The Cressbrook Dale Lava and Litton Tuff, between Longstone and Hucklow Edges, Derbyshire

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Abstract: With only a small exposure near the head of its eponymous dale, the Cressbrook Dale Lava is the least exposed of the major lava flows interbedded within the Carboniferous platform-carbonate succession of the Derbyshire Peak District. It underlies a large area of the limestone plateau between Longstone Edge and the Eyam and Hucklow edges. The recent closure of all of the quarries and underground mines in this area provided a stimulus to locate and compile the existing subsurface information relating to the lava-field and, supplemented by airborne geophysical survey results, to use these data to interpret the buried volcanic landscape. The same sub-surface data-set is used to interpret the spatial distribution of the overlying Litton Tuff.

Within the regional north-south crustal extension that affected central and northern Britain on the north side of the Wales-Brabant High during the early part of the Carboniferous, a province of subsiding platforms, tilt-blocks and half-grabens developed beneath a shallow continental sea. Intra-plate magmatism accompanied the lithospheric thinning, with basic igneous rocks erupting at different times from a number of small, local volcanic centres scattered across a region extending from the Midland Valley of Scotland to the Bristol and Gloucester area (Waters & Davies, 2006).

In the White Peak area of the Derbyshire Peak District, various types of igneous rocks (lavas, tuffs, sills, dykes and vents) are common within the thick sequence of Visean platform and ramp carbonates that comprise much of the distinctive, dissected limestone plateau. Data from the BGS HiRES aeromagnetic survey indicate that the outcrops of igneous rocks in the White Peak are only part of a much larger volcanic field, most of which is concealed at depth beneath Millstone Grit and Coal Measures farther east. Because no large volcano structures have been discovered so far, geological literature describes the lavas in the White Peak as probably originating from four separate centres, each being active in a different area at different times (Smith et al., 2005). These volcanic centres could have been clusters of small vents or multiple points of eruption along linear fissures, instead of individual, large volcanic massifs. Repeated flows of lava coalesced to form larger accumulations up to several tens of metres thick. Brief explosive eruptions of fine ash also escaped from smaller volcanic cones. Ash from these intermittent eruptions rained down onto the shallow sea, settling on the floor of the tropical lagoon or emergent land surfaces. Where these ash-fall sediments are preserved as recognisable layers in the limestone, they have generally decomposed to thin layers of soft clay, known as wayboards (Walkden, 1974).

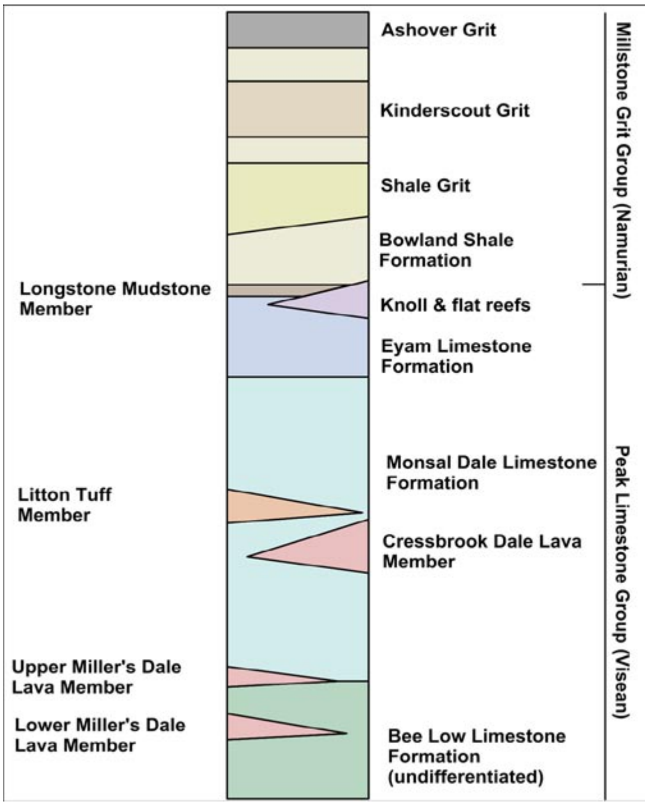


***Figure 1**. Upper Visean lithostratigraphy in the area.*

In the northern White Peak, the basaltic lavas and tuffs are interbedded with the Asbian Bee Low and the Brigantian Monsal Dale Limestones (Fig. 1). Where the igneous units form locally significant components of the carbonate succession, they are named as beds or members. Where the combined thickness of igneous rocks exceeds that of the associated limestone, they are known as the Fallgate Volcanic Formation (Aitkenhead, et al., 1985; Waters et al., 2007).

Early descriptions of the igneous rocks of the White Peak, known to the lead miners of previous centuries as *toadstone* or *channel* (Whitehurst, 1778; Farey, 1811) were followed by more detailed works (Geikie, 1897; Bemrose, 1907). Notable later publications include Walkden (1977), Walters and Ineson (1981) and the Geological Survey Memoirs (Smith et al., 1967; Stevenson & Gaunt, 1971; Aitkenhead et al., 1985). Other detailed assessments of the igneous rocks do not relate to the Cressbrook Dale Lava.

Three of the four volcanic centres in the White Peak, those at Tunstead, Matlock and Alport, have been partially eroded and their associated lava flows are

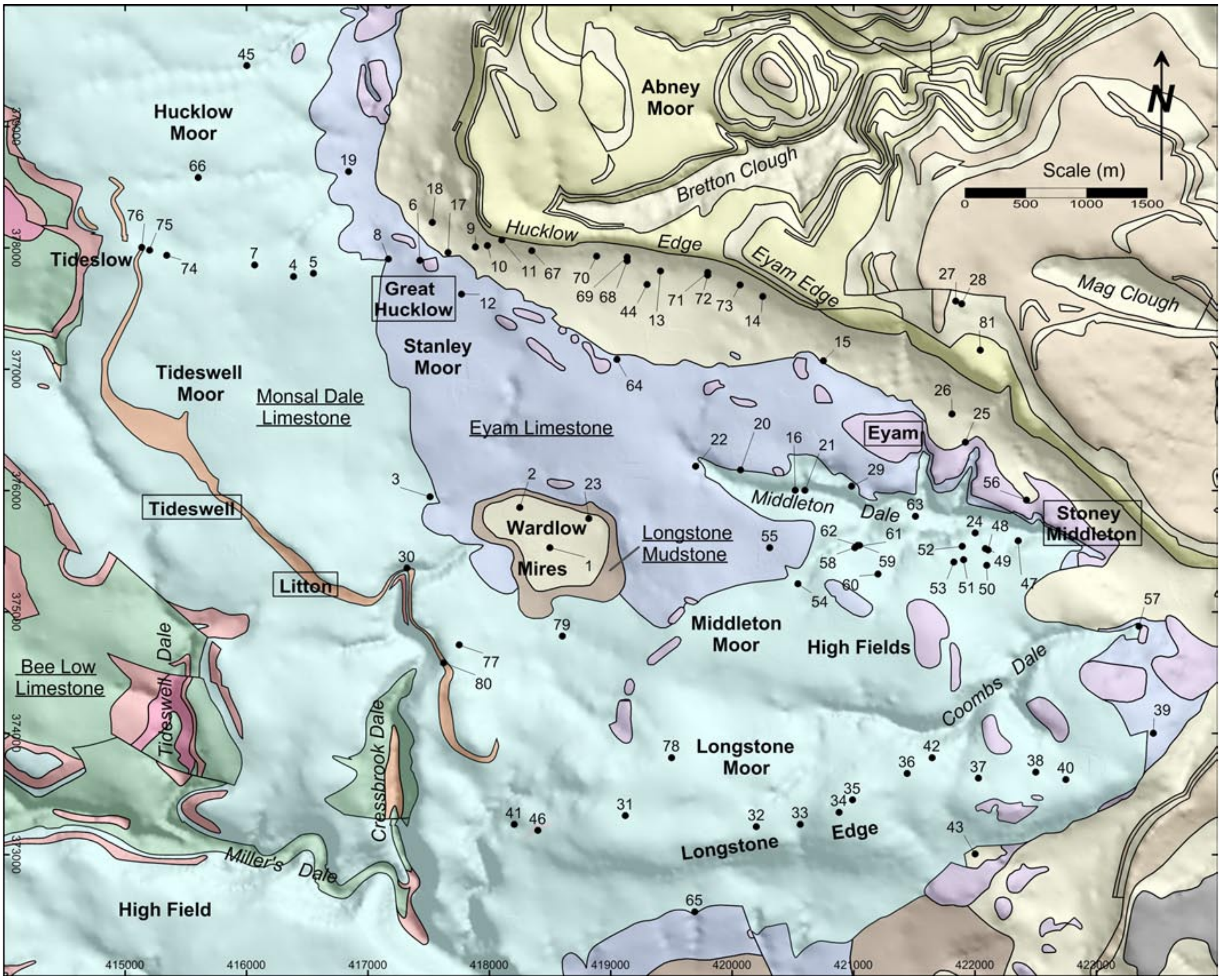


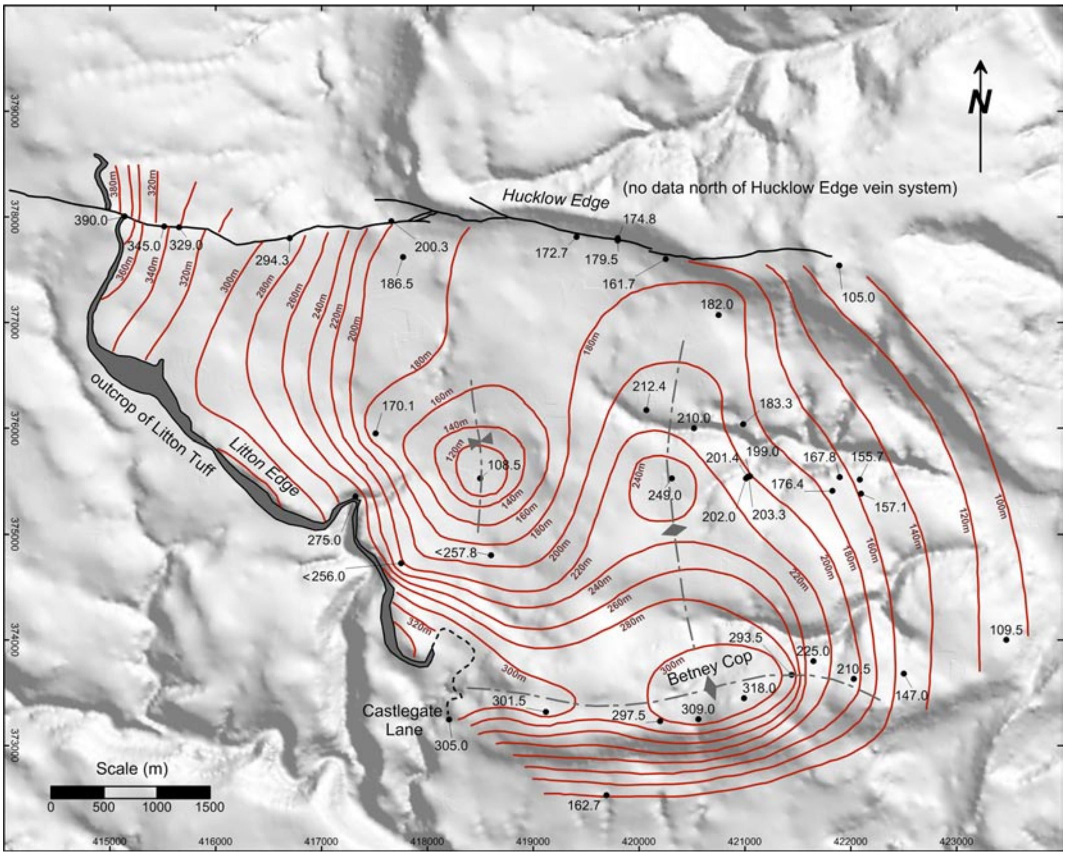
Figure 2. Outline geology of the area (relief shading after Ordnance Survey OpenData). Data locations refer to the Appendix Table. Colours are the same as in Figure 1.

exposed at surface outcrops, both natural and artificial. However, the fourth volcanic centre, located roughly beneath Eyam Edge (Fig. 2), is preserved intact, almost entirely concealed by a cover of overlying limestone, shale and gritstone. Its only surface exposure is a small outcrop close to the head of Cressbrook Dale, near Peter's Stone, and it is known as the Cressbrook Dale Lava (Aitkenhead et al., 1985). The general extent of the Cressbrook Dale Lava is known from many sub-surface intersections in old mines and boreholes spread across Middleton and Longstone Moors. Nearly all of these sites also penetrate the overlying Litton Tuff (Aitkenhead et al., 1985), a wayboard that is one of the few tuffs in the White Peak mappable as a unit.

The Monsal Dale Limestone forms much of the surface bedrock. This was deposited in a shallow sea on a sloping shelf or ramp (the Derbyshire High) that graded laterally into deeper marine environments. This limestone is generally a pale-grey, thickly-bedded biosparite and biopelsparite calcarenite. Individual bedding plane surfaces are commonly traceable over long distances, and some exhibit palaeokarstic or pressure-dissolution textures and morphology. A few beds of limestone, generally thin, not continuous, and with bivalves and corals, have been used as local marker horizons. The outcrop of the overlying, thinly-bedded Eyam Limestone, together with some associated reefs, forms a narrow fringe around the eastern side of the Monsal Dale Limestone plateau at the base of the Namurian shale and gritstone succession, though it widens in the structural depression of the Wardlow Mires basin. The older Bee Low Limestone forms the outcrop west of Tideswell Dale and Tideslow.

This area lies on the eastern side of a Variscan anticline, and most of the beds dip gently east. Towards the eastern limit of the Monsal Dale Limestone outcrop, as seen in cliffs behind Stoney Middleton, the dips are steeper where the concealed eastern margin of the platform is approached. This reef margin may trend northwest from Stoney Middleton, beneath the Namurian strata that form Abney Moor, and may be contiguous with the Castleton reef belt (Ford, 1977). The Visean limestones of the Peak District were subjected to changing stress fields during and after deposition, related to the evolving Variscan foreland

Figure 3. Altitudes of the top of the Litton Tuff, with structure contours drawn at 20m intervals.



tectonics (Quirk, 1993). An early phase of extensional rifting and fracturing, controlled by NW-SE basement faults, was followed by compression and shearing, resulting in a series of regional, east-west strike-slip faults. The Visean limestone platform continued to be affected by further phases of fracturing during the late Carboniferous, following burial by Namurian and Westphalian fluvio-deltaic sediments. Many of the fractures and faults became mineralised by pulses of migrating hydrothermal fluids, mainly during the latest Westphalian and Stephanian (Plant & Jones, 1989).

The main mineral workings are clustered around Longstone Edge, Middleton Dale and the extensive Hucklow Edge vein system. The first and last of these are associated with regional east-west fault zones. The Longstone Edge escarpment is a prominent landscape feature formed by a steep, southerly-dipping monoclinal fold in the Monsal Dale Limestone beds. It is also associated with a complicated system of tensional fractures and wrench faults aligned in the same orientation, many of which have been mineralised (Hunter, 2009). Farther north, the Hucklow Edge vein system is a zone of sub-parallel, interconnecting wrench faults in the limestones; it extends for 9 km, nearly half of which is concealed beneath a cover of Namurian shales and gritstones (Hunter, 2011). Both these vein systems were mined extensively for lead ore between the 17th and 19th centuries and both supported large-scale, open-cast and underground fluorspar workings in the 20th century. Extraction of fluorspar from the Hucklow Edge vein system (Milldam Mine) ceased in 1999, while mining at Longstone Edge ended in 2010.

The distribution, thickness and general structure of both the Litton Tuff and the Cressbrook Dale Lava have been recorded between Longstone Edge and the Eyam and Hucklow Edges (Fig. 2). The shafts and boreholes that are the data sources are listed in an Appendix Table. These sources include both published and unpublished papers, reports, mine sections, borehole logs and field observations. The published documents consist mainly of British Geological Survey (BGS) Memoirs and Mineral Resource Reports, while the remainder include geological assessments conducted by quarrying and mining companies, archived historical papers and observations made by explorers of the numerous lead mines scattered across these moors. Most of the data sources are clustered in the three areas associated with the main mineral workings, Longstone Edge, Middleton Dale and Hucklow Edge.

The Litton Tuff

The Litton Tuff Member is a deposit of air-fall volcanic ash and dust mapped as a distinct bed within the Monsal Dale Limestone Formation. The western part of this bed has been removed by erosion, but the eastern part remains concealed beneath 50-60m of limestone (Fig. 3). Its outcrop extends over at least 6 km around the villages of Litton and Tideswell, where the weathered, clayey material is soft and is usually obscured beneath a layer of soil and thick turf. At its southern end, the tuff is very thin and has not been traced as a mappable unit, but a temporary exposure in 2004 revealed it in a shallow mineral working near Castlegate Lane (Fig. 4).

***Figure 4**. Temporary exposure of the Litton Tuff (grey and yellow clay) overlain by the Monsal Dale Limestone at Castlegate Lane in 2004; section is 3m high.*

The Litton Tuff was also intersected by the Sallet Hole Mine between the eastern adit entrance in Coombs Dale and the newer decline at the western end of Longstone Edge, at Watersaw Rake (Fig. 5). These underground exposures (no longer accessible) showed that the Litton Tuff can occur as two or more leaves of pyroclastic material separated by thin beds of limestone.

The structural contours (Fig. 3) define large-scale undulations superimposed upon the regional dip to the east; these contours depict only generalised surfaces and include some uncertainty. The tuff is conformable with the bedding of the limestone, so these contours also indicate the structure of the upper Monsal Dale Limestone. The synclinal Wardlow Mires Basin and an unnamed anticline lie north of a domed, east-west anticline aligned with the Longstone Edge monocline beneath the higher ground of Betney Cop. These gentle undulations have been described as folds formed by Variscan deformation (Stevenson & Gaunt, 1971), but there may be an alternative explanation (see below).

***Figure 5**. Thin layers of Litton Tuff within the Monsal Dale Limestone, in underground workings beneath Longstone Edge, 2008; section is 1.5m high.*

The sinistral fault movement associated with the Hucklow Edge vein system has created a vertical offset of the eastwards-dipping strata across the fault. There are insufficient data points from north of the fault to determine structure. Sinistral fault displacement on the Longstone Edge vein system has also created a minor, vertical offset of the strata on its northern side (but this is too small to plot and has been ignored). Horizontal slickensides are common in the mineral workings of both vein systems. The horizontal displacement on the Longstone Edge fault system can be estimated where the two halves of the Betney Cop domal structure are offset by about 130m (Hunter, 2009).

It is evident from the thicknesses of the Litton Tuff that it represents the combined ash-fall footprint from at least two volcanic vents (Fig. 6). One lies west of Tideswell, and the other is buried beneath Bleaklow, on Longstone Edge. A third, minor vent may exist west of Bleaklow, and a fourth may possibly occur in the vicinity of High Fields. Observations in underground workings beneath Longstone Edge of more than one leaf of the Litton Tuff (thicker than those in Figure 5 and separated by thin beds of limestone) suggest that the multiple vents produced sequential eruptions. The ash-fall from the Tideswell source appears to have spread over a wider area than that from the Bleaklow vent, though it thins rapidly from over 30m to under 1m across a distance of 2 km. Some of the thinner recorded intersections of the Litton Tuff, particularly beneath Hucklow Edge, may not be reliable because they could relate to thin wayboards at slightly different stratigraphical levels. At least two wayboards were recorded in 19th century sections of mines between Great Hucklow and Tideslow. One of these could be associated with a second outcrop of unnamed tuff north of Tideslow (Hunter, 2011).

The 5m contour lines shown in the eastern half on Figure 6 could be re-drawn differently to connect the Bleaklow and High Fields areas into a single tuff deposit elongated north-south. Both options are feasible using the data points, but the drawn contour lines are preferred since the discovery in 2009 of a grey, clayey tuff during limestone production at Goddard's Quarry, on the north side of High Fields. This additional tuff is not plotted on Figure 6. Although it appears to be stratigraphically higher than the Litton Tuff, which was located by pre-development drilling around the quarry, it hints at the existence of a local, small volcanic vent that may have been reactivated. The discovery of tuff,

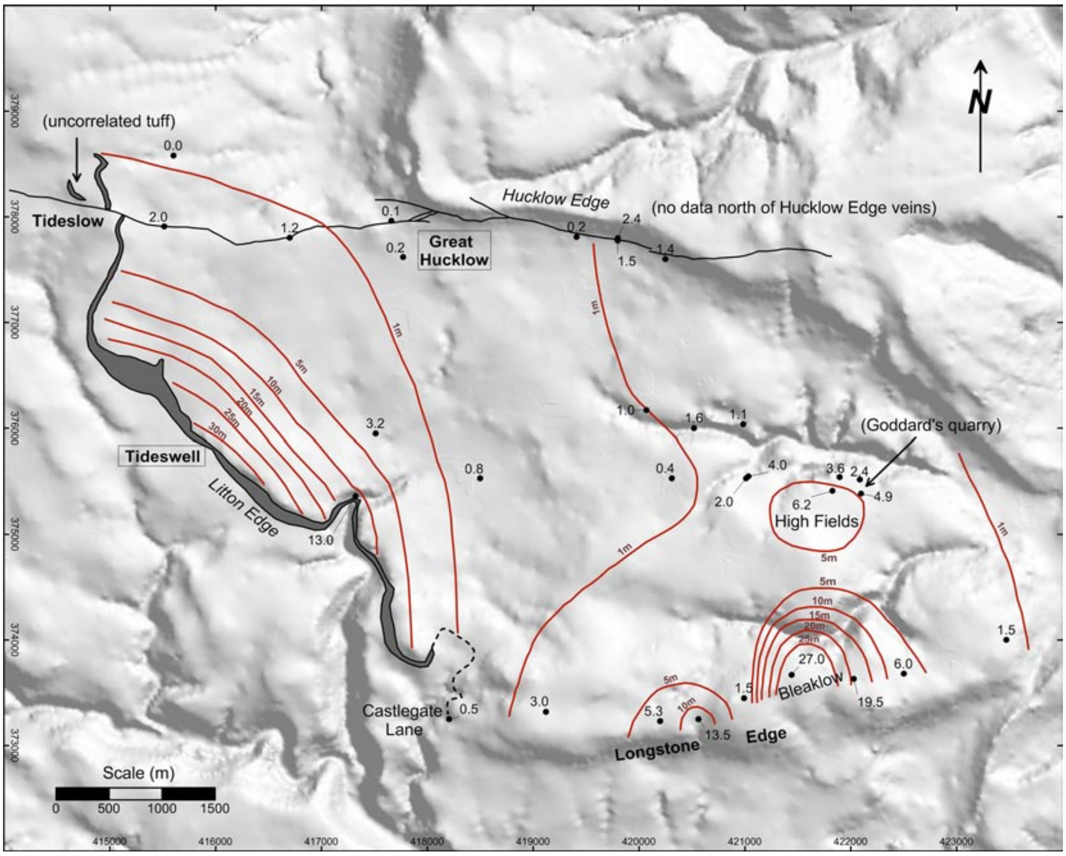


Figure 6. *Thicknesses of the Litton Tuff, indicated by isopachytes drawn at 5m intervals.*

where limestone was expected, was one factor behind the early closure of this quarry. A possible volcanic centre near High Fields may also relate to local reversals of dip in the overlying limestone along the north side of Coombs Dale on a plateau where the predominant dip is north and northeast.

The Cressbrook Dale Lava

Though this lava is known to be a significant component of the Monsal Dale Limestone sequence beneath much of the area, its outcrop is limited to a thin exposure of dark, vesicular basalt near the head of Cressbrook Dale (Fig. 7). It lies below the Litton Tuff, at depths beneath the plateau surface ranging from 28m, where the anticline ridge crosses beneath Middleton Dale, to around 100m beneath much of Longstone Edge, and 180m at the eastern end. Consequently, it has been intersected by fewer boreholes and mine shafts than have penetrated the Litton Tuff. Even fewer boreholes have penetrated completely through the lava. Figure 8 shows structural contours on the lava, and also its probable western limit within the limestone.

Along the Hucklow Edge vein system, more elevations of the upper surface of the Cressbrook Dale Lava are known that exist for the Litton Tuff, because the lava toadstone was readily recognised in the mines and boreholes, whereas the Litton Tuff is so thin it would have been difficult to identify with certainty. The undulations in the upper surface of the lava are comparable to those of the Litton Tuff (Fig. 3) because they are associated with the same regional dip and the same folds. However, these two surfaces are not parallel

Figure 7. Outcrops of the Cressbrook Dale Lava (CDL) and Litton Tuff (LT) in northern Cressbrook Dale.

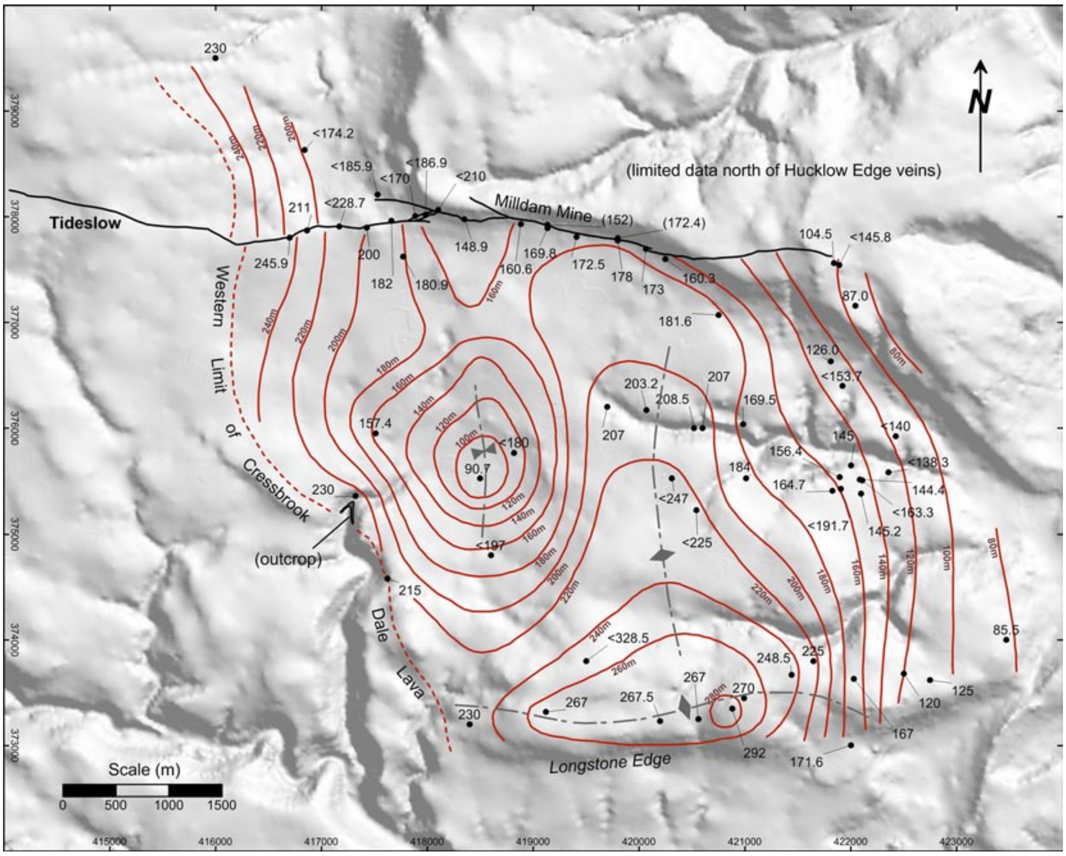


Figure 8. Altitudes of the top of the Cressbrook Dale Lava, with structural contours at 20m intervals.

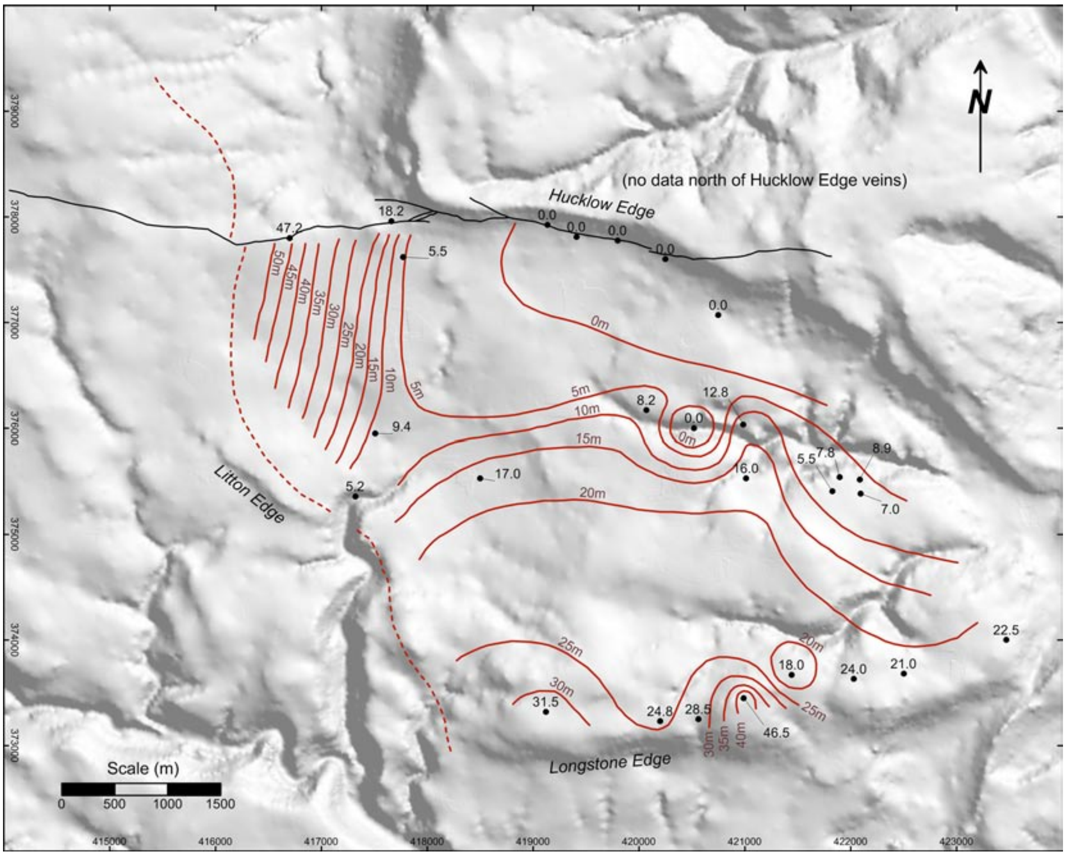
to each other; they converge in a north-easterly direction from Longstone Edge and Litton Edge towards Eyam-Hucklow Edge. This convergence indicates that a local sea-floor relief of up to 50m had been infilled and possibly levelled when the air-fall Litton Tuff fell into the sea (Fig. 9). Cyclic changes in relative sea level, due to local tectonics and the late-Visean glacio-eustacy, may have caused repeated drowning and re-emergence of the flanks of the volcanic terrain. As a consequence, the contact between the lava and its limestone cover is likely to be interbedded and more complicated than this simplistic model implies. The conical mounds of ash that accumulated around the Litton Tuff vents would have formed new features on the sea floor.

Lithological logs for the boreholes located along the Eyam-Hucklow Edge usually show a thin layer of tuff lying directly on the upper surface of the Cressbrook Dale Lava. This thin tuff probably correlates with the Litton Tuff in the Wardlow Mires No.1 borehole (Stevenson & Gaunt, 1971). Uncertainty is created by the wide spacing between the data points, but it is reasonable to assume by extrapolation that the horizon of the Litton Tuff lies very close to, and possibly coincides with, the eroded upper surface of the Cressbrook Dale Lava beneath the Eyam-Hucklow Edge.

In common with many of the rake-vein lead mines of the White Peak, the veins mined beneath Hucklow Edge deteriorated in width and quality as they passed downwards from the limestone into the igneous rock. The upper surface of the lava, which is usually altered to a clay, also behaves as an aquiclude, and drainage problems were commonly encountered in the deeper mines as they approached this hydrogeological barrier. In the modern Milldam fluorspar mine, which extracted gangue minerals left behind by the 18th and 19th century lead miners, the location of the upper surface of the lava was determined by underground drilling prior to the development of new levels, declines and stopes. Subsequent tunnelling was positioned to avoid intersections with the lava because its uppermost layer would soften and degrade following exposure to air and water, causing operational problems in the mine and the mill.

Two pairs of underground drill holes from Milldam Mine enable the vertical fault-offset across the Hucklow Edge vein system to be measured (elevations of the upper surface of the lava on the northern, down-thrown side are in brackets on Figure 8). Further west along this vein system, towards Tideslow, some old mine workings recorded the upper surface of the lava on the northern side of the fault, but the recorded elevations do not identify on which side of the fault they are located. Consequently, it is not possible to extend the structural contours very far on the northern side of the vein system. Another underground borehole from Milldam Mine has recorded a deeper intersection (148.9m AOD) with the upper surface of the lava than the adjacent known elevations on either side of it. This could indicate a northerly extension of the Wardlow Mires basin into a valley in the upper surface of the lava, but is depicted on Figure 8 as a separate, northerly-facing depression; its significance is discussed below.

Figure 9. *Thicknesses of limestone separating the Litton Tuff and the Cressbrook Dale Lava, with isopachytes drawn at 5m intervals.*



Some of the old drill cores from Milldam Mine show the contact of the Cressbrook Dale Lava with the limestone above(Fig. 10). The layer of decomposed tuff, now reduced to clayey, grey dust, is the same unit, possibly the Litton Tuff, that is shown in contact with the upper surface of the lava in lithological logs for most of the other Eyam-Hucklow Edge boreholes. Bleaching of the upper 2-3m of the Cressbrook Dale Lava is evident in all of the Milldam cores that were examined. The bleaching may represent weathering of an emergent land surface before it was smothered in volcanic ash, or it may have been the result of alteration caused by the ash. It is likely that the lava surface was already submerged beneath the wave-base at the time of the ash-fall, or the tuff would not have been preserved.

The thickest accumulation of the Cressbrook Dale Lava occurs beneath the area between Eyam and Foolow, becoming thinner towards the west and south and eventually terminating on its western side approximately beneath Litton Edge (Fig. 11). The lava is usually described from borehole cores as a dark grey-green, fine-grained, olivine basalt with both massive and amygdaloidal textures. A thick sequence of auto-

Figure 10*. Drill core that penetrated tuffs, possibly the Litton Tuff, and through the upper surface of the Cressbrook Dale Lava, from borehole 22/91 in Milldam Mine. Top left is pale limestone (at the stratigraphic top), followed by decomposed tuff to its right; the bleached and altered upper zone of the lava is in the two middle rows; unaltered, dark, amygdaloidal lava is in the lowest line; scale rule is 15 cm long.*

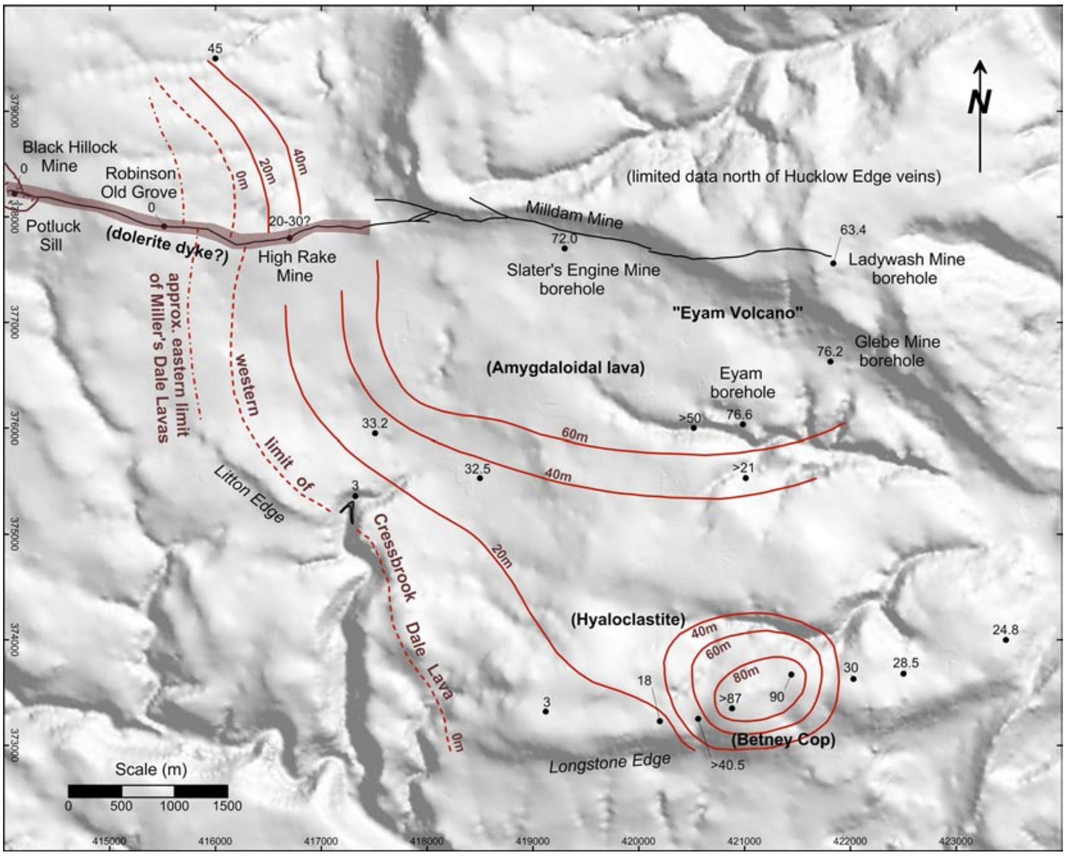


Figure 11*. Thicknesses of the Cressbrook Dale Lava, with isopachytes drawn at 20m intervals.*

brecciated lava lies in the lower part of the unit in the Wardlow Mires No.1 and Eyam boreholes (Walters & Ineson, 1981). The shape, dimensions and location of this large volcanic mass seem sufficient to justify applying the name *Eyam Volcano*. A separate volcanic mound, of similar thickness but smaller lateral extent occurs beneath Betney Cop, on Longstone Edge. Its extent has been partly delineated by a series of boreholes and it is described as hyaloclastite and tuff (Aitkenhead et al., 1985), implying that this localised volcanic vent only erupted underwater and did not create an island with sub-aerial lava flows. The hyaloclastite ie exposed in Sallet Hole Mine (Fig. 12). Walters and Ineson (1981) considered the Longstone Edge volcanics as a separate and possibly older eruption than the main Cressbrook Dale Lava, but Aitkenhead et al. (1985) correlated the two igneous units and regarded them as different components of the same volcanic event. Using the Longstone Edge boreholes the same authors also identified another thin lava below the Cressbrook Dale Lava, but they described it as a northerly extension of the older Shacklow Wood Lava, derived from the Alport volcanic centre. The lava outcrop above the River Wye at Cressbrook Mill is considered to be part of the Upper Miller's Dale Lava (Gatliff, (1982).

Figure 12*. Bedded hyaloclastite (pale grey) exposed underground in Sallet Hole Mine, Longstone Edge in 2005; section is about 1.5m high.*

Several intrusive sills of olivine-dolerite crop out to the west. One of these, the Potluck Sill, partly intrudes into the Lower Miller's Dale Lava, demonstrating that it is younger than that eruption. Between the 1760s and 1790s, Black Hillock Mine (Fig. 11) was sunk into a narrow mineral vein associated with the faulted contact between the lava and the sill (Walters, 1980). The miners were expecting to penetrate through the toadstone to investigate the anticipated continuation (and enlargement) of the mineral vein in the limestone beneath. Unfortunately for the investors in this unlucky venture, the shaft was abandoned while probably still in igneous rock (the historical accounts are not entirely clear about this) at a depth of 220m, because of increased water inflows and the lack of any evidence of ore. It is likely that the shaft penetrated at least 94 fathoms, ~180m, of toadstone. Farther east, a similar result befell High Rake Mine in the 1840s (Hunter, 2011). This shaft encountered the upper surface of the toadstone at a depth of 84m below ground, but the miners were still in igneous rock when it was abandoned at a depth of 216m, indicating a thickness of at least 132m. Both these mines are in the Hucklow Rake vein system. No other mine along the same vein ever managed to penetrate through the toadstone, though none was as deep as the Black Hillock and High Rake mines.

Both the Lower and Upper Miller's Dale Lavas have concealed extensions east of the Potluck Sill, but these do not extend as far as High Rake Mine (Gatliff, 1982), and gradually become thinner as they approach their distal limits. Therefore neither the Miller's Dale Lavas nor the Cressbrook Dale Lava have sufficient thickness in this area to account for the *bottomless toadstone*. Loose rock in the archaeologically important hillocks at High Rake Mine indicates that at least some of the toadstone was amygdaloidal lava, confirming the description by Green et al. (1887). Therefore it seems likely that the Cressbrook Dale Lava was the first igneous rock encountered during shaft sinking, where it may have represented the uppermost 20-30m of toadstone. Green et al. (1887) do not state the depth to which the lava extended nor the nature of its contacts.

Previous attempts to explain the abnormal thickness of igneous rock encountered by these mine shafts have proposed that they were sunk into vertical volcanic feeder pipes or into a thick, concealed intrusive sill (Walters, 1980; Walters & Ineson, 1981; Rieuwerts, 2007). The first theory assumes that the Potluck Sill is associated with, and directly above, a vertical volcanic feeder pipe. This cannot be disproved, but it invokes a coincidence that the High Rake shaft was also sunk into a separate feeder pipe 2.6 km away. Such feeder pipes would need to be either sufficiently large or uniformly vertical so that the mine shafts did not break out through their sides. The second theory, of a thick intrusive body underlying a wide area from Great Hucklow to Tideslow, also cannot be disproved, but the absence of any identifiable magnetic anomaly (see below) opens this concept to doubt.

An alternative model proposes that the deep mine shafts along Hucklow Rake may have both been sunk into a concealed vertical dyke extending westwards from the Eyam Volcano to the Potluck Sill (Hunter, 2011). Its relationship to a parent volcanic plug could be similar to the radial dykes around the eroded Tertiary volcano at Shiprock, New Mexico, USA. One of only three known examples of probable dolerite dykes in the northern White Peak crops out west of the Potluck Sill (Stevenson & Gaunt, 1971). Though only known from soil auger samples, it is linear and narrow and appears to connect the Potluck Sill with the Mount Pleasant Sill a few hundred metres further west. Its mapped orientation aligns with the projected end of the proposed dyke beneath the Hucklow Rake vein system, and it could represent a distal extension.

The concept of a deeper, concealed dyke may be supported by the structure of the Monsal Dale Limestone that overlies it. The position of the proposed dyke is marked by an east-west ridge of high ground connecting Hucklow Edge with Tideslow. It forms part of the surface drainage divide between catchments draining north towards the River Noe and south to the River Wye. Like the land surface, the limestone dips away from the ridge on both sides. These opposing dips could have been initiated by flexing of the limestone beds across the rigid dyke during burial settlement, allowing tension fractures to develop along the hinge. Subsequently, Variscan east-west wrench faulting exploited the weakened fracture zone, enlarging some of the fractures and allowing a major system of hydrothermal mineral veins to develop. Evidence supporting the concealed dyke hypothesis is limited and circumstantial, though no more so than the alternative explanation of multiple volcanic vents conveniently aligned beneath the Hucklow Edge vein system.

The magnetic anomalies

In 1998 a high-resolution airborne geophysical survey was commissioned by the BGS to cover an area of 14,000 km^2 of the English Midlands, including the Peak District (Shaw, 2005). A magnetic gradiometer was one of the standard instruments carried by the aircraft. To reveal additional details about the concealed Cressbrook Dale Lava, the original values of magnetic flux density have been manually re-contoured to intervals of 5 nanotesla (Fig. 13).

Magnetic anomalies are identified by letters on Figure 13. Most prominent is the large, positive anomaly (A) cresting near Crosslow House, north of the road between Eyam and Foolow. The entire anomaly defined by the 15 nt contour extends along the southern scarp of Eyam-Hucklow Edge, from Stoney Middleton to beyond Foolow. It includes a second anomaly peak (B), while a third magnetic maximum (C) forms a separate but adjacent anomaly on Stanley Moor. All three of these magnetic peaks lie within the 60m lava isopachyte (Fig. 11), and it seems reasonable to associate this A-B-C magnetic anomaly with the thickest accumulation of lava associated with the proposed Eyam Volcano. The complete contours of this anomaly may also enclose the other half of the Eyam Volcano at depth north and east of Eyam-Hucklow Edge. The volcanic mass appears to extend as far north as the Abney Syncline (near Bretton Clough) and eastwards towards the River Derwent, as predicted by Walters and Ineson (1981).

The steeply-dipping, eastern reef-margin of the Visean carbonate platform has been intersected by two crosscuts east and north from the Glebe and Ladywash mines (J. Beck, pers. comm.) (Fig. 13). The platform

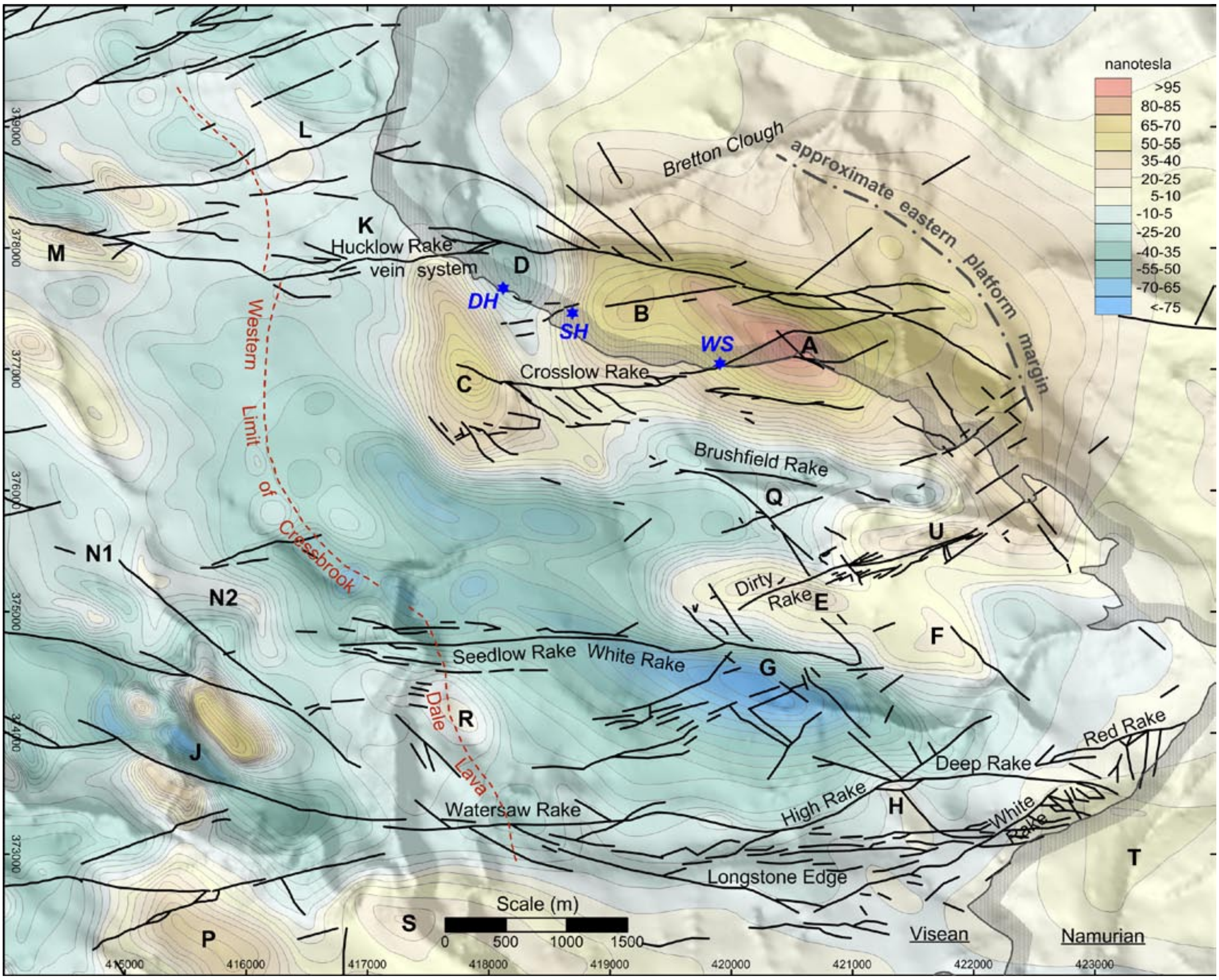


***Figure 13**. Total-field magnetic flux densities, with anomalies lettered as in text, and mineral veins superimposed; (after BGS HiRES survey). Blue stars are relevant stream sinks; DH, Duce Hole Swallet; SH, Swevic House Swallet; WS, Waterfall Swallet.*

margin trends northwest across the flank of the A-B magnetic anomaly, close to a group of three minor magnetic maxima. It appears that the Eyam volcano erupted very close to the eastern margin of the carbonate platform, and post-eruption carbonate sediments (the upper Monsal Dale Limestone) built up around it.

A magnetic negative (D) coincides with the depression in the upper surface of the Cressbrook Dale Lava discovered by underground drilling in Milldam Mine (Fig. 8). This suggests that the Stanley Moor anomaly (C) is likely to represent an individual volcanic mound in the lava field, and the contours of the A-B-C anomaly may provide a general image of the topography of this part of the concealed volcanic landscape. Apart from the Great Hucklow No. 7 borehole (Fig. 2, #12), there are no other borehole data to confirm its shape. The Great Hucklow borehole was terminated soon after it penetrated the lava, so did not reveal its thickness.

Additional evidence to support the suggestion that magnetic features B-C-D may approximate to the shape of the upper surface of the lava lies in the hydrogeology. Groundwater flow in the limestone is karstic, and open cavities were commonly encountered by the miners. Water sinking at Duce Hole Swallet (Fig. 13), flows underground northwards beneath the surface drainage divide, and across the Hucklow Rake mineral vein system, to rise 3 km away, after a fall of 105m, at Bagshawe Cavern, near Bradwell (Christopher et al., 1977). In contrast, water sinking at Waterfall Swallet probably flows south and then east before entering Carlswark Cavern, near Stoney Middleton, and draining to the Moorwood Sough (J. Beck, pers. comm.). Swevic House Swallet has been shown to drain both north and south (Gunn, 1998), so is very close to the groundwater divide. It appears that mounds and valleys in the impervious upper surface of the lava could locally influence the paths of groundwater flow.

The outcrop of the Litton Tuff along Litton Edge (Fig. 6) has no magnetic signal, indicating that it has a low magnetic susceptibility unlikely to affect any signal from the underlying lava. This may be caused by the presence of pyrite rather than iron oxide minerals.

The thick hyaloclastite beneath Longstone Edge, between Betney Cop and Bleaklow is associated with a weak anomaly (H), but this material also appears to have a low magnetic signal compared to that of the lava beneath the southern side of Eyam-Hucklow Edge (both lie beneath about 100m of sedimentary cover). This may be due to a melt temperature less than 500ºC or to rapid underwater quenching, either of which may have prevented ferromagnetic minerals from aligning with the Earth's magnetic field (M. Harwood, pers. comm.). Moderate positive anomalies (E and F) occur around High Fields, while a steep gradient exists between these feature and a deep magnetic low (G) along upper Coombs Dale. A shallower magnetic low (Q) separates the E-F and A-B-C magnetic highs. The E-F magnetic anomaly may lie over another volcanic mound, but there is insufficient borehole data to confirm this. The local thickening of the Litton Tuff, and the tuff in Goddard's Quarry, may be associated with a reactivation of an earlier volcanic mound in this area. The steep gradient between E and G may define a sharp boundary between the lava from the Eyam vent and the hyaloclastite erupted from Longstone Edge; alternatively, the deep low at G may be associated with a gap between the two flows where no volcanic material exists.

A prominent dipole anomaly (J) is associated with the outcrop of the Tideswell Sill, and a smaller dipole anomaly (M) lies over the faulted intersection between the Upper and Lower Miller's Dale Lavas and the Potluck Sill. These older lavas only appear to be associated with irregular, low-amplitude anomalies near their outcrops (N1 and N2), with no indication of any concealed thickening as they dip eastwards towards their terminations. The amplitude of the magnetic signal from the Potluck Sill (west of these maps) is low compared to anomaly A, and is difficult to reconcile with the 180 m of dolerite that is known to underlie it.

Magnetic anomalies P and S imply that another accumulation of concealed volcanic rocks underlies Brushfield Moor and Monsal Dale. Anomaly P is unlikely to be related to the Upper Miller's Dale Lava; this thins eastwards from its outcrop around Miller's Dale and Taddington and is represented by only 3m of tuffaceous mudstone at a depth of 73 m in a borehole just north of the Brushfield farms. The Lower Miller's Dale Lava is also unlikely to be very thick there, or it may be absent, as in Cressbrook Dale. These anomalies are more likely to relate to a deeper source (deeper than the 100m in the borehole), and may relate to the Lees Bottom Lava or the Shacklow Wood Lava. Magnetic anomaly R coincides with Wardlow Hay Cop, and currently has no explanation, other than potential volcanic material at depth. Anomaly T lies on Namurian outcrops, with no other information to identify its cause.

The featureless area at K (Fig. 13) encloses High Rake Mine and the 132m of concealed igneous rock encountered during shaft sinking. There is no recognisable magnetic anomaly to associate with either an intrusive sill or an accumulation of lava of that thickness. Equally, there is no distinctive linear magnetic anomaly to confirm the existence of a dyke, although this may be the consequence of its depth below the ground surface and its presumed narrow width. Even though the geophysical flight lines crossed the proposed dyke at an angle of 45º, the resolution of small-wavelength magnetic signals, such as might be expected from a narrow, deep source, is limited by the flight line ground clearance, which was 90m for this survey. A similar problem with non-detectable east-west dykes has been encountered in Scotland (Busby et al., 2009). The east-west alignment of dipole anomaly M suggests that it may be associated more with an intrusive dyke as it nears the ground surface rather than with the outcrops of the Miller's Dale Lavas.

Comparison of the magnetic and structural maps (Figs. 3, 8 and 13), shows that the Wardlow Mires structural basin (as defined by the upper surfaces of both the Cressbrook Dale Lava and the Litton Tuff), coincides with the area of low magnetic relief between the positive anomalies C, E and R. Located between possible volcanic mounds, this is an area where the lava is likely to be thinner. The synclinal structure could be re-interpreted as having been initiated by draping carbonate sediment over an uneven sea-floor topography on the submerged lava field, with subsequent infilling of the deeper areas. Gentle folding caused by Variscan deformation may have deepened a pre-existing sedimentary basin trapped between rigid volcanic mounds, rather than being solely responsible for its creation. Similarly, the anticlinal structure east of the Wardlow Mires basin coincides with the magnetic highs A, E and H. Rather than being a simple tectonic feature, perhaps this was also a group of draped volcanic mounds enhanced by later compressional folding?

The rapid west-to-east decrease in thickness of the limestone between the Cressbrook Dale Lava and the Litton Tuff (Fig. 9) is consistent with the shoaling of the sea floor against the probable volcanic mound suggested by magnetic anomaly C (Fig. 13). The proposed area of convergence of the Tuff with the Lava, where the limestone may have zero thickness, coincides with the A-B magnetic high associated with the Eyam Volcano.

Implications for mineralisation

Numerous fracture-controlled mineral veins transect the limestone plateau between Longstone Edge and Eyam-Hucklow Edge (Fig. 13). Most have a calcite-fluorite-barite mineral suite with minor galena (Rieuwerts, 2007; Ford & Rieuwerts, 2000). Vein widths are very variable, and fracturing of the limestone occurred in more than one phase (Quirk, 1993; Hunter, 2009). Many of the shorter veins belong to an apparently conjugate set with NE-SW and SE-NW orientations, while the longer veins have a general east-west orientation. The latter, particularly the High Rake and Hucklow Rake systems are large-scale mineralised structures that have been mined intermittently for at least four centuries. Production of fluorspar from High Rake only ceased in 2010, while Hucklow Rake, though not mined since 1999, is still considered to contain significant resources of the mineral.

Horizontal slickensides on faulted surfaces are commonly associated with the larger-scale east-west veins, and en-echelon, sinistral displacements of ~130m and 150m respectively can be estimated for the High and the Hucklow Rake vein systems. In contrast, many of the NE-SW and SE-NW veins, often called scrins, were narrower and less well mineralised. They are generally parallel to the major joint sets in the limestone and some scrins may be little more than enlarged joints filled with mineral. The short, east-west mineral veins located along the scarp slope of Longstone Edge have vertical slickensides, and are interpreted as early tensional fractures associated with flexing along the monoclinal axis (Hunter, 2009). These early fractures appear to have been intersected and laterally displaced by the later White Rake wrench fault.

Some of these mineral veins are aligned with magnetic anomalies related to the lava field concealed beneath (Fig. 13). A radiating pattern of mineral veins at Bleaklow is located at magnetic anomaly H, which lies above the thickest combined accumulation of igneous rock (Cressbrook Dale Lava and Litton Tuff together) along Longstone Edge. The radial pattern of veins may have originated as early fractures associated with settlement and flexing over the volcanic dome before a lateral stress field was imposed. East-west wrench faulting caused by the stress field appears to have exploited this previously weakened zone to create the important High Rake – Deep Rake mineral vein system. Repeated episodes of mining have probably obliterated all structural evidence of mineral phases in the main intersection zone. However, exposures of scrins visible today in the side-walls of the High Rake – Bow Rake open-pit mine suggest that they differ from the major east-west vein system, being narrower, barely mineralised and with no obvious indication of lateral displacement (Fig. 14). These characteristics are consistent with their formation as a separate and possibly earlier generation of fractures, although proof of this is lacking.

Other coincidental alignments between mineral veins and magnetic anomalies (Fig. 13) include: White Rake with the steep gradient between anomalies E and G; Dirty Rake, which connects anomalies E and U; Crosslow Rake, which connects anomalies A and C, including a bifurcation on either side of anomaly A; and the Hucklow Rake system, which is aligned with the northern side of anomalies A, B and C and then extends westwards to anomaly M, possibly following a deeper intrusive dyke. All of these named mineral veins belong to the larger, better-mineralised group that lie east-west and were the product of later-phase wrench faulting. Neither Watersaw Rake nor Seedlow Rake are associated with prominent magnetic features, although veins or unmineralised faults extend westwards from Watersaw Rake towards anomaly J (associated with the Tideswell Sill) and around the northern flank of anomalies P and S. The magnetically quiet area between Wardlow Mires and Tideslow (Fig. 2), which is underlain by thinning Cressbrook Dale Lava and a thickening Litton Tuff, is notable for the apparent absence of mineralised faults and fractures. The northern area of magnetic interference (Fig. 13, L) is most likely to be caused by the intersection of a series of ENE-WSW mineral veins with easterly-dipping lava beds. These veins shows sinistral faulted displacements, comparable to the main east-west veins, and also appear to converge westwards towards the area surrounding the Peak Forest Sill.

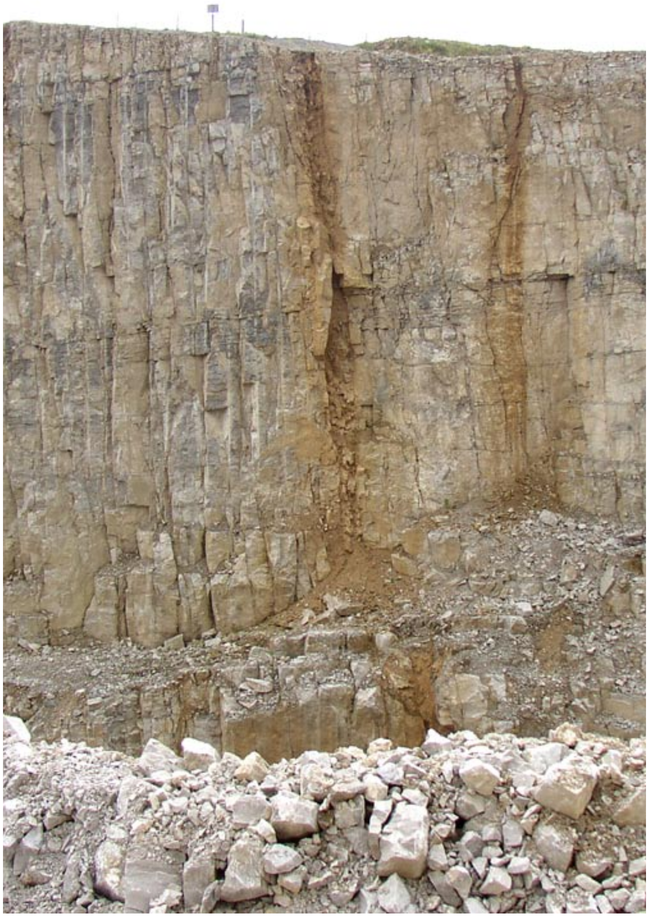


Figure 14. *Wager's Vein (dark brown) cutting Monsal Dale Limestone in the High Rake open pit mine near on Longstone Edge in 2009; face height is 60m.*

The Eyam Volcano

Interpretation of the subsurface geology and airborne geophysics indicates that a lava field with a cluster of several individual volcanic mounds of variable relief exists concealed beneath the undulating limestone plateau between Longstone Edge and Eyam-Hucklow Edge. The largest of these mounds, containing massive and amygdaloidal basalt at least 72m thick, lies west of Eyam and is here named the *Eyam Volcano*. It could have formed an emergent island in the shallow Brigantian sea, surrounded by smaller volcanic cones on an irregular sea floor. It was subsequently buried during relative sea-level rise by onlapping layers of carbonate sediment that formed the remainder of the Monsal Dale Limestone. The extinct lava field, after becoming enveloped by the limestone mass, may have behaved as a rigid foundation rock that continued to influence the subsequent local geological evolution, beginning with reactivated eruptions of volcanic ash (part of the Litton Tuff) and differential settlement and compaction of the overlying limestone. During the period of Variscan deformation, the inherited structure of the lava field appears to have exerted some control upon the gentle folding of the limestone, as well as the locations and orientation of fracturing, major wrench-faulting and the hydrothermal mineral veins that have been extensively exploited.

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ID	name	source	ID	name	source
1	Wardlow Mires borehole No.1	1, p.91, 378	42	Sallet Hole Mine sough	11, p.123
2	Wardlow Mires borehole No.2	1, p.378	43	Hard Shaft	9, p.60
3	Littonfields borehole	1, p.69, 373	44	Slater's Engine borehole	11, p.124.
4	High Rake Mine shaft	2	45	Shuttle Rake Mine	9, p.53
5	High Rake underground raise	2	46	Crossdale shaft	9, p.60
6	Hill Top Mine shaft	3	47	Goddard's borehole 1	12
7	Mock Mine	3	48	Goddard's borehole 2	12
8	Nether Liberty Mine	3	49	Goddard's borehole 3	12
9	Smithy Coe Mine	3	50	Goddard's borehole 4	12
10	Old Edge Mine	3	51	Goddard's borehole 5	12
11	New Edge Mine	3	52	Goddard's borehole 6	12
12	Great Hucklow No.7 borehole	1, p.94, 102	53	Goddard's borehole 7	12
13	Hucklow Edge No.1 borehole	1, p.92, 367	54	Victory shaft	4
14	Hucklow Edge No.2 borehole	1, p.94, 371	55	Burnt Heath shaft	4
15	Dustypit Mine	1, p.94	56	Cliffstile Mine shaft	4
16	Middleton Dale (No.4) borehole	1, p.96, 375	57	Wren Park Mine	5
17	Milldam Mine shaft	1, p.94	58	Darlton borehole DH1	13
18	Broad Low (No.6) borehole	1, p.94	59	Darlton borehole DH2	13
19	Little Hucklow borehole	1, p.94	60	Darlton borehole DH3	13
20	Earnslow Mine shaft	4	61	Darlton borehole DH4	13
21	Watergrove sough intsecn.2	5, p.123	62	Darlton borehole DH5	13
22	Watergrove sough intsecn.1	1, p.94	63	Darlton borehole DH6	13
23	Watergrove forefield shaft	6, p.42	64	Limestone borehole 17NE14	14
24	Victory Level intsecn.	5	65	Limestone borehole 17SE12	14
25	Glebe Mine shaft	1, p.95	66	Limestone borehole 17NE12/13	14
26	Glebe Mine u/g borehole	16, p.86	67	Milldam bhole 35/89 (slit 5)	10
27	Ladywash Mine u/g borehole	1, p.95, 372	68	Milldam bhole 1/91 (slit 14 S side)	10
28	Ladywash Mine shaft	1, p.28	69	Milldam bhole 72/90 (slit 14 N side)	10
29	Eyam borehole	7, p.57	70	Milldam bhole 59/90 (turnaround)	10
30	Cressbrook Dale outcrop	Field visit	71	Milldam bhole 22/91 (C drive, N side)	10
31	Longstone Edge bhole SK17 SE/2	8, p.32	72	Milldam bhole 23/91 (C drive, S side)	10
32	Longstone Edge bhole SK27 SE/19	8, p.32	73	Middleton Engine Mine	10
33	Longstone Edge bhole SK27 SW/4	8, p.32	74	Tideslow New Engine shaft	15
34	Longstone Edge bhole SK27 SW/5	8, p.32	75	Robinson Old Grove	15
35	Longstone Edge bhole SK27 SW/8	8, p.32	76	Litton Tuff outcrop	Field visit
36	Longstone Edge bhole SK27 SW/1	8, p.32	77	Wardlow Sough raise	4
37	Longstone Edge bhole SK27 SW/20	8, p.32	78	Cackle Mackle Mines	4
38	Longstone Edge bhole SK27 SW/10	8, p.32	79	Seedlow Mine shaft	4
39	Longstone Edge bhole SK27 SW/15	8, p.32	80	Neptune Mine	Field visit & 4
40	Deep Rake (Backdale Mine)	9, p.61	81	Old Edge vein crosscut borehole	16, p.86
41	Castlegate Lane outcrop	Field visit			

source	reference
1	Stevenson & Gaunt, 1971
2	Bagshaw Collection, 1852
3	Lead in the veins, 2009
4	Beck, 1980 & pers. comm.
5	Rieuwerts, 2007
6	Ford, 2010
7	Gatliff, 1982
8	Aitkenhead et al., 1985
9	Carruthers & Strahan, 1923
10	Glebe Mines Ltd
11	Walters & Ineson, 1981
12	Cemex UK Ltd
13	Tarmac Central Ltd
14	Gatliff, 1982
15	Cook, 1780
16	Dunham, 1952

Appendix Table.
Sources of numerical data used for the structural interpretations. Locations as on Figure 2.