The Raven's Crag Tuff, a silicic tuff-ring deposit in the Duddon Basin of the Borrowdale Volcanic Group, Dunnerdale Fells

Clive Boulter

Abstract

The basal 20 m of the Caw Formation at Raven's Crag in the Duddon basin is a tuff-ring deposit of cross-stratified accretionary lapilli-tuff created by subaerial pyroclastic currents that swept across a landscape containing scarp slopes located along volcanotectonic faults that were active whilst the underlying ignimbrite was being erupted. The lateral equivalent of the Raven's Crag Tuff, a kilometre to the north in the Stainton Ground Quarries, is a lacustrine sequence. Between these localities, the basal Caw unit is a mixture of volcaniclastic debris flows and turbidites that have reworked the Raven's Crag subaerial accretionary lapilli-tuff demonstrating that ultrafine rim-type accretionary lapilli can withstand aqueous transport. A possible source for the large quantities of water needed to create the accretionary lapilli was the lake centered on Stainton Ground. To create the deposit's characteristics requires interaction between a water-saturated eruption-column – umbrella-cloud system and pyroclastic density currents in concert with their Phoenix clouds. Some of the several trends of volcanotectonic faults in the area were probably active before, during, and after, the Raven's Crag tuff-ring eruption.

Introduction

This contribution concentrates on the basal twenty metres of the predominantly-epiclastic Caw Formation on Raven's Crag (Figure 1) in the Duddon Basin.

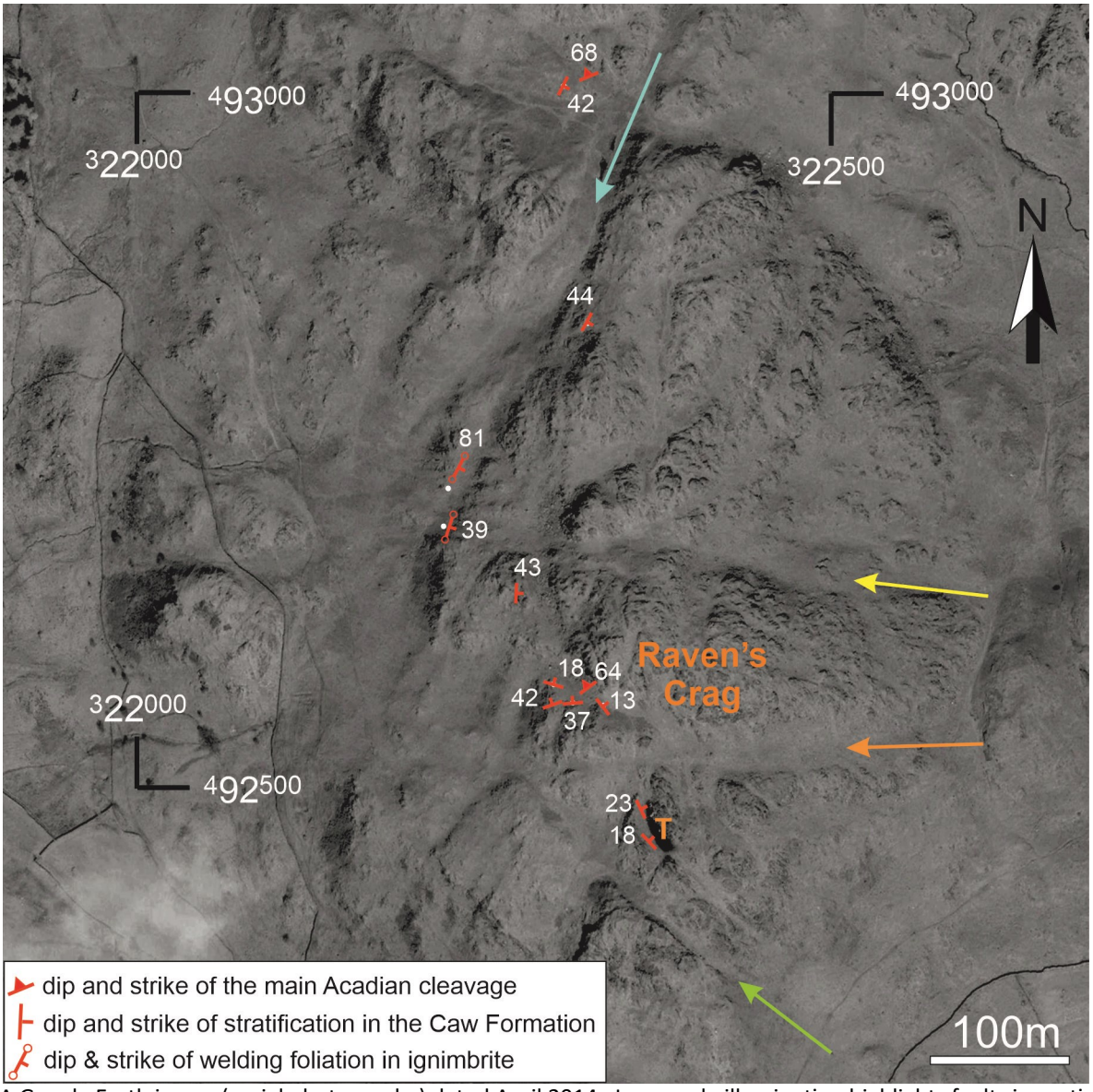


Figure 1 A Google Earth image (aerial photography) dated April 2014. Low-angle illumination highlights faults in particular. The arrowed slacks are along volcanotectonic faults. All the bedding orientation data on this figure are from the basal Caw Formation. Stratal dips decrease from north to south and there is a kink-like deflection of the layering north of the orange-arrowed slack.

Millward et al. (2000) and Johnson & Brown (1992) have provided the regional and local context for this study. The locality is within the Duddon Basin which according to Millward (2002, 2004) did not involve caldera-forming eruptions apart from in its earliest phase. Evidence for this interpretation was not explicitly set out but several observations may have led to this conclusion including the low concentration of inferred volcanotectonic faults in the Duddon compared to the Scafell Caldera (Figure 15 of Stone et al. 2010). In the upper part of the Duddon succession, given the size of several silicic ignimbrite sheets with thicknesses up to 600 m it would be exceptional if they were not involved in caldera formation. Boulter (2022) has identified many volcanotectonic faults immediately to the northeast of Raven's Crag and has provided evidence for reactivation of some of these faults in the ignimbrite underlying the Caw Formation during eruption of the ignimbrite overlying the Caw Formation.

The Caw Formation is predominantly epiclastic comprising a sequence of volcaniclastic sandstones, breccia, and conglomerate, that generally coarsens-upwards. Millward et al. (2000) state that "Tuff interbeds up to 2 m thick are common in the basal part and many contain accretionary lapilli up to 1 cm..". Johnson & Brown (1992) infer an airfall origin for the tuffs. It is this basal part of the Caw Formation which is reinterpreted in this analysis. Below the Caw Formation, the Stickle Pike Member of the Lickle Formation is a rhyolitic eutaxitic to parataxitic lapilli-tuff with a weakly-welded upper ten metres. On Raven's Crag, the basal Caw Formation is well-bedded creating a contrast with the massive nature of the underlying Stickle Pike Member thus it is a boundary that is fairly-readily recognizable in the field from a practical mapping point of view.

The main Acadian cleavage is reasonably well-developed on Raven's Crag but rarely causes a strong enough overprint to obscure depositional structures. There are zones where features such as accretionary lapilli show no strain-related alignment despite the Stainton Ground slate quarries being less than a kilometre away. From Stainton Quarries near Kiln Bank Cross to Raven's Edge there is a general north-south strike with moderate dips to the east though Figure 1 reveals some variations at Raven's Crag.

New Observations

Figure 1 is a Google Earth image (aerial photography) taken in April before any significant vegetation growth; this, together with low-angle sunlight, highlights structural features almost as well as LiDAR but with better resolution than openly-available LiDAR data. On this image several east-west slacks are evident and the two most prominent of this set are indicated by orange and yellow arrows. The basal twenty metres of the Caw Formation is exposed to the east and west of the tarn labelled T on Figure 1. Southwards from where the orange-arrowed slack intersects this basal 20 m, until where exposure is lost, the entire basal unit has several uniform properties. Chemical analyses are not available, but the pale-weathering suggests a dacitic to rhyolitic composition. In grain-size terms, apart from accretionary lapilli, it is rare to see grains larger than very-coarse sand/ coarse ash. This basal unit is stratified throughout and almost all is cross-stratified. Also, accretionary lapilli are common throughout with many horizons having high-concentrations of these ash aggregates. Most distinctive amongst the variety of sedimentary structures are examples of stoss-side aggradation in dune bedforms; the clearest example is illustrated in Figure 2. These cross-beds have roughly symmetrical lee and stoss side slopes, internal truncations, and stoss layers that continuously go over the dune crest to parallel the lower truncated layers. In Figure 2 accretionary lapilli are more common in the layers above the internal erosional surface. Chute and pool structures are found scattered through the deposit again implying stratification that built into the current direction after turbulence scoured the substrate. Also, minor variations include convex tops to dune forms indicating formation under a standing wave. Trough-style cross-bedding is another minor component. Most common are examples of low-angle and irregular cross-stratification which are difficult to categorize at the scale of the typical exposure. Overall, the characteristics of the cross-bedding matches those of upper flow regime environments. Stoss sides generally face towards the NNE when planar bedding is restored to horizontal but the strain related to the main cleavage has not been quantified though the cleavage intensity is low so distortions are not expected to be large.

The widely-distributed accretionary lapilli are mainly in the 5 to 20 mm size range. They are all of the ultrafine-rim type of van Eaton & Wilson (2013) being several layers of ultrafine ash around a structureless coarse-ash core (Figure 3). Of significance is the common presence of rim fragments. Van Eaton & Wilson have developed a model to explain the characteristics of this type of accretionary lapilli involving initial formation of structureless coarse/medium-ash pellets in eruption plumes and umbrella clouds. Varying degrees of column collapse are then required such that Phoenix clouds above the resultant pyroclastic density currents provide the ultrafine ash to coat the ash pellets. Finally the accretionary lapilli fall into the ground-hugging turbulent pyroclastic currents to be baked/hardened making them more resilient such that collisions create the rim



Figure 2 Just north of the tarn on Figure 1 this exposure, in the basal Caw Formation, is the clearest example of classic upper flow-regime cross-stratification in the accretionary lapilli-tuff (SD 22404 92511). The layers on the left, above the truncation surface, continuously drape the dune form. The layers on the left-hand side built-up against the pyroclastic current which flowed from left to right. The field of view is approximately one metre wide.

(backset features) are the result of supercritical (upper flow regime) flows which are easily achieved in pyroclastic density currents, an environment in keeping with hardened coatings to accretionary lapilli and the production of rim fragments.

To the north of the slack marked by the yellow arrow on Figure 1 there is a change in the facies characteristics of the lowermost Caw Formation. By SD 2230 9277 the primary pyroclastic deposits are only three metres thick. Above this much-reduced pyroclastic basal layer there are two thick (each approx. two metres) debris flow deposits (Figure 4) together with turbidites, some of which are close to a metre thick. A distinctive feature

fragments. A key part of the process is the requirement for a high moisture-content in the eruption plume of up to 20 weight percent to form the massive ash-pellet cores of the ultrafine rim-type accretionary lapilli. Ash aggregation will not take place in a dry eruption plume because water droplets/steam are needed to promote particle cohesion.

The stoss-aggrading nature of many of the bedforms in the basal zone of the Caw Formation is typical of deposits generated by dilute pyroclastic currents, an inference supported by the presence of ultrafine rim-type accretionary lapilli. On this basis all the lowermost twenty metres of the Caw are primary pyroclastic deposits. Upstream-dipping beds



Figure 3 Representative accretionary lapilli from primary pyroclastic deposits on Raven's Crag. The largest of the lapilli are around 10 mm and the small tabular-fragments are broken pieces of ultrafine rims. A moderate main Acadian cleavage causes some alignment from top right to bottom left.

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Figure 4 A debris flow deposit at SD 22377 92357. The overall pimply aspect is created by accretionary lapilli which mainly stand proud of the weathered surface. The lower half of the bed has large clasts of the substrate which were incorporated into the flow as it eroded its base. Field of view is about a metre wide.

of the two main debrites is that they have reworked the accretionary lapilli deposits. Both contain abundant individual accretionary lapilli with sparse clasts of accretionary lapilli tuff up to 25x16 cm implying that the primary pyroclastics were readily disaggregated because lithification at the time was minimal apart from some very localized volumes. Unabraded accretionary lapilli are usually taken to indicate a primary pyroclastic origin for a deposit yet, in the Raven's Crag debrites, whole accretionary lapilli are the norm (Figure 5) and the rim fragments are probably also reworked. Other characteristics of the debrites include erosive bases cutting at least 1.2 m into the substrate; in doing so blocks of the underlying material, up to 26 x 17 cm, become isolated in the debris flow deposits but all stages of the separation process of the substrate are preserved. Though these blocks are concentrated towards the base of the debris flows, others are found at almost all levels within these beds. Accretionary lapilli show no signs of grain-size grading within the debrites having fairly-uniform distributions dispersed throughout each of the beds. Very-weak lamination at the tops of the debrites is seen in some exposures.

Stainton Ground Quarries near Kiln Bank Cross worked the lowermost part of the Caw Formation and hence are at the same stratigraphic position as the Raven's Crag pyroclastics (British Geological Survey, 1996). Many sedimentary structures seen on cleavage planes (low-strain sections) from the quarries are not definitive for determining the depositional environment. However, there are enough samples with graded beds and turbidite A-C and E divisions to indicate a lacustrine setting in keeping with many of the worked slates in the Borrowdale Volcanic Group.

Besides the roughly east-west slacks on Figure 1 there is a prominent NNE-SSW slack (blue arrow) and a NW-SE slack (green arrow). Along the NNE slack, welding fabrics in the Stickle Pike Member are deflected from their typical regional dips of 30 to 40^{o} to dips around 80^{o}. At SD 22314 93095 there is an angular step in the Stickle-Caw boundary of several metres and, in this immediate area, there are abundant clastic dykes in the Stickle Pike. Along the slack arrowed in green, the Stickle Pike has swarms of clastic dykes in and around its contact with the Caw pyroclastic unit centered on SD 2242 9238. South of the tarn (T on Fig. 1) the dip of the sequence is much reduced and the interrelations with the topography has created a broad area sub-parallel to the contact. This has produced a complex outcrop pattern for the Stickle-Caw contact as well as a broad area of clastic dykes in the Stickle Pike because it is within a few metres of the base of the Caw. On either side of the orange arrowed slack, centered on SD 2231 9252, there are common clastic dykes and zones of silicification in the Stickle member. Between the orange and yellow arrowed slacks there is a kink-like deflection of the Caw-Stickle boundary which shifts this contact about 100 m. Ductile deflections of welding fabrics are characteristic of volcanotectonic faults and, just a couple of kilometres to the east, Boulter (2022) has shown the steps in contacts, and clastic dykes, are associated with volcanotectonic faults. On this basis the slacks on Figure 1 are all interpreted as syn-caldera collapse volcanotectonic faults.

Discussion & Conclusions

Initially restricting comments to the area around the tarn at Raven's Crag [T on Figure 1), the bottom 20 metres of the Caw Formation have all the characteristics of subaerial, and dilute, pyroclastic density current deposits. Particularly the stoss-side accumulation on dune



Figure 5 A closeup of the accretionary lapilli bearing debris flow at SD 22377 92357. Accretionary lapilli mainly stand proud of the weathered surface but some are shown in section; most are spherical but some are elliptical. They mainly range from 10 to 20 mm in diameter. The large clasts are from the sub-strate.

bedforms is key to this analysis. Significant quantities of external water were involved in the explosivity as evidenced by the abundance of accretionary lapilli which require a very moist ash cloud for the promotion of ash aggregate formation. To achieve this, large quantities of water have to gain access to the magma. Immediately north of Raven's Crag, to the north of the yellow arrowed slack on Figure 1, the basal part of the Caw is dominated by turbidites and debrites with only a few metres of primary pyroclastics right at the base. The turbidites require a lake to have formed and this appears to have extended to the Stainton Ground Quarries thus providing a potential source of external water. This inference is supported by the sparse palaeocurrent data that shows the pyroclastic currents flowed from north to south. As is seen to the northeast at Tail Crag there was a topography on the top of the Stickle Pike Member when its associated explosivity ceased (Boulter, 2022). This topography must have been sufficient to keep the Raven's Crag area subaerial whilst to the north a depression bounded by volcanotectonic faults became filled with lake water. It is also possible that the topography, present at the end of the Stickle Pike event, evolved during the explosivity that created the Raven's Crag Tuff. Following the van Eaton & Wilson (2013) model for forming accretionary lapilli of the ultrafine-rim type, eruption columns kilometres in height are required. This style of accretionary lapilli involves Phoenix clouds above pyroclastic density currents providing ultrafine-ash to coat ash pellets formed in saturated eruption columns and umbrella clouds. These complexly-structured accretionary lapilli then drop into the pyroclastic currents to become hardened to an extent that on colliding with neighbours the rims fragment to contribute to the particle diversity. Overall, the volcanological model for this assemblage is a moderate-sized tuff ring.

In conclusion, the basal Caw Formation on Raven's Crag is entirely pyroclastic formed from dilute pyroclastic density currents. The driving force for the explosivity probably was lake water accessing the magma producing very moist eruption clouds leading to widespread ash aggregation as expressed by abundant accretionary lapilli. A dynamically unstable phreatoplinian eruption column of significant vertical height is implicated in the creation of the Raven's Crag Tuff. As is the case a couple of kilometres to the northeast, volcanotectonic faults are common at Raven's Crag implying piecemeal caldera collapse was associated with formation of the Stickle Pike ignimbrite sheet.

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