A micro-maar fed by a reused volcanotectonic fault, Tail Crag, Duddon Basin, Borrowdale Volcanic Group

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Abstract

At the end of the Stickle Pike Member explosive eruption, the top surface of the ignimbrite sheet was marked by steeply-dipping scarps created by movement on volcanotectonic faults. Despite the high degree of fracturing associated with these faults, as shown by swarms of clastic dykes, they did not produce talus slopes perhaps because they were of limited height. The most significant of the fault scarps, the Tail Crag, separates distinct sedimentary facies in the earliest Caw Formation deposits showing that the topography on the top of the Stickle Pike Member was sufficient to influence sedimentary processes. When pyroclastic activity resumed the Tail Crag volcanotectonic fault was reactivated and was a feeder to the Lag Bank ignimbrite deposit. Initially magma in the fault interacted with groundwater in the Caw Formation deposits forming low-density pyroclastic currents which deposited accretionary lapilli tuff and cross-bedded stratified lapilli -tuff. Some of this tuff sequence was brecciated and fell into the fault creating a small-scale maar with a diameter of ~150 m. Before the bulk of the Lag Bank was erupted a deposit of pyroclastic block-breccia was localized either side of the trace of the Tail Crag fault above the stratified tuff.

Introduction

The Duddon Basin succession is something of an enigma in that only one of its major explosive eruptions (Waberthwaite) has been attributed to caldera formation despite the size of three of the later explosive events, each of which produced ignimbrites with maximum thicknesses around 600 m (Millward et al. 2000). Millward (2002) stated that apart from the earliest explosive event, the Waberthwaite Formation, there is no evidence that other ignimbrite units in the Duddon Basin formed calderas. It has been suggested that the uppermost approximately two kilometres of the succession was accommodated by downsag and extension (Millward 2004). These interpretations are reinforced by the terminology applied to the major units in the region; basin for the Duddon and caldera for Scafell. As seen in a synoptic overview of volcanotectonic faults in the Borrowdale Volcanic Group there is a stark contrast between the high-density of these faults in the Scafell Caldera and their inferred sparse distribution in the Duddon Basin (Figure 15 in Stone et al. 2010). Another indication of the probable involvement of volcanotectonics in the region is the very significant angular-unconformity, to the southwest of Coniston Old Man, between the upper parts of the Duddon stratigraphy, and the lacustrine Tilberthwaite Formation (Millward et al. 2000).

Sedimentary-facies contrasts across an east-west trending topographic slack in the Dunnerdale Fells (Figure 1) prompted a study of the local geology and an examination of remotely-sensed images which revealed a large number of previously-undocumented potential volcanotectonic faults. These observations may have

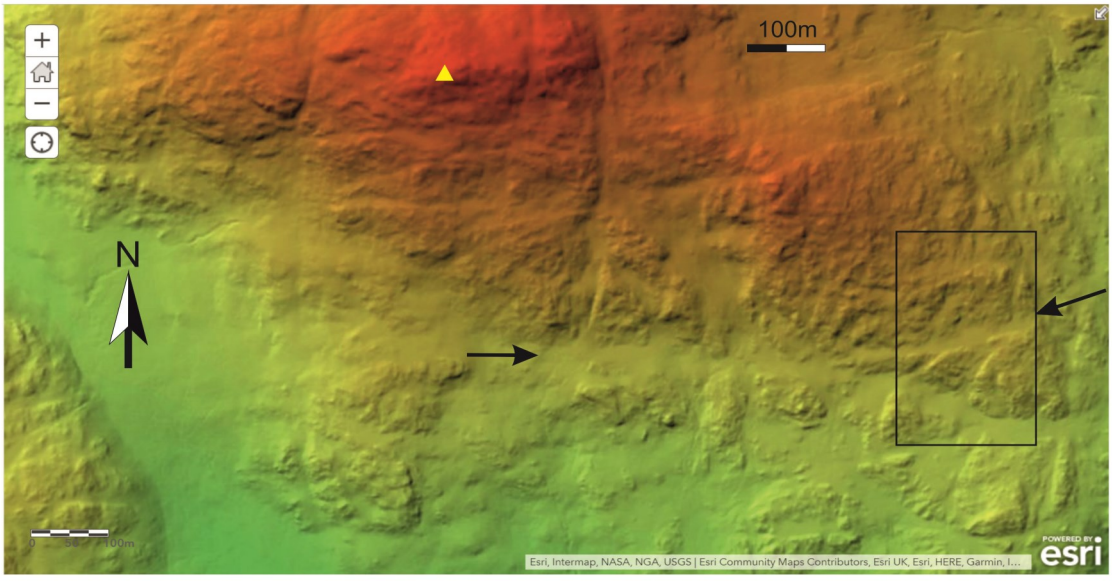


Figure 1.

A LiDAR image of the area south of Caw summit (triangle). Several east-west lineaments are representative of a trend common in the wider region. The arrowed lineament is the broadest slack locally and has been informally named the Tail Crag Fault. The box has been mapped in detail (Figure 6). The image is the 2020 1m DTM LIDAR Composite Tinted Shaded Relief model produced by the Environment Agency. The Tinted Shaded Relief (TSR) is a color 3D representation of the terrain, created by merging the images from the Elevation-coded and Hillshade methods (Open Government Licence OGLv3

far-reaching consequences for the volcanological model of the Duddon Basin which is a major component of the Borrowdale Volcanic Group.

Geological Setting

The Duddon Basin post-dates the initial phase of catastrophic explosivity in the well-documented Scafell Caldera and occupies a substantial portion of the Borrowdale Volcanic Group outcrop. Approximately 70% of the three-kilometre-thick sequence in the Duddon Basin is pyroclastic starting with andesitic ignimbrites and airfall tuffs, ending with mainly dacitic ignimbrite. Towards the upper part of the sequence, the relationships between three stratigraphic elements have proved particularly informative and these are the focus of this contribution having been studied in an area southwest of Caw summit close to Tail Crag (SD 237942) (Figure 1). A predominantly epiclastic horizon, the Caw Formation, is sandwiched between two ignimbritic layers; all three units have been described in some detail by Millward et al. (2000). Under the Caw Formation is the Stickle Pike Member of the Lickle Formation which is a rhyolitic eutaxitic to parataxitic lapilli-tuff with a weakly welded upper ten metres. Above the Caw Formation is the Lag Bank Formation which is a dacitic lapilli-tuff with moderate to dense welding though sparse fiammé limit the expression of the welding in exposures. In the study area, Millward et al. (2000) recorded a basal Lag Bank breccia with blocks up to 80 cm; they considered it to have formed in-situ because of explosive interaction between the hot ignimbrite and underlying wet sediments of the Caw Formation. Mitchell (1956) mapped the same horizon as a laterally restricted, and thin, rhyolite lava but did not mention the brecciation. The Ambleside Memoir (Millward et al. 2000) describes the Caw Formation as being entirely epiclastic but, locally, its basal 20 metres is primary pyroclastic in origin being stratified and cross-stratified lapilli-tuff containing abundant accretionary lapilli (Boulter 2022). Immediately south of the study area this basal section is represented by a few metres of turbidites that contain some reworked accretionary lapilli. Reworked accretionary lapilli in turbidites decrease in abundance northwards such that they are not present in the area of Figure 1. The bulk of the Caw Formation comprises poorly-sorted volcaniclastic sandstone, coarse sandstone, and gravel-grade conglomerates. Generally, the Caw Formation is considered to coarsen upwards but the trends in the study area reveal a more varied pattern.

Structurally, in the immediate area around Caw, strikes are generally close to north-south and dips to the east between 30 and 40 degrees are typical (British Geological Survey, 1996). Sparse SSW-NNE to N-S faults are shown to be regionally important on the Ambleside 1:50,000 Sheet (BGS 1996) though a NW-SE set becomes more important towards the southwest. Of significance on the 1:50,000 map is a series of east-west segments along the Caw-Lag Bank boundary though they are not shown on the BGS map as being fault-related. The main -Acadian cleavage is present but only rarely obscures primary depositional features.

New Observations

Across the slack arrowed on Figure 1 there is an abrupt change in sedimentary facies in the basal Caw Formation. To the south of the slack the deposits are of the medium-grained turbidite family (Stow & Smillie, 2020) displaying well-defined bedding (Figure 2). To the north of the slack the deposits are of the coarse-grained



Figure 2 Basal Caw Formation south of the Tail Crag Fault; deposits of the medium-grained turbidite family (Stow & Smillie, 2020) displaying well-defined bedding (SD 23355 93906). A-C divisions of the Bouma sequence are well-developed with C divisions being particularly distinctive. Mobile phone for scale.

turbidite family (Figure 3) and, though they are stratified, beds are less well-defined than in the south partly because mudrock horizons are rare. In the northern zone, Lowe-model sedimentary structures are compatible with deposition from high-concentration turbidity currents (Stow & Smillie, 2020). Tracing the contact, between the Stickle Pike Member and the Caw Formation, from SD 2345 9355 to SD 2327 9403 its overall trend is close to north-south but in several places it takes highly-angular deflections, up to fifteen metres in length, to an east-west trend. Clusters of sub-vertical clastic dykes within the Stickle Pike Member are co-located with many of these deflections.



Figure 4 Clastic dykes at the top of the Stickle Pike Member exposed on a gently-inclined surface (SD 23250 94015). Most of the clastic dykes are one to two cm wide.

The dykes have complex geometries (Figure 4) and start at the Stickle-Caw interface penetrating at least three metres into the Stickle Pike Member. On steeply-inclined exposures that trend at high-angles to the main Acadian cleavage, the dykes are roughly planar having converged towards the cleavage plane because of ductile strain. On gently inclined sufaces (Figure 4) the dykes display a crude polygonal pattern. Texturally the dykes have comparable characteristics to the overlying medium-grained turbidites including grain-size grading in cm-scale beds in their uppermost sections. The greatest concentration of clastic dykes is in the 70 metres immediately south of the arrowed slack on Figure 1 where there is a twenty-metre strike offset of the Stickle-Caw boundary with a right-lateral sense of strike separation. This is the largest of the east-west deflections of the boundary seen in the traverse from SD 2345 9355. Only one of these deflections is perfectly exposed; at SD 23277 94000 part of a four metre step in the contact shows bedding in the Caw Formation turbidites abutting the Stickle Pike Member almost at right-angles (Figure 5). At this boundary the clastic dykes in the Stickle Pike unit are truncated indicating that the sedimentary dykes were not superimposed on both the Caw and the Stickle Pike units. The grading seen in some dykes shows that fissures in the Stickle Pike Formation ignimbrite were open when sub-aqueous deposition commenced in the Caw Formation undoubtedly in



Figure 3 Basal Caw Formation north of the Tail Crag Fault; deposits are of the coarse-grained turbidite family with Lowe-model sedimentary structures (Stow & Smillie, 2020) and, though they are stratified, beds are less well-defined than in the south partly because mudrock horizons are rare (SD 23273 94098). The joint face is 2.1 m tall.

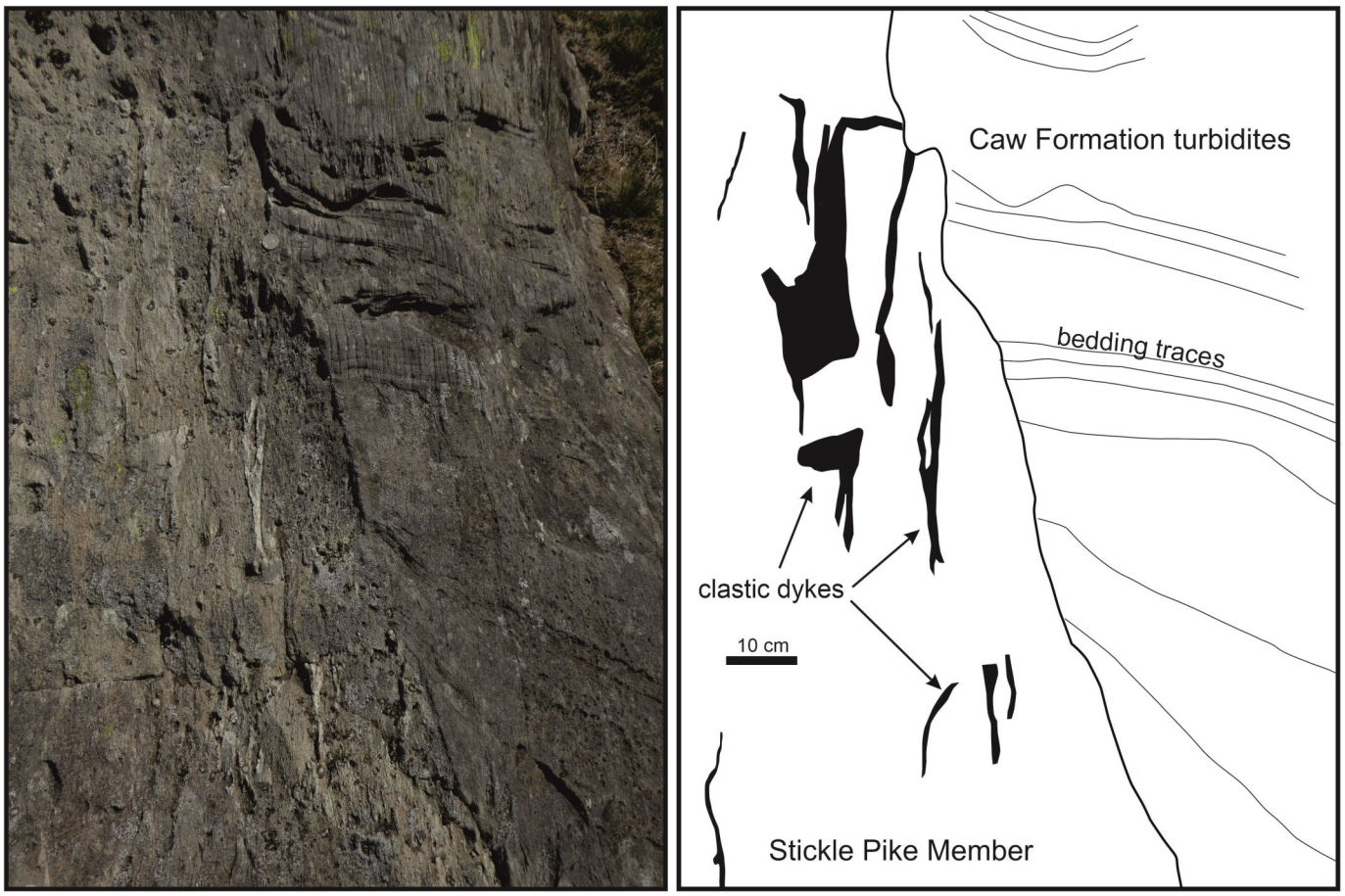


Figure 5 Photograph and line drawing interpretation of the palaeotopography at the top of the Stickle Pike Member in which clastic dykes are common (SD 23277 94000). The well-bedded unit on the left-hand side is Caw Formation turbidites which but up against the Stickle Pike Member. Besides textural differences, the contact between the two units can be identified by the presence or absence of clastic dykes. The exposure is viewed looking easterly.

a lacustrine setting. Because grading is preserved in the dykes they are Neptunean in nature where the sediment was washed into open fractures rather than being infilled by forceful injection of remobilized sediment.

Further crucial information on the significance of the main slack is provided by relationships at its eastern end where it loses definition at the point where it intersects the boundary between the Caw and Lag Bank Formations. Detailed mapping (Figure 6) around this termination has identified several units restricted to this immediate area. Between the southern splay and the main Tail Crag Fault, the first Lag Bank deposits are stratified lapilli-tuff with some cross-stratification and several accretionary lapilli horizons. Some of this material is brecciated with dm-scale fragments. In contrast to the moderate regional dips, isolated exposures in, and on the margin of, the slack have sub-vertical to overturned dips as shown by truncated cross-bedding. The varying dips imply rotated blocks on a scale of several metres. To the north of the Tail Crag Fault, the first Lag Bank deposits are typical of the bulk of the unit being dominantly massive lapilli-tuff with weakly-aligned sparse fiammé. The sense of strike offset along the Tail Crag Fault, shown by the Lag Bank in the mapped area (Figure 6), is opposite to that on the Stickle/Caw contact. The stratified lapilli-tuff shows no offset across the fault northwards from the block between the main fault and the splay. This horizon is not present south of the splay fault and it extends only a few tens of metres north of the main fault. Above the stratified lapilli-tuff, on both sides of the Tail Crag Fault, there is a structureless lithic-rich breccia. The most striking aspect of this breccia is blocks up to 3x2 metres in size. Two types of rhyolitic blocks predominate; one is nodular on a scale of five to ten millimetres and the other is either flow-banded or high-grade welded ignimbrite. In the former type, the nodular texture is so pervasive that it is impossible to determine the original nature of the material which could have been a rhyolite flow or ignimbritic. Again, the lithic-rich breccia is not present south of the splay and the unit fades just north of the area mapped (Figure 6) though the northwards taper is overlapped by a similar block-breccia.

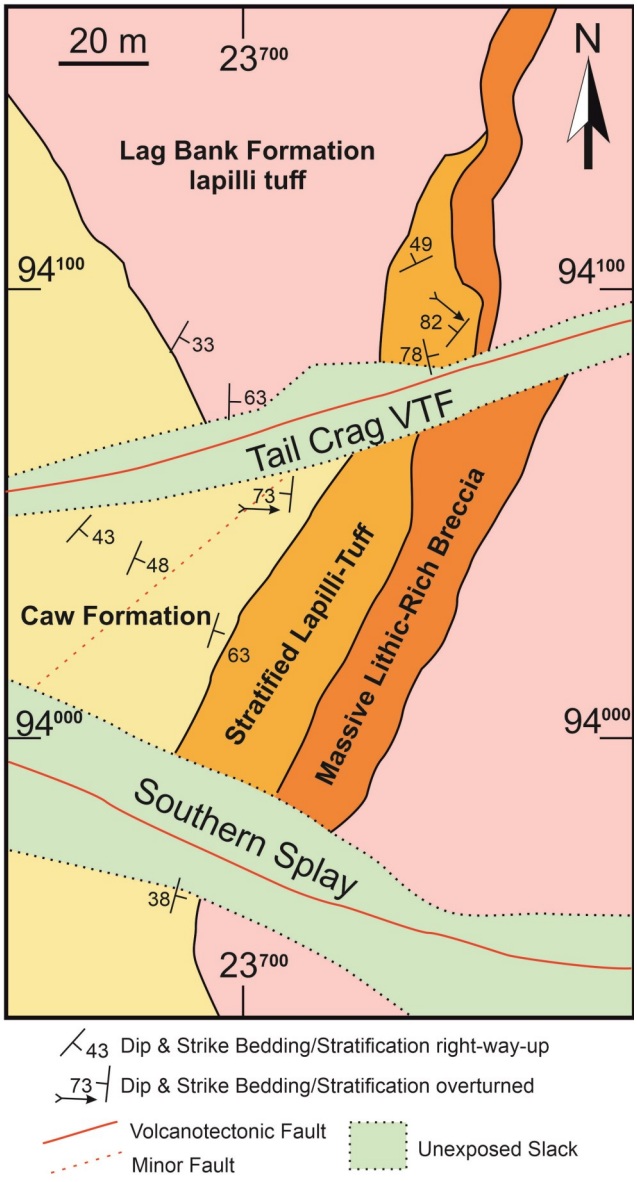


Figure 6 A geological map of the area outlined by a box on Figure 1. Geological relationships are shown at the intersection of the Tail Crag volcanotectonic fault with the boundary between the Caw and Lag Bank Formations. Departures from the regional bedding attitudes (sub-vertical to overturned) were created by explosive brecciation during formation of the micro-maar structure.

Discussion

Direct observation of a preserved palaeotopography on the top of the Stickle Pike Member (Figure 5) provides a template for interpreting the widespread angular-deflections in the contact between this unit and the overlying Caw Formation. These features were scarps left at the end of the Stickle Pike Member eruption and are characteristic of morphologies created by piecemeal caldera-collapse. On this basis the Tail Crag Fault is inferred to be the largest such structure in the area studied and the abrupt contrast in sedimentary style across this fault is attributed to a scarp developed on a metre- to decametre-scale. The turbidites to the south of the Tail Crag Fault were deposited in a lake by medium-density turbidity currents whereas to the north high-concentration turbidity currents transported the sediment. Opposite senses of strike offset at either end of the Tail Crag Fault indicate that the fault was reactivated during the Lag Bank eruption making reconstructions of the topography at the start of Caw Formation deposition uncertain especially when the mechanism responsible for the regional dip is unconstrained as is the timing. The dip may be due to block rotation during piecemeal break-up of the magma chamber roof but cannot be proven. Which way the scarp faced on the Tail Crag Fault is unknown but it did control sedimentation and the fault's origin lies in volcano-tectonics.

The localization of early components of the Lag Bank Formation at its intersection with the Tail Crag Fault demonstrates that the volcanotectonic fault was reactivated as a magma feeder channel in this later explosive eruption. The stratified, and cross-stratified, lapilli-tuffs at this intersection have all the hallmarks of a phreatomagmatic eruption related to magma-groundwater interaction that produced dilute pyroclastic density currents with a high water-content. The latter promotes ash aggregation as evidenced by the accretionary lapilli. Deposits with these characteristics are typically found in tuff-rings or maar-diatreme systems distinguished by the degree they excavate into the pre-eruption surface. Explosivity at maar-diatreme volcanoes typically starts at shallow levels at an aquifer and the seat of the explosions migrate downwards as a cone of depression develops in the aquifer. A combination of sub-surface explosivity and expansion of the diatreme produces a complex of fragmented magma and country rock together with slumped blocks, fault blocks, and isolated rotated rafts of upper-level materials. At the surface the volcano is surrounded by a tephra ring similar to the stratified lapilli-tuff described at Tail Crag except that usually the tephra is lithic rich. Lithics are common in maar-diatremes in hard rocks but the Caw Formation was poorly consolidated at the time of the eruption and soft-substrates will simply disaggregate. In the Tail Crag example the rotated rafts upper level deposits have not descended any significant amount into the feeder fissure so it appears that the volcano was in the very early stages of producing a maar -diatreme. The term "mini-maar" has previously been applied to the products of experiments. Given the incipient nature of the Tail Crag product application of the term micro-maar may be appropriate here. In this scenario the Tail Crag volcanotectonic fault has some of the characteristics of a diatreme.

The lithic-rich massive breccia above the tephra ring deposits is typical of co-ignimbrite lag breccias where large dense lithic clasts sink through a pyroclastic density current. Erosion of fissure walls in the early stages of caldera eruptions creates the large blocks in a vent widening process. Because the source for the clasts is not represented at present exposure levels they must come from units up or down dip along the Tail Crag Fault to explain the localized distribution either side of the fault trace. After these small-scale events the bulk of the Lag Bank ignimbrite was deposited.

Conclusions

1. The Stickle Pike Member was deposited by pyroclastic density currents erupting from volcanotectonic faults. At the end of the eruption, scarps along these faults created a topography that influenced lacustrine sedimentation in the Caw Formation and the most striking sedimentary-facies contrast is across the Tail Crag volcanotectonic fault. Fracture concentrations around the volcanotectonic faults hosted the initial Caw Formation deposits in the form of clastic dykes.

2. The Tail Crag volcanotectonic fault was reused when magmatism early in the Lag Bank ignimbritic eruption met groundwater in the fault and formed a localised, and shallow, maar-diatreme with a limited tephra ring. Blocks of the tephra ring fell limited distances into the feeder fissure.

3. A co-ignimbrite breccia was sourced along the Tail Crag Fault but source materials are not exposed at present exposure levels.

4. Voluminous Lag Bank ignimbrite buried the region.

5. Volcanotectonic faults are common in this part of the Duddon “Basin” and were formed during piecemeal caldera-collapse indicating that the volcanic model for this element of the Borrowdale Volcanic Group requires re-examining.

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