mining Historical Society, Newsletter 108, 2012.

Before heading to **Locality 6** you should go to SD 23377 93433 to remotely sense **Locality 7** to decide if you want to get up close to the rock face which involves a bit of a hike using an Open Access route.

Locality 6 SD 23451 93202

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

Locality 7 SD 23413 93461

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

Fanned columnar cooling-joints in welded ignimbrite of the Stickle Pike Member, Lickle Formation, Stephenson Ground Crags. Exposure approx. 7 m high.

The welding fabric defined by flattened pumice clasts is at high angles to the length of the columns [just about visible in the photo].

Locality 7 welding fabric.

In a fallen block the flattened pumice fragments can be seen standing proud to define a strong foliation. Most of the fiammé are between two and three cm long. Joint faces in the crag are smooth but the welding foliation is still visible. Again better defined on fallen blocks are zones of alteration which tend to locally subdue or obscure the eutaxitic fabric.

Supplementary Material – source of the stone water yeats

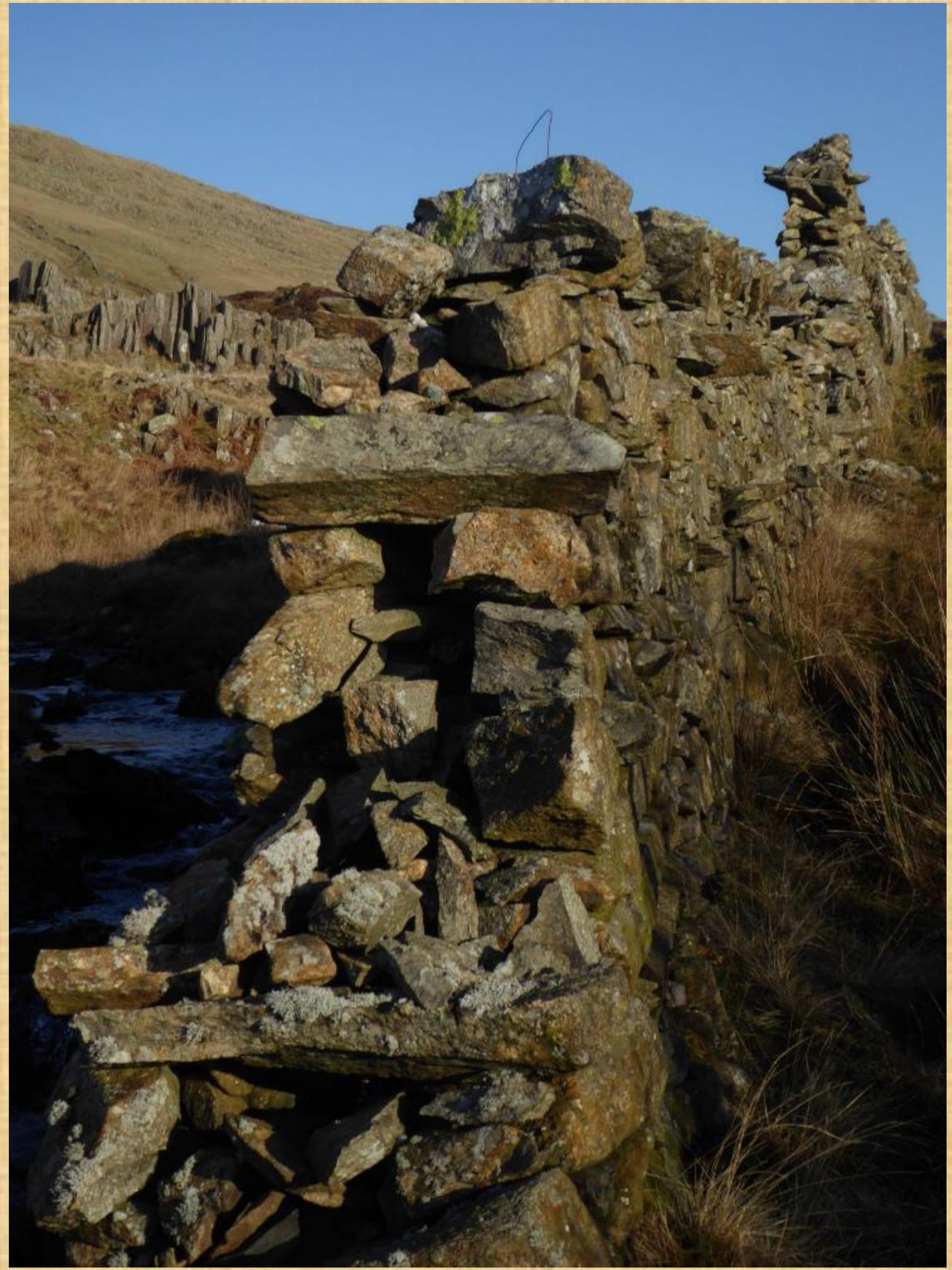
The “rhyolite quarry” at SD 2454 9463 and hexagonal rock columns [Lag Bank Formation]. This is columnar cooling-jointed welded ignimbrite and probably was the source of the bars in the local water yeats. Visiting this locality would make it a long day possibly best left to a full day studying the maar/diatreme at Tail Crag and the sill-related hydrothermal vent complex on White Maiden.

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

A reasonably regular column.

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

Welding fabric fairly well defined.



Columns: good for through stones and coping stones but not as great for building stones.

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