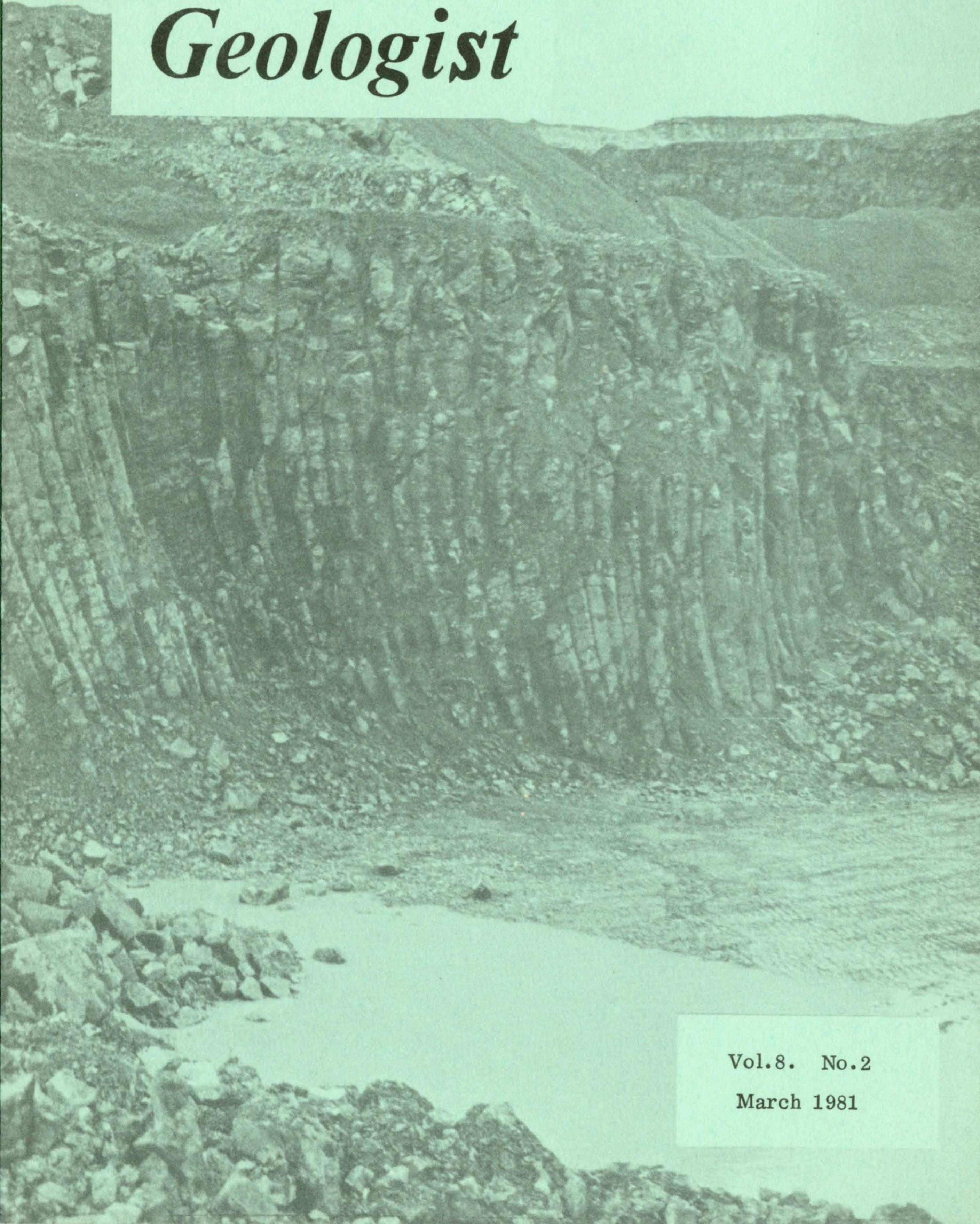
THE
Mercian Geologist



Vol.8. No.2
March 1981

EAST MIDLANDS GEOLOGICAL SOCIETY

THE MERCIAN GEOLOGIST

Editor:

F. M. Taylor.

Volume 8

Number 2

March 1981

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ISSN 0025 990X

Printed by the Nottingham University Press.

Front Cover: Waterswallows Quarry, Buxton; polygonal jointing in sill. See also Plate 3. Photo taken by M.G. Lodge.

A REVIEW OF THE DISTRIBUTION AND CORRELATION OF IGNEOUS ROCKS IN DERBYSHIRE, ENGLAND

by

S.G. Walters and P.R. Ineson

Summary

The classical work on the igneous horizons in Derbyshire was published by Bemrose in 1894 and 1907. Although many of Bemrose's localities have long since been obscured, recent exploratory drilling, mining, opencast work and temporary exposures have provided additional details. The county is subdivided into four geographical regions, the Matlock - Wirksworth, Alport - Bakewell - Taddington Dale, Castleton - Buxton - Tideswell and the Eyam - Longstone - Litton regions.

The geographical distribution and thickness variations as well as the stratigraphical horizon of the sills, lavas/tuffs, wayboards, dykes and vents are described and illustrated in detail. The sills include those at Bonsall, Ible, Waterswallows, Peak Forest, Potluck and Mount Pleasant. Dykes are recorded at Buxton Bridge and in Great Rocks Dale. Grangemill, Ember Lane, Bonsall Moor, Calton Hill, Ditch Cliff and the Speedwell Littoral Cone are examples of previously evoked vent structures. Some of the extensive tuff horizons are located at Shothouse Spring, Ravensdale, Dove Holes, Pindale, Litton and Longstone Edge. In Derbyshire, four lavas are well known, the Matlock Upper and Lower, and the Miller's Dale Upper and Lower Lavas of the Matlock - Wirksworth and Castleton - Buxton - Tideswell regions respectively. However, a number of additional horizons are exposed or have been encountered in mines and boreholes. Included in this group are the Winster Moor, Alport Upper (Conksbury Bridge and Lathkill Lodge), Alport Lower (Bradford Dale), Shacklow Wood, Lees Bottom, Millclose, Cave Dale, Cressbrook Dale and Cressbrook Mill Lavas.

This review, based on previous publications, recent borehole information and present day field observations, includes correlation tables for the above mentioned igneous horizons in Derbyshire.

Nature and Scope of the Review

The Dinantian limestones exposed in the South Pennines contain a varied assemblage of contemporaneous basaltic lava flows, tuff horizons and vents, together with intrusive sills and dykes. In general all the igneous rocks are poorly exposed and especially so in the north between Castleton and Buxton, as well as in the east between Bakewell and Wirksworth; only in the Matlock area are reasonable outcrops encountered.

Mercian Geologist, vol.8, no.2,
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cover and plates 2-4

A number of igneous horizons are known to extend to the east under the Namurian strata, for volcanic products have been recorded (Ramsbottom *et al.*, 1962) from the limestone inliers at Ashover and Crich. Igneous activity has not been noted in the south-western part of the South Pennines, around Dove Dale nor in the Manifold Valley.

Bemrose's publications in 1894 and 1907 have, in general, remained the only systematic account of the igneous activity in the region. He divided the same into two parts, a north-west or Miller's Dale area, and a south-east or Matlock area, which included Ashover and Crich. Within these two areas, Bemrose (1907) recognised two major lava horizons, the Miller's Dale Upper and Lower and the Matlock Upper and Lower Lavas, but noted that the two sets of lavas lay at different stratigraphical horizons. In doing so, he destroyed the concept advocated by Pilkington (1789), Watson (1811, 1813) and Farey (1811), etc. of the continuity of the 'main toadstones' over the whole South Pennine orefield. In addition to these four lavas, he recognised a number of additional volcanic horizons, which he was unable to correlate.

Subsequent to Bemrose's field observations, information on the stratigraphical complexities and subsurface distribution of the various igneous horizons has increased considerably. Individual, but localised publication (Traill (1940), Shirley (1950) and Walters (1980)), together with general compilations (Institute of Geological Sciences sheets (SK26SW, etc.), mining companies borehole data (personal communications) and the authors' field observations, have added to this knowledge. The inter-relationships of Bemrose's 'uncorrelated lavas' can now be elucidated and many have subsurface developments far in excess of his 'main lavas'. In addition, further lava flows have been recognised that have no surface expression. This was exemplified at Millclose Mine by Traill (1940) and Shirley (1950) who recorded seven lava horizons.

The present compilation attempts to synthesise current knowledge on the stratigraphy of the numerous lava and tuff horizons. This has involved a detailed examination of old mining records (Sheffield City Library and Derbyshire Records Office, Matlock) and early literature sources, e.g. Hopkins (1834). These documents contain a wealth of information, with respect to the location and thickness of the igneous horizons, but must be interpreted with due caution. Information from the above has been combined with details from boreholes, often unpublished but given to the authors,* together with observations from recent mining activity, exploration of disused mines and exposures in opencast sites, mines and quarries developed after Bemrose's publications.

The frequency of surface and subsurface exposures, together with borehole information permit the volcanic horizons to be traced and invariably correlated, over distances of up to 10 km. Elsewhere and especially beneath the Namurian cover, information is scarce and correlation more intuitive. Attempts in using K-Ar isotopic age determinations for correlative purposes have not been successful due to the complex post-extrusive hydrothermal events. Fitch, Miller & Williams (1970) and Ineson & Mitchell (1973) report that the material gives consistently younger ages, more probably related to mineralising episodes than the extrusive activity.

At present, thirty distinct lava or tuff horizons can be recognised, the outcrops of which are poorly exposed. They are often marked by an inconspicuous feature or may be traced over 'marshy ground', the upper limit of which is often a spring line. Recourse to auger holes, animal and mine spoil is often necessary in order to trace an outcrop. Only rarely are actual boundaries observed and in the foregoing text and figures all boundaries and outcrops etc. are conjectural unless otherwise stated. A major part of the South Pennines has recently been resurveyed by the Institute of Geological Sciences and the outcrop distributions given in this paper are based on their published maps with modifications arising from borehole data and the authors' field observations.

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*The authors were provided with borehole logs and core, etc. on the understanding that no details be released at this stage, other than for the igneous horizons.

Historical Summary

Mining records indicate a varied and often confusing terminology with respect to these deposits. The most common term is 'toadstone' - a word of uncertain derivation (see Ford, 1977). Records also refer to 'blackstone', this may in a number of instances be equated to either the lavas or to bituminous limestones. 'Channel' - a term used in the northern area may likewise be a synonym for toadstone or refer to clay alteration products. Occasionally the term 'dunstone' is used for the igneous horizons at outcrop, but more commonly indicates dolomite. Weathered amygdaloidal lava and toadstone-clays (Garnett, 1923) are cited as 'cat dirt', while 'wayboards' may be either tuffaceous clay partings or residual (clastic/insoluble) clay horizons within the stratigraphical sequence (Walkden, 1972). Whitehurst (1778) initially described these rocks and recognised their intrusive igneous origin. In the Matlock area he depicted three toadstone horizons with 'a vent structure' at Grangemill. Faujas de St. Fond (1779) refuted an intrusive origin, regarding them as 'traps' or sedimentary precipitates, after the Neptunists' school of thought.

An extrusive origin was subsequently proposed and advocated by Pilkington (1789), Watson (1811, 1813), Farey (1811) and Hopkins (1834) all of whom considered that Derbyshire had three toadstone horizons. Farey, in particular, placed emphasis on three continuous toadstone horizons; however, in addition, he recognised areas with 'chance beds', that is, localised toadstones, e.g. Mogshaw Mine at Sheldon.

Significant contributions were the Geological Survey Memoirs (Green *et al.*, 1869, 1887) in which the volcanic nature of the deposits was substantiated, but the validity of their persistent nature was questioned.

Without doubt the most authoritative account of the deposits is Bemrose's 1894 and 1907 papers. In his first paper he provided detailed petrographic descriptions of the lavas and tuffs. The diversity of rock types was enumerated by Geikie (1897), who encouraged Bemrose to remap the field relationships, the results of which he published in 1907.

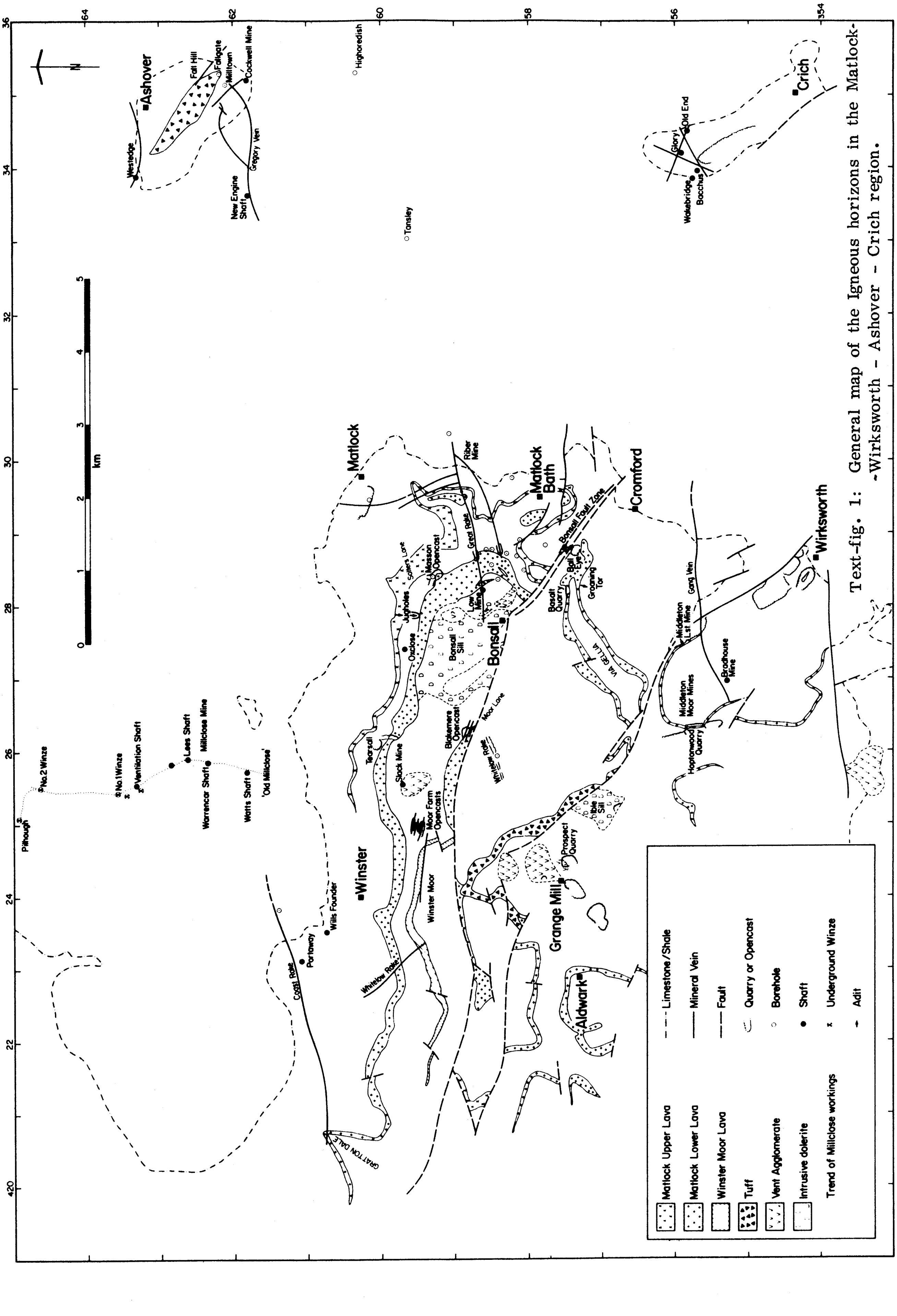
Geographically the igneous rocks are found in four regions: (1) Matlock to Wirksworth; (2) Alport to Bakewell; (3) Castleton to Buxton; (4) Eyam to Longstone Edge. The two main lava groups erected by Bemrose are retained but are further subdivided to include extensive sub-surface developments of igneous material in the Eyam and Bakewell - Alport areas.

1. The Matlock - Wirksworth region including Ashover and Crich

A number of lavas, tuffs, vents and sills occur in the region (text-fig. 1). The Matlock Upper and Lower Lavas predominate in a varied sequence of igneous rocks, and are to be found from Wirksworth in the south to Gratton Dale in the west. The northerly extent of these horizons is in the area of Millclose Mine (Darley Dale) while the eastern boundary cannot be stated due to insufficient information. One or both of the lavas may extend towards Ashover and in part constitute the complex volcanic sequence located beneath the limestone inlier.

The third lava is the Winster Moor Lava. It has a restricted geographical distribution and is confined to the ground between Gratton Dale, Winster and Bonsall Moors and the workings of Millclose Mine. Considerable confusion has arisen due to previous papers failing to report the Lava, or inserting it at an incorrect stratigraphical horizon.

Two sills, the Ible and Bonsall Sills, named after the villages where they are well exposed, are also described, as well as a number of tuff horizons. The Matlock - Wirksworth region also contains a number of vent structures. Those at Ember Lane and Grangemill are well known and documented, however at least another two are to be found in this region.



Text-fig. 1: General map of the Igneous horizons in the Matlock-Wirksworth - Ashover - Crich region.

A complex volcanic sequence is known to underlie the Ashover Inlier and a less complex, but otherwise insufficiently documented sequence is located in the Crich area. The Ashover area presents considerable difficulties with respect to the correlation of the volcanics with similar strata to the west.

The Winster Moor Lava

The Winster Moor Lava occurs at the Asbian/Brigantian (George *et al.*, 1976) boundary. Exposures are minimal, so much so that the Lava was not recognised until recently as a distinct unit (Shirley, 1950).

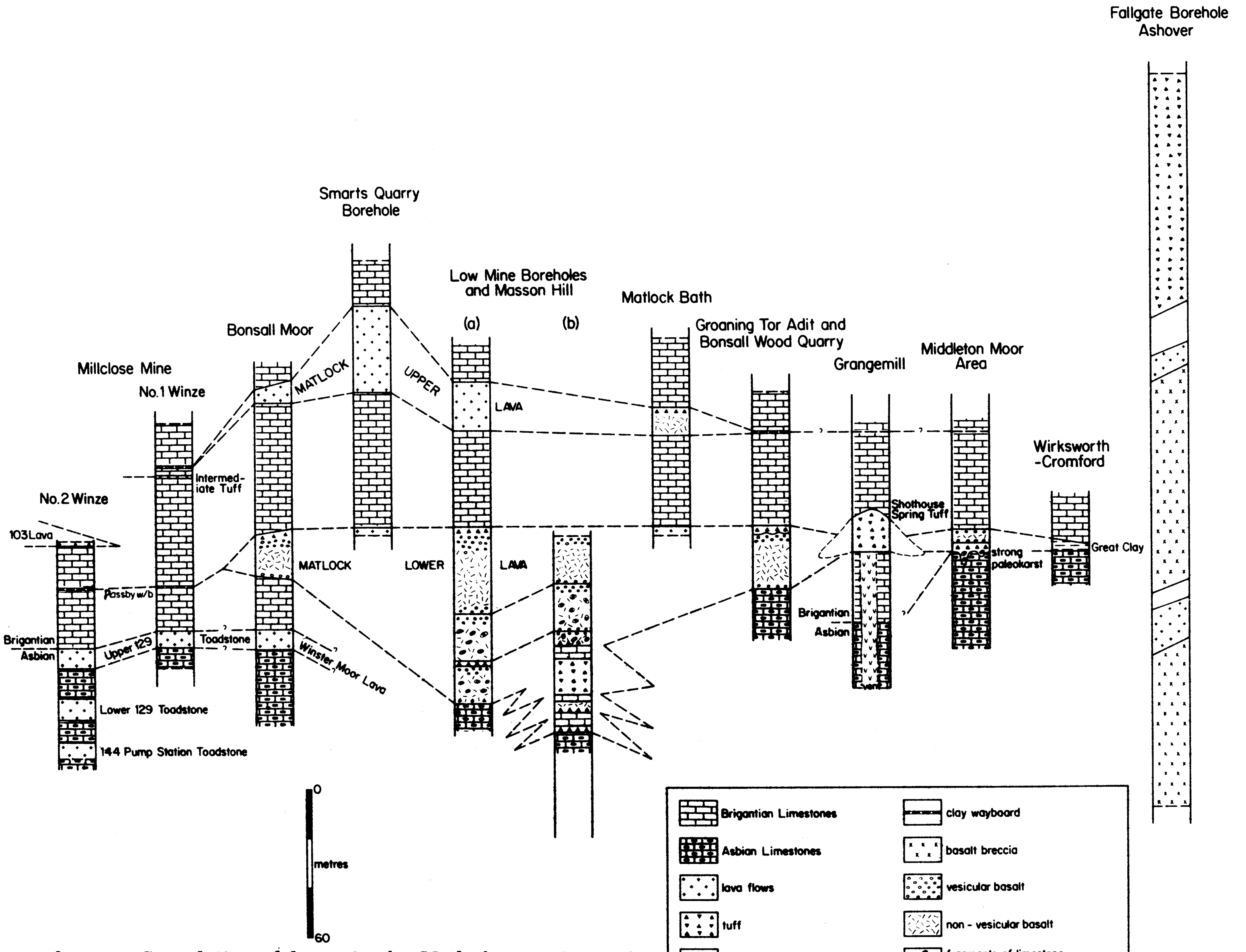
Pilkington (1789) recorded a 'third toadstone' some 10 m thick at Hang Worm Mine (3 miles south-west of Snitterton). Strahan (in: Green *et al.*, 1887) recorded a thin bed of toadstone, east of Winster Moor Farm, below the Matlock Lower Lava, and reported apparent irregularities in toadstone thicknesses at Whitelow Rake (text-fig. 1). The present authors attribute this apparent irregularity in the thickness of toadstone to the juxtaposition of the Winster Moor Lava and the Matlock Lower Lava and Strahan's failure to recognise the Winster Moor Lava as a separate lava flow in this area. However neither Bemrose (1907) nor Traill (1940) recognised the Winster Moor Lava.

The Lava was named by Shirley (1950) who subsequently reported outcrops on Winster and Bonsall Moors (1959). It has been traced westwards to Gratton Dale where due to rapid thinning, the Lava is represented as a wayboard; the southerly limits and exact extent beneath Bonsall Moor have, as yet, to be defined. The Institute of Geological Sciences map, 1:50,000 Sheet 111 (Buxton), show an isolated outcrop of weathered Winster Moor Lava near Grange Quarry (SK220.560). This is difficult to reconcile with the known geographical distribution of the Lava. The eastern limit of the Lava is at present uncertain.

The northerly extension of the Winster Moor Lava, into the Stanton Syncline and the Millclose workings was, until recently, conjectural. This arose because previous authors failed to recognise the Lava as a distinct horizon, as well as uncertainties with respect to the exact position of the Matlock Lower Lava. Additional complexities were introduced with respect to the location of the Asbian/Brigantian boundary. The latter is based on the change from the massive bedded pale limestones of the (Asbian) Hoptonwood Group to the thinner bedded, darker and more variable facies of the (Brigantian) Matlock Group. In Millclose Mine this change was recognised above the Upper 129 Toadstone, where a thick sequence (30 m) of bituminous limestones are documented (text-fig. 2). At outcrop, Smith *et al.*, (1967) and Shirley (1950) considered the Matlock Lower Lava to lie at this lithological change, but to be overlain by a locally attenuated sequence of bituminous limestones. Traill (1940) considered the Matlock Lower Lava to terminate before Old Millclose Mine. He postulated that it may be correlated, through Millclose Mine by means of the Passby Wayboard - 13.4 to 22.9 m above the Upper 129 Toadstone horizon. The stratigraphical implications of this hypothesis were recognised by Shirley (1950) although his subsequent interpretation, rather confused the problem.

The apparent absence of bituminous limestones beneath the horizon of the Matlock Lower Lava at outcrop was attributed to either a facies change or an erosional episode. Shirley (1950) considered that in Gratton Dale (text-fig. 1) the Matlock Lower Lava (the Tearsall Farm Lava) wedged out. He assigned outcrops of lava in the Gratton Dale area to his 'Gratton Dale Lava" which he considered to be stratigraphically between the horizon of the Winster Moor and the Matlock Lower Lavas. In recognising bituminous limestones from above the "Gratton Dale Lava horizon", that is, from below that which he considered to be the level of the Matlock Lower Lava, he correlated this sequence with the Upper 129 Toadstone and bituminous limestone of Millclose Mine. Subsequently the Matlock Lower Lava and the Gratton Dale Lava have been shown to be the same (Institute Geol. Sci., 1976b) thereby invalidating Shirley's hypothesis.

Smith *et al.* (1967) continued and increased the confusion by not considering the horizon of the Winster Moor Lava in their discussion of the Asbian/Brigantian boundary and the correlation of the Millclose and Matlock Lavas. They considered three possibilities for the correlation



Text-fig. 2: Correlation of lavas in the Matlock - Wirksworth - Ashover - Crich region.

of the Upper 129 Toadstone (Asbian/Brigantian boundary) of Millclose Mine with successions at outcrop:

1. Shirley's (1950) hypothesis outlined above.
2. On the 'grounds of thickness', all lavas in Millclose Mine below the Upper 129 Lava; Upper 129 Toadstone, Lower 129 and 144 Pump Station Lava; pass laterally into the Matlock Lower Lava. This implies that the Matlock Lower Lava straddles the Brigantian/Asbian boundary in the Matlock area and its extrusion represents a period of time equivalent to these three lavas and intervening limestones seen in North Millclose.
3. The Matlock Lower Lava correlates with the Upper 129 Toadstone (not the Passby Wayboard) and the apparent diminution of the bituminous limestones sequence at outcrop is a facies change, as the limestones are traced towards the Matlock Anticline.

Not one of these possibilities is accepted by the present authors. Recent opencast mining north of Moor Farm on Bonsall Moor has exposed a sequence of some 20 m of bituminous limestones between the Winster Moor Lava and the Matlock Lower Lava. This indicates that the failure of previous workers to recognise such a sequence, was due to poor exposures. It is therefore proposed that the Winster Moor Lava is equivalent in age to the Upper 129 Toadstone, and that the two lavas occur at the Asbian/Brigantian boundary. It is possible that these two horizons are part of the same flow.

Shirley (1950) noted some 30 m of bituminous 'D_2" limestones above the Upper 129 Toadstone at Millclose Mine, passing upwards into pale coloured, coral rich horizons above the horizon of the Passby Wayboard. Similar sequences are now recognised at outcrop with 20 m of bituminous limestone beneath the Matlock Lower Lava. At Tearsall Opencast Site, approximately 5 m of bituminous limestones lie on the Lava and are overlain by rich coral horizons. This sequence correlates with the similar facies change seen in Millclose Mine. Thus the Matlock Lower Lava and its probable equivalent, the Passby Wayboard, lie within the Brigantian. The redefined horizon for the base of the Brigantian has been recognised (I.G.S. Buxton Sheet 1:50,000 No.111) and located, around Grangemill, beneath the Matlock Lower Lava even where the Winster Moor Lava is absent.

Worley (1978a) in one of the more recent compilations on the stratigraphical occurrence of the lava horizons, placed the Asbian/Brigantian boundary at Millclose Mine even lower, at the Lower 129 Toadstone horizon. The authors cannot locate supporting evidence to substantiate this hypothesis.

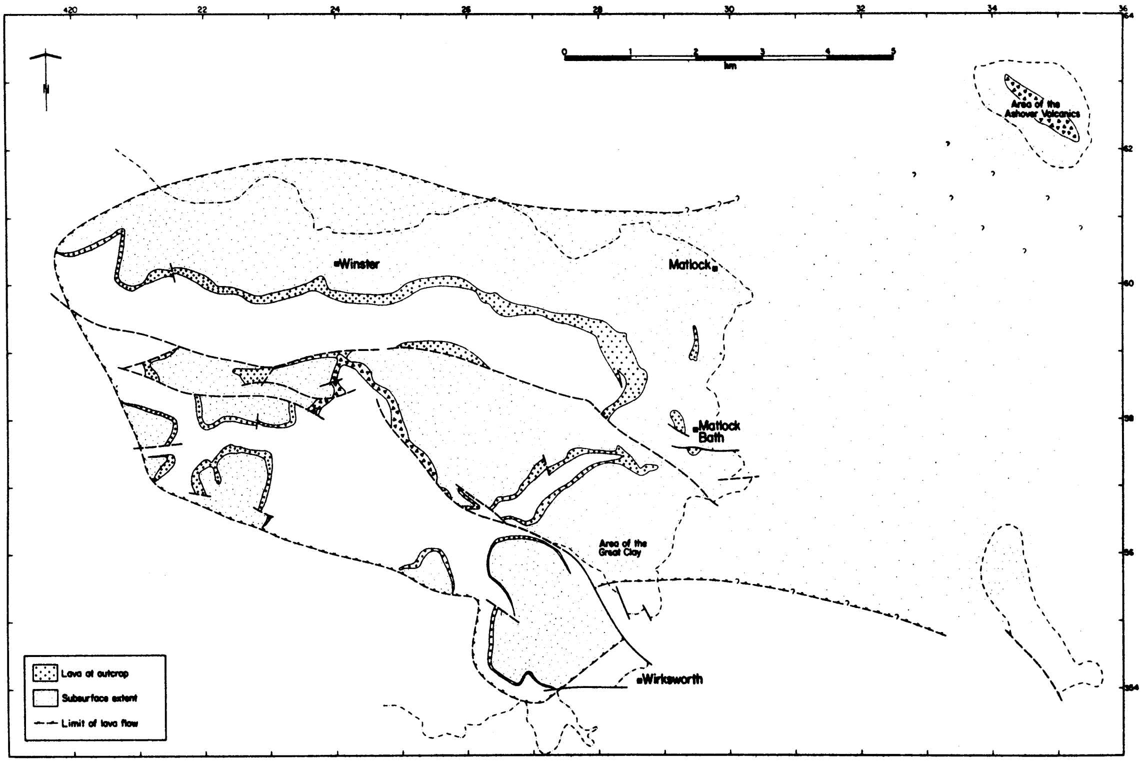
Matlock Lower Lava

Geographical Distribution

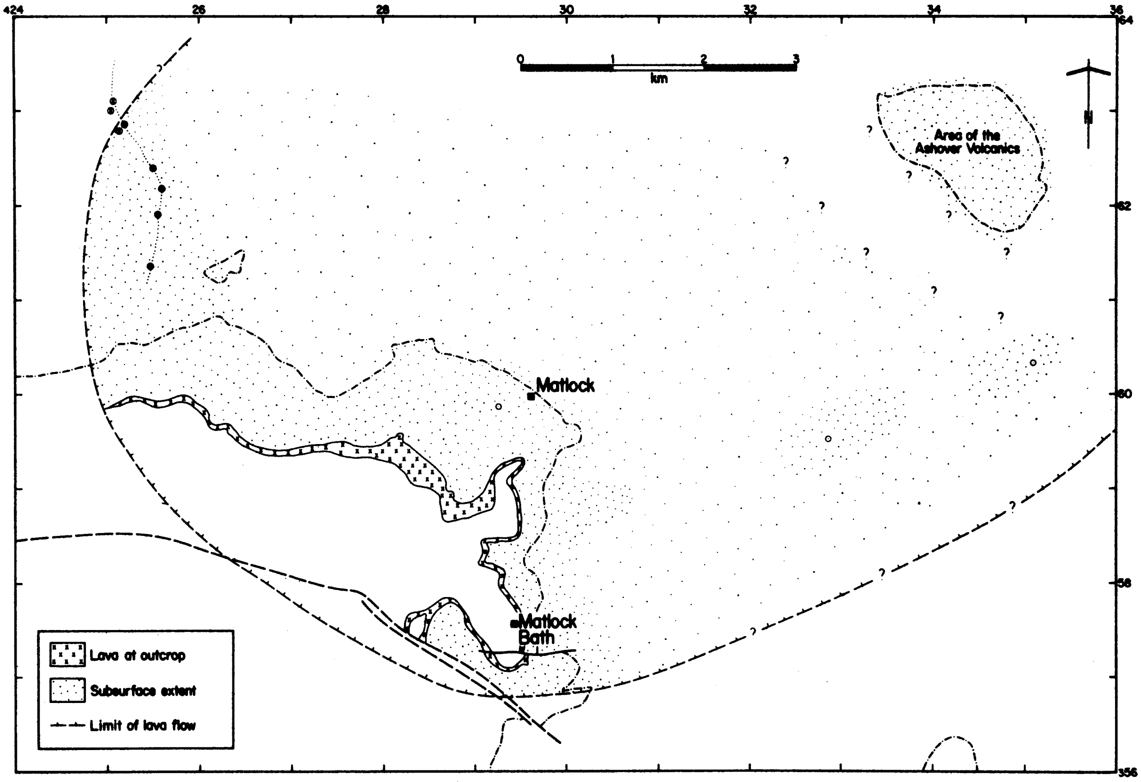
The Matlock Lower Lava has an extensive but poorly exposed outcrop extending from west of Gratton Dale to Masson Hill and the Bonsall area (text-figs. 1 & 3). It is recognised in inliers in the Derwent gorge at Matlock and Matlock Bath. South of the Bonsall Fault, the Lava outcrops at the bottom of the Via Gellia around Ball Eye rising in altitude towards the west. On the northern side of the valley the Lava passes laterally into a tuff associated with the Grangemill vents. The western extremity is to be found in the fault-complicated outcrops at Aldwark. South of the Via Gellia it can be traced to Middleton Moor, but has not been located south of Godfreyhole (text-figs. 2 & 3).

Masson Hill Area

The authors consider that the lava reaches its maximum thickness in the Masson Hill area where a series of boreholes (drilled by Exsud in 1971) on Great Rake proved 99 m of lavas and tuffs (text-fig. 2).



Text-fig. 3: The geographical distribution of the Matlock Lower Lava, stippling denotes subsurface extent and density denotes certainty.



Text-fig. 4: The geographical distribution of the Matlock Upper Lava.

Three distinct flows, characterised by vesicular upper and lower surfaces and separated by ash or decomposed clay, are recognised. The lower two units contain an abundance of marmorised limestone and angular basaltic fragments which result in an almost agglomeratic texture. The upper unit is exposed in an old opencast site on Masson Hill, where Great Rake has been worked within the Lava. The interaction of the mineralisation with the Lava has given rise to a zone of bleached and intensely altered lava.

Beneath the three flows, 40 m of ashes and lavas have been encountered. A varied assemblage of thin flows, ashes, calcareous ashes and tuffaceous limestones are interbedded with thin limestones. The complex sequence is difficult to correlate between individual boreholes. The maximum development may represent the flanks of a developing cone with sporadic and localised pyroclastic eruptions followed by periods of quiescence and inundation. The cone developed and was the precursor to the main effusive phases that culminated in the extrusion of the Matlock Lower Lava.

Associated with the Lava a number of vent feeders have been recognised in the area. They illustrate an alignment parallel to the Matlock anticline. Typical of such vents is at Ember Lane, 350 m southwest of Low Mine (SK284.586). Bemrose (1894) described it initially as a problematical exposure of tuffaceous limestone passing into bedded ash, and subsequently (1907) proposed that the exposures were best explained as an agglomerate filled vent. An unusual feature is the preponderance of limestone clasts with altered pumice fragments in an iron-stained matrix of shards and comminuted volcanic material. Trenching (pers. comm. N.J.D. Butcher) has indicated an intimate relationship between the lava and the 'agglomerate'. This 'vent' may represent the flanks and feeder for a (40 m) tuff rich limestone succession beneath the Matlock Lower Lava around Low Mine.

Smith *et al.* (1967) located an abundance of tuffaceous limestone built into field walls some 600 m north-west of Low Mine and suggested another vent. Bemrose (1907) considered the outcrop to represent a bedded tuff. As its stratigraphical horizon is beneath the Matlock Lower Lava, it is more probably related to the basal ash and lava 'agglomerate' sequence seen at Low Mine.

Ixer (1975) from borehole evidence, indicated that the lava was 80 m thick around Masson Hill Opencast Pit. At Masson Hill the basal 4-13 m of the Matlock Lower Lava is typified by a sequence of lava, tuffaceous limestone and tuff (the Masson Tuff of Ixer) which most probably equates with the sequence at Low Mine. In addition, Worley & Dorning (1977) recognised a 1 m tuff above the Matlock Lower Lava. The 'Little Toadstone' of Dunham (1952) and Ixer (1975) is a thick clay wayboard a few metres above the lava. Dunham (1952) proposed that the Little Toadstone exercised considerable influence on the replacement of limestone by fluorite and the localisation of the mineral deposits. This hypothesis cannot be demonstrated from exposures in the recent extension of Masson Hill Quarry for the wayboard is of such a minimal thickness that in all probability it would not have acted as a temporary cap rock. This wayboard horizon cannot be located in a southerly direction, but a thick and highly variable wayboard occurs in Masson Mine and in Jugholes Mine to the north. Boreholes on Bonsall Moor have located a thick graded tuff with abundant pumice fragments and glass shards in a calcareous matrix at a similar stratigraphical horizon. This unit the authors equate with the 'Little Toadstone' on Masson Hill.

At Tearsall Mine (SK262.600) Bemrose (1907) noted exposures of a fissile, bedded tuff overlying a vesicular lava, which has recently been re-exposed. Smith *et al.* (1967) recorded a thickness of some 25 m for the Matlock Lower Lava at Tearsall Mine which equates with Pilkington's record (1789) of 15 fathoms (27.4 m) of blackstone from this area.

Whitehurst (1778) noted a shaft at Slack Mine (SK257.597) which had been sunk 40 to 50 fathoms in toadstone without reaching the base, while other shafts only some 55 m to the west and east indicated the same horizon as being 20 fathoms (36.5 m) thick. Slack Mine had in fact been sunk into the Bonsall Moor Vent of Smith *et al.* (1967). Tuffaceous agglomerate fragments are present on the mine dumps.

In a southerly direction the lava is interpreted as occupying the southern limb of the Matlock anticline north of the Bonsall Fault. Highly weathered material overlies a silica/ fluorite replacement deposit in the Blakemere Lane opencast site (SK261.589) in an area of complex faulting. Bemrose (1907) recorded a problematical outcrop of agglomerate some 500 m south-east from this opencast site along Moor Lane.

Western Outcrop Area

West of Bonsall Moor, Green *et al.* (1887) recorded a thickness of 36 m for the Lower Lava in Wills Founder Mine (SK235.617). Worley (1977) from the same mine, described the uppermost part as exhibiting 'pseudo- spheroidal pillow structures'.

ALCOA boreholes penetrated the lava while investigating Coast Rake, north of Winster, and proved it to be 27-35 m thick. It was also intersected at Portaway Mine, while to the south, an opencast site on Whitelow Rake (SK232.598) cut through the lava. Further to the west the lava thins and finally disappears west of Gratton Dale. The northern extent of the Lava is certainly south of Millclose Mine as it was not located in any of the 20th century exploratory drifts from Watts shaft.

South of the Bonsall Fault

The Matlock Lower Lava is exposed in the Bonsall Wood Basalt Quarry where it is 25 m thick. On the south side of the Via Gellia the lava has been intersected in Groaning Tor Adit (SK2830.5722). It is overlain by 3.5 m of tuff, weathered to a toadstone clay in the uppermost 15 cm. The central zone of the tuff contains angular blocks of basalt and limestone which pass into graded tuff. The base is intensely iron-stained and rests on a vesicular basalt. The flow (senso-stricto) has an upper vesicular horizon which quickly grades into a hard 'relatively' fresh compact basalt. The lava is traced along the Via Gellia until displaced by the Gulph Fault.

Around Grange Mill (SK266.569) the Lower Lava has been interpreted by Smith *et al.* (1967) as passing laterally into the Shothouse Spring Tuff which had previously been regarded as being below the Matlock Lower Lava. The Shothouse Spring Tuff is spatially related to the Grangemill vents and dykes associated with the vents. The locality described by Geikie (1897) and Bemrose (1907) is visible opposite Grangemill. West of Grangemill this tuff grades into the basalt which finally terminates in the Aldwark area.

The interplay of the Grangemill vents and the Matlock Lower Lava is difficult to assess. The lava does not increase in thickness adjacent to the vents, as it does at Low Mine, indeed the Shothouse Spring Tuff replaces the lava. It may be the case that the vents are associated with small cones in a localised positive area around which the lava flowed.

South of the Via Gellia the Lava can be traced around Middleton Moor and has been recorded from numerous lead mines. Above Hoptonwood Quarries (SK263.558) recent excavations exposed a thickness of 6.7 m with a 3 m thick tuff overlain by a thin lava. Green *et al.* (1887) recorded some 13 m of tuff at nearby Bradhouse Mine. Worley (1978) refuted this figure and noted the tuff as being 3 m thick, which is consistent with the present reappraisal. The lava in this area, we suggest, may equate with a lobate flow front as it dilates once more in a southerly direction to Godfreyhole. A thickness of 10 m is recorded from boreholes on Middleton Moor (Worley, 1978).

Middleton Moor

In sections above Middleton-by-Wirksworth Limestone Mine (SK277.557) the Matlock Lower Lava is located beneath cambered Matlock limestones. Fresh spheroids of basalt suspended in a toadstone-clay matrix and a diminution in thickness indicate localised 'squeezing' of the lava. In the Mine, the Lower Lava rests on a palaeokarst surface in the Hoptonwood limestones. Karstic pits, up to 10 m deep, infilled with weathered blocks of lava, tuff and limestone in a clay matrix occur beneath the Matlock Lower Lava. This erosional interval may equate with Brigantian Limestones located between the Winster Moor Lava and the Matlock Lower Lava in the northern area (text-fig. 2).

South of Middleton Limestone Mine the Lava rapidly thins. Although no longer exposed, Smith *et al.* (1907) recorded a problematical flow front of 20 m of weathered and brecciated lava interdigitating with limestones (SK278.555, text-fig. 3).

Cromford-Wirksworth Area

The continuation of the Matlock Lower Lava into the Cromford-Wirksworth area is unclear. A thin lava was seen in the floor of Middlepeak Quarry (SK287.546). Farey (1811) recorded a number of mines between Cromford, Middleton and Wirksworth as working veins in the '3rd and 4th lime' which implies recognition of the '3rd Toadstone' or Lower Lava.

Gang Mine yielded galena from the '1st Toadstone'. Old mining records refer to the 'Great Clay' and infer that it was thicker than normal wayboards. Marked on a 1777 plan of Cromford Sough, it was intersected either side of the Bolehill Anticline. The Great Clay was located in Brandrix and Rantertaker Mines working Gang Vein at SK289.557 and SK289.684 respectively. At the former locality, the Meerbrook Sough, some 54 ft. (16.5 m) below Cromford Sough (Oakman, 1978) intersected the Great Clay, here said to be 6 fathoms (11 m) thick. A section by Wheatcroft (1831) depicts the Great Clay displaced by the Gulph Fault, and indicates its location 160 ft. (46.8 m) beneath the base of the shales. Alsop (1845) equated the Matlock Lower Lava with the Great Clay of Wirksworth.

East of River Derwent and Crich

The Matlock Lower Lava can be traced east of Low Mine and in two inliers flooring the Derwent Valley at Matlock and Matlock Bath (text-fig. 1). Between Matlock Bath and Low Mine the position of the top of the lava has been proved in a series of boreholes drilled by Exsud during 1971 and 1972. Watson (1813) recorded a shaft on Bacon Rake as sunk through the 'basaltic amygdaloid with a cinder top' - 40 fathoms thick' (73 m). The weathered upper surface can be located below the pipe deposits in this area, e.g. Wapping Mine.

East of the River Derwent, beneath the Namurian cover, the Matlock Lower Lava has not been located. A lava has been recorded from Crich. The Crich mines were some of the few mines to prove 'rich ore' beneath the toadstone and thus stimulated similar, but unprofitable ventures, elsewhere in the orefield. Bacchus Mine cut through 20 fathoms (36.6 m) of lava whilst Pearsons Venture Mine found an 11 fathom (20 m) development according to Green *et al.* (1887, p.154). In the centre of the anticlinal structure, at Glory Mine (SK343.559) the toadstone was 9½ fathoms thick (17.4 m). Bemrose (1894a) briefly described the occurrence of lead ore in lava and the associated alteration encountered in Glory Vein at Wakebridge Mine. At Old End Mine (SK346.558) the lava was 9½ fathoms thick (17.4 m).

The variable thickness of the toadstone (Lava) in the Crich area was noted by Alsop (1845) who stated: 'a thick bed of toadstone sunk through at one shaft diminishes to a foot or two in thickness at the other'. This statement is difficult to reconcile with published data for the area, but may indicate a local flow front.

The lava at Crich is located at a similar stratigraphical horizon as the Matlock Lower Lava in the Matlock area and may therefore be part of the same flow (Smith, *et al.*, 1967). The eastern limits are unknown; however 'igneous horizons' have been located beneath the Derbyshire coalfield (Smith *et al.*, 1967).

Matlock Upper Lava

The Matlock Upper Lava has, in comparison to the Matlock Lower Lava, a restricted outcrop. It extends from Tearsall Mine (SK262.600) in the west to Masson Hill (SK286.587) and the Derwent gorge in the east. The southernmost extremity is at Ball Eye Quarry in the Via Gellia. South of the Bonsall Fault it does not form a mappable unit (text-fig. 4).

The maximum development is observed in the Masson Hill-Jugholes area (text-fig. 2). According to Dunham (1952) the lava is 21.5 m thick on Masson Hill and at least 24 m thick at Jugholes Mine, where it is exposed in the entrance to the lower adit. A more recent compilation by Worley (1978) indicates 35 m of lava on Masson Hill, while in Oxclose shaft (SK275.599) 29 m is proved.

Vesicular and non-vesicular basalts are exposed along Salters Lane and similar outcrops can be traced below the summit of Masson Hill. From borehole evidence the Matlock Upper Lava can be traced adjacent to Seven Rakes vein at Cawdor Quarry, Matlock, where it is 36 m thick (Smith *et al.*, 1967). Lead ore was recovered (Farey, 1811) from within the Lava at Seven Rakes Mine, and below High Tor (SK296.593) there are old opencast workings in the Lava.

Varvill (1959) noted that in Riber Mine, the Matlock Upper Lava was some 20 m thick. In a southerly direction it can be traced along the Derwent gorge towards Cromford. Exsud's boreholes at Upperwood proved the Upper Lava to be approximately 10 m thick. Around Ball Eye Quarry, in the Via Gellia, it is involved with the Bonsall Fault zone, where Butcher (1976) proposes fault and thrust repetitions to explain the complexities.

In Groaning Tor adit, on the southern slopes of the Via Gellia (SK283.572), a 1 m wayboard lies some 40 m above the Matlock Lower Lava. This wayboard is the last vestige of the Matlock Upper Lava. A similar correlation may be evoked with thick wayboards located in cores from Bonsall and Middleton Moors, although a definitive statement is not possible.

In a northerly direction the Lava can be traced into Millclose Mine where it is 18 m thick in Watts Shaft and 23 m thick in Lees Shaft (Traill, 1940). North of these localities, Traill recorded a termination prior to No. 1 Winze. Recent borehole information confirms Traill's outline distribution map and supports his hypothesis of an emanative centre to the north of Matlock (text-fig. 4).

East of Matlock, the top of the Matlock Upper Lava has been proved in a series of boreholes in the Riber Castle, Tansley and Highoredish area (Ramsbottom *et al.*, 1962). The Lava is absent at Crich, although Alsop (1845) reported a clay wayboard varying from 30 cm to 4 m and containing nodules of compact toadstone. A similar relationship cannot today be observed, but Smith *et al.* (1967) considered that Alsop's report may refer to the uppermost clay wayboard in the Matlock Group and equated it with the Upper Lava. If their supposition is correct it may infer the possibility of a flow front in the vicinity. Although the Highoredish borehole intersected the Matlock Upper Lava, the horizon cannot be traced with certainty, into the volcanic sequence at Ashover (1.7 km to the north). Additional clay wayboards, in the Crich area, were reported by Sargent (1912).

Ashover Area

Correlation of the tuff sequence exposed in the core of the Ashover anticline has always been uncertain. As Bemrose (1907) noted, the top of the sequence lies close to the level of the Matlock Upper Lava, but the date of the initial volcanic activity is not known.

Mining during the 18th and 19th centuries proved abnormally dilated 'toadstone' sequences. Cockwell Mine on driving north intersected toadstone on the Great Rake. The Blue Hillock shaft, sunk in 1781, and an exploratory level, proved the 'toadstone' to be 24 yds (22 m) thick. A northward continuation of the exploratory level, towards the centre of the anticline was driven in toadstone while a second exploratory underground shaft, 274 m northwest of Fall Mill, proved 54.9 m of tuff. Band (1976) indicated that, from shaft bottom, a boring for a 'considerable distance' did not bottom the toadstone. Green *et al.* (1887) recorded Milltown Mine shaft as 82 m deep, and stated that it encountered toadstone. New Engine shaft of Gregory Mine, on the western flanks, is depicted on old sections as reaching the top of the toadstone. The toadstone (upper surface) was intersected at a depth of 54.9 m in Westedge Engine shaft in the northern Ashover area. Farey (1811) recorded that lead ore was worked in the toadstone. A shaft on Townhead vein, some 230 m north-north-west of Ashover Church, proved toadstone 55 m beneath the top of the limestone. On the eastern flanks of the inlier, the top of the toadstone was intersected 84 m below the base of the shales, in Hogsland shaft, on Fall Hill vein.

Documentary evidence for the central area was provided by Ramsbottom *et al.* (1962) who indicated that the Fallgate borehole intersected an exceptionally thick (293 m) volcanic assemblage. A 95 m tuff as well as basaltic flows and autobreccias were recorded. The borehole was abandoned prior to penetrating the full volcanic sequence. The pyroclastic sequence may represent the core and flanks of a volcanic cone. The Milltown borehole, located on the flanks of the anticline, some 183 m south of the Fallgate borehole, indicated a rapid thinning of the tuff as well as failing to penetrate the full sequence in its 137.5 m.

The Ashover area clearly marks the site of a substantial volcanic cone centred on the Fallgate area. Distributional analyses of the Matlock Upper and Lower Lavas do not support the proposition that Ashover was a major contributor to the flows in the Matlock area. Although the Upper Matlock lava has been located between Matlock and Ashover, from borehole evidence it is inferred that the Ashover inlier represents the centre of a large but localised volcanic cone. The stratigraphical horizon of the Ashover 'volcanics' is uncertain, as correlation demands the lower limits, as yet unencountered, to be specified. A recent paper by P. Kelman (1980) provides additional information.

The Bonsall Sill

The Bonsall Sill is one of the largest igneous bodies in the South Pennine area and is intruded into the crest of the Matlock Anticline. It has an outcrop (text-fig. 1) approaching 1 km^2 but is poorly exposed. The dolerite varies, from a coarse ophitic type with remnants of fresh olivine, to a finer grained marginal facies described by Bemrose (1904) and Gibson & Wedd (1913). The coarse type is exposed in a small quarry at SK276.593 and the marginal type can be found to the south-west of Low Farm at SK281.588. A full petrographic and geochemical analysis of both types was given by Ixer (1972). A series of boreholes in the Becks Mere region (Smith *et al.* (1967), failed to reach the base of the Sill at a depth of 55 m. Becks Mere No. 1 borehole (SK275.593) intersected a 6.4 m thick amygdaloidal horizon with the 'normal' coarse dolerite, at a depth of 33.5 m.

Along its northern margin the dolerite is in contact with the base of the Matlock Lower Lava although the exact relationship is not clear. The sill may have invaded 'a line of weakness' between the lava and limestone, a situation in common with a number of the Derbyshire sills. To the south the sill terminates against the Bonsall Fault zone.

The Ible Sill

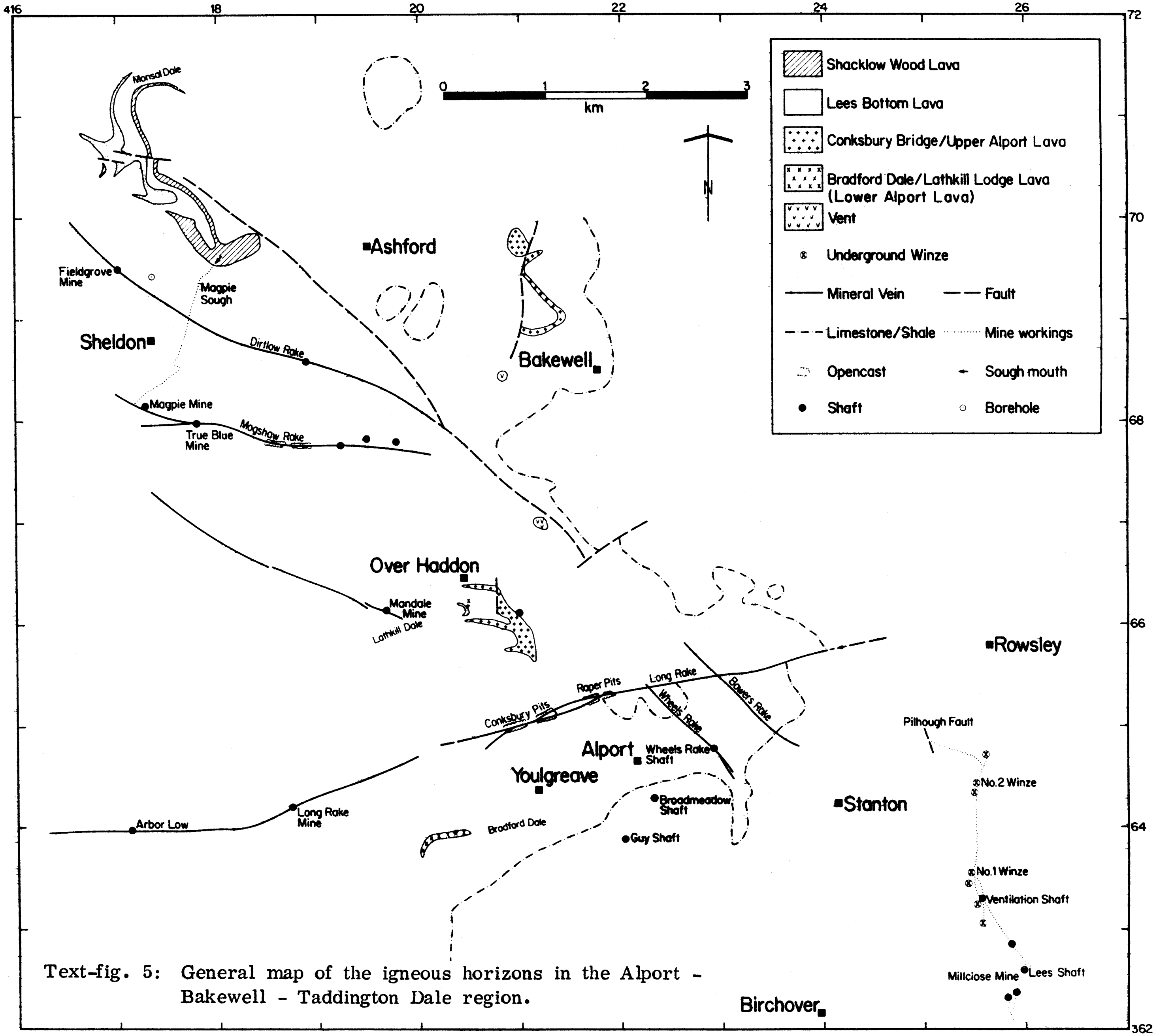
The Ible Sill outcrops at the western end of the Via Gellia (text-fig. 1). It was described by Bemrose (1907) as a typical ophitic olivine-dolerite. An exposure of the sill is located in the disused roadstone quarry at SK253.568 where some 30 m are visible. Bemrose (1907) noted marmorisation of the underlying limestone on the south side of the sill, however, this is now obscured by tip material.

Within the quarry the dolerite is traversed by disorientated calcite veinlets. Fibrous material within the calcite veinlets was thought by Garnett (1923) to be chrysotile asbestos. This suggestion was refuted by Sarjeant (1967) who considered the material to be a chlorite-montmorillonite clay mineral. The dolerite is strongly chloritised and calcitised with ilmenite altered to leucoxene. A distinct pervasive alteration horizon, up to 1.5 m wide, cuts across the sill. The genesis of this horizon is unknown for it is not related to local mineralisation aureoles, but may be connected with a hydrothermal alteration phase related to the cooling of the sill. The alteration has not been observed in the other Derbyshire olivine-dolerite sills.

The Prospect Tuff Mound

Prospect Quarry, Grangemill (SK245.574) reveals a mound-like weathered tuff exposure, against which the enclosing limestones decrease in thickness. From field evidence it appears to be comparable with similar exposures of a tuff mound in the quarries of Associated Portland Cement Manufactures (A.P.C.M.) at Hope (Eden *et al.*, 1964).

The tuff mound, containing blocks of marmorised limestone, is associated with porcellaneous horizons at the top of the Griffe Grange limestones, now thought to be partly Lower Asbian in age. If this is the case, the tuff is older than the Lower Brigantian vents at Grangemill, and represents the oldest known volcanic centre in the southern Pennine orefield. Associated lava flows have not been recorded or located.



Text-fig. 5: General map of the igneous horizons in the Alport - Bakewell - Taddington Dale region.

2. The Alport - Bakewell - Taddington Dale region

The igneous rocks of this region (text-fig. 5) are poorly represented at outcrop. The isolated, discontinuous nature of which has given rise to difficulties and confusion as to their correlation. They are, however, of considerable sub-surface extent and have been intersected in numerous boreholes and mine workings. Six lava/tuff horizons are located in the region. together with the complex succession in Millclose Mine. The lava/tuffs are: The Alport Upper and Lower, The Bradford Dale, The Conksbury Bridge, The Lathkill Lodge, The Shacklow Wood and The Lees Bottom Lavas. An additional number of lavas are reported from Millclose Mine, some of which can be equated to other lavas in the Alport area, however not all the units have lateral equivalents. Likewise, not all the above lavas are at different stratigraphical horizons, indeed it is proposed that the Alport Lower Lava is equivalent to the Bradford Dale Lava and the Alport Upper Lava is equivalent laterally to both the Conksbury Bridge and the Lathkill Lodge Lavas.

The 18th and 19th centuries witnessed intense mining activity in the Alport area and documentary evidence from that period indicates that the miners only fully understood the location and influence of strata above the Alport Upper Lava.

The Alport Lower Lava

Initial documentary evidence relating to the Alport Lower Lava arose from the exploration in depth at Wheels Rake Shaft (SK228.649) (text-figs. 5 & 7). Deep trials here were the first and only workings in the area to penetrate the hydrological compartment below the Alport Upper Lava, and excessive water was encountered (Oakman, 1978). Even with the erection of a water wheel it proved impossible to drain the shaft and sink it to the Lower Lava. Nevertheless, an exploratory boring was undertaken in the toadstone. Green *et al.* (1887) quote a figure of 56 fathoms (102.4 m) for the thickness of the Alport Lower Lava from 'information supplied by Mr. Toft'. This figure is still quoted on recent maps (Inst. Geol. Sci., 1976b). The present authors considered that this was a remarkable depth for lead miners to drill, and investigation of the original document (Bagshaw Collection No. 587[79]) has indicated that this was a misquote by Green *et al.* (1887) the actual value being a more realistic 56 ft. (17 m). This mistaken thickness of 102.4 m has, however, lead certain authors (Traill, 1940) to postulate a vent feeder for the lava. Such an hypothesis is now clearly erroneous.

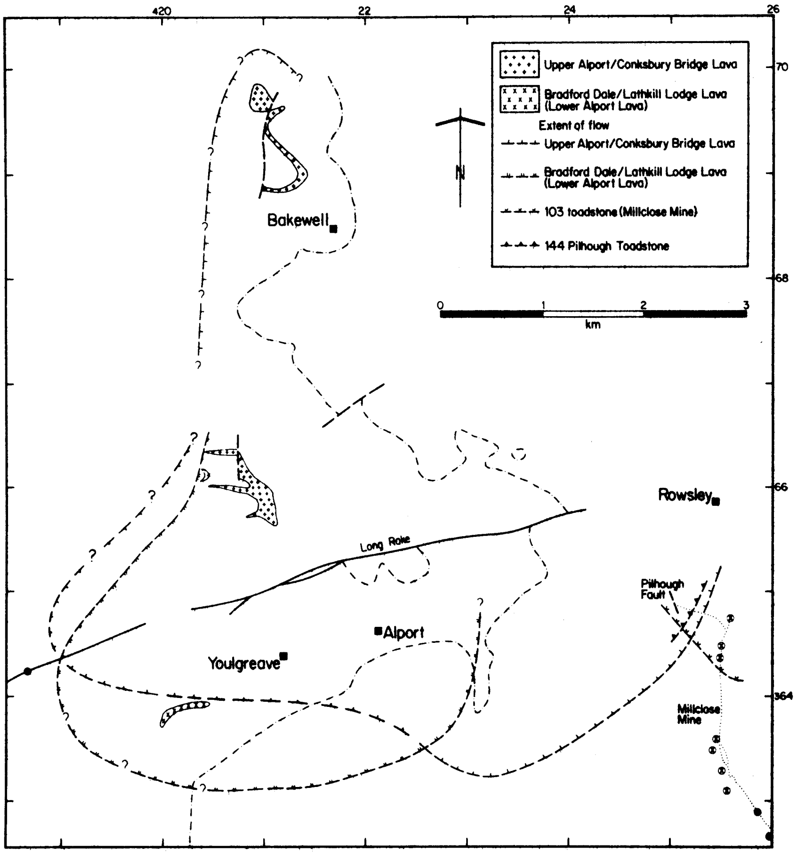
The Alport Lower Lava may also be correlated with the 'Bradford Dale Lava' exposed to the south-west of Youlgreave. Shirley (1957) noted that the Bradford Dale Lava lies 45.7 m below the *Orionastrea placenta* band, whereas the Alport Upper Lava when traced into the Conksbury area lies only 12 m below the *O. placenta* band. This, together with the westerly attenuation of the Alport Upper Lava before Bradford Dale, supports the present correlation (text-fig. 8).

South-east of Alport, the Lower Lava was not intersected by ALCOA in 1974. A vestige of its development in the Alport area is evident, for it is represented by a thick wayboard.

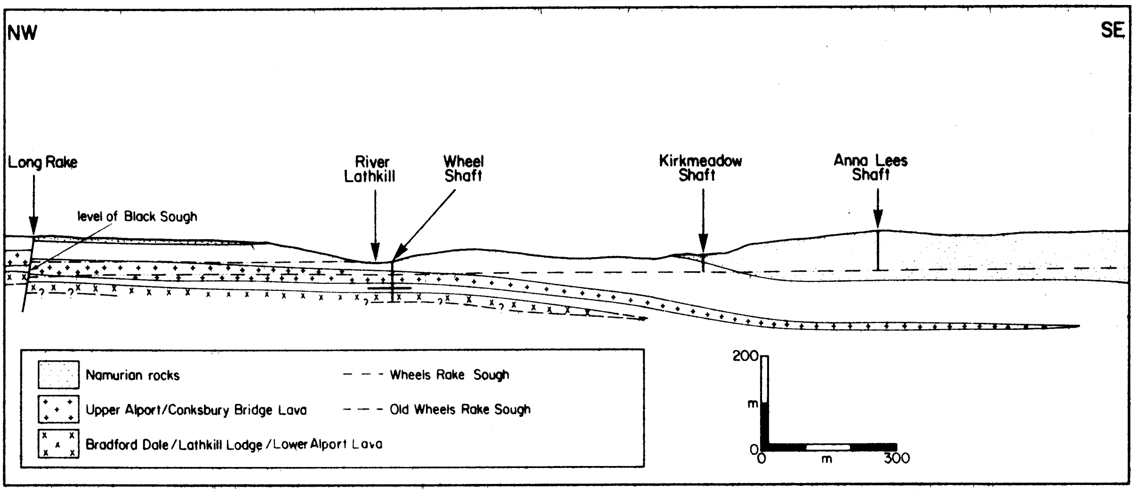
The Alport Lower Lava has been located in a series of boreholes around Conksbury Opencast site. Although the boreholes failed to penetrate the base of the lava, they did indicate a minimum thickness of 15 m. These findings are in accordance with the new interpretation of the Wheels Rake Shaft section, where there is a minimum development of 17 m for the Alport Lower Lava.

The Alport Upper Lava

The Lava is not exposed at surface. It was first encountered when Wheels Rake Old Sough was driven north along the vein from the River Lathkill (SK228.645). During 1786, these workings - in toadstone - encountered a vein in the forefield of the sough. The vein was in all probability Long or Ladies Rake, the powerful east-west reversed fault zone which forms the northern boundary to the mining area.



Text-fig. 6: Geographical distribution of lavas in the Alport - Millclose Mine area.



Text-fig. 7: Section along the line of Wheels Rake (after Butcher, 1976, with additional borehole data).

The Black Sough drainage level was driven westwards along Long Rake from Pickory Corner (SK246.658) on the River Wye. It entered lava near the intersection of Long Rake and Wheels Rake, where Green *et al.* (1887) noted that it was 17 fathoms (31 m) thick. From this intersection a branch was driven south-east along the Wheels Rake 17.4 m below the Old Sough (Oakman, 1978) initially in toadstone and finally passing into the overlying limestone (text-fig. 7).

Deeper drainage was provided by Hillcar Sough and its many branches. The Wheels Rake branch of Hillcar Sough was driven north-west along the vein and encountered the Alport Upper Lava at Wheels Rake Shaft (SK228.649). With the intention of conducting the first deep trial beneath the Upper Lava, a water wheel was erected and sinking commenced. The Upper Lava proved to be 25 m thick and separated from a lower lava by 13.7 m of limestone (Green *et al.*, 1869).

To the south-west of Wheels Rake Shaft, Broadmeadow Shaft (SK224.644) (text-fig. 5) intersected toadstone 21 fathoms (38.4 m) below the level of Hillcar Sough, at a similar stratigraphical horizon to the Alport Upper Lava. Guy Shaft (SK219.641) in the 1840's was sunk beneath Hillcar Sough to a depth of 32.2 m. It failed to locate toadstone, but did intersect two water-bearing wayboards at 65.8 and 80 m below the base of the shales. Tentative correlation places the lower of these two horizons at that of the Upper Lava, intersected in Wheels Rake and Broadmeadow Shafts. The implication of this correlation, is that the Alport Upper Lava decreases in thickness towards the west.

The Upper Lava has been located to the south-east of Alport, in a series of boreholes drilled by ALCOA in 1974. It was some 26 m thick in the area to the south-east of Wheels Rake Shaft, with a diminution in thickness as it was traced in a southerly direction towards Birchover.

Further evidence for the stratigraphical location and thickness of the Alport Upper Lava is from Raper and Conksbury opencast sites (SK217.653 and 210.650 respectively), where it floors these two operations on Long Rake. A thickness of 23 m is recorded (borehole logs) for the lava underlain by some 4.5 m of limestone. Butcher (1976) has shown that the lava thins west of the Conksbury Opencast Site, and is absent to the west of Long Rake spar mines, while to the north-west of the opencast site the lava is represented, at outcrop, by the Conksbury Bridge Lava.

Conksbury Bridge and Lathkill Lodge Lavas

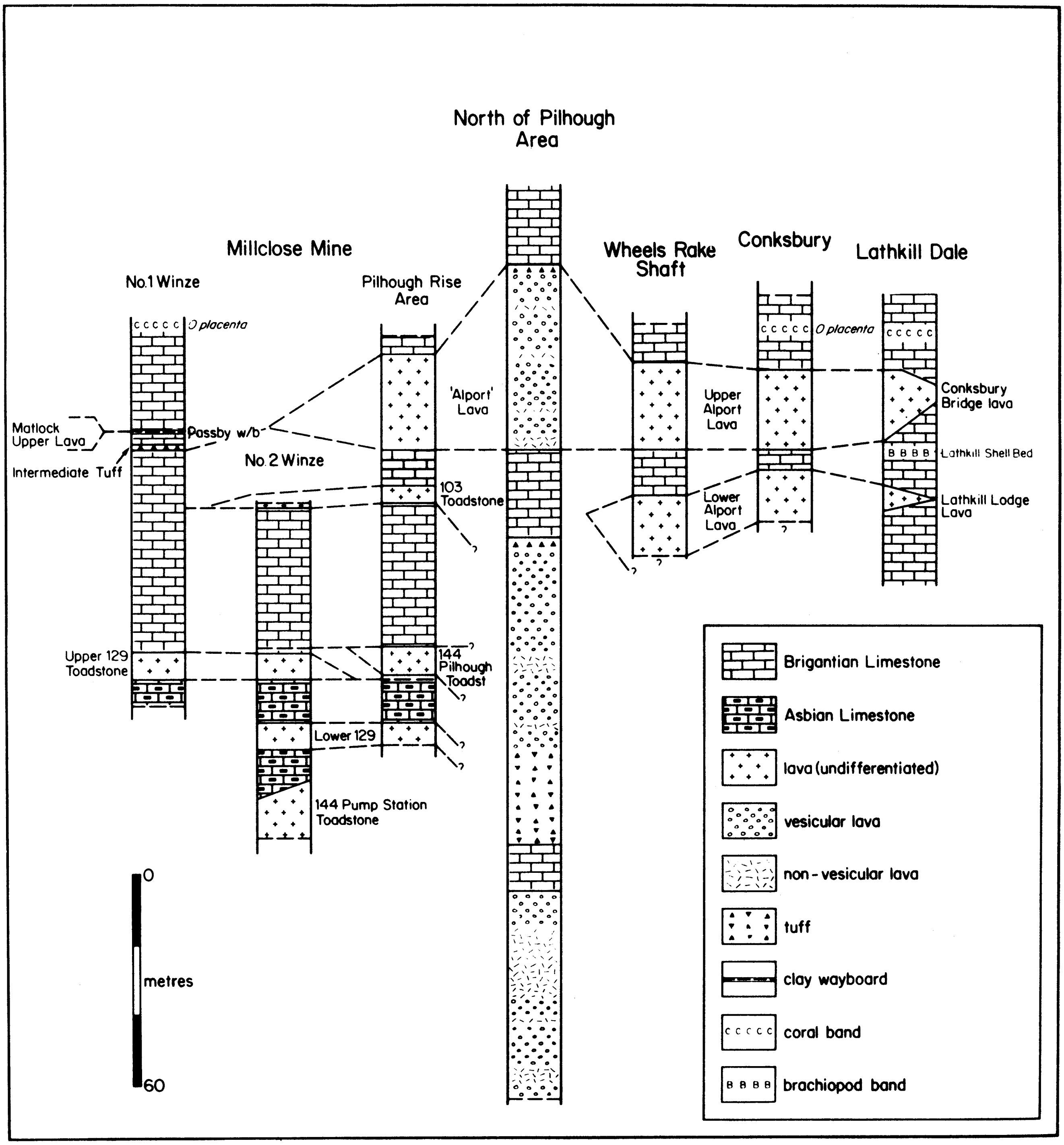
Using the *Orionastraea placenta* band mainly as the stratigraphical reference, the Alport Upper and Lower Lavas equate with the Conksbury Bridge and Lathkill Lodge Lavas, exposed in the lower reaches of Lathkill Dale north of Alport.

Lathkill Dale

The top of the Conksbury Bridge Lava is exposed along the northern side of the Dale (text-fig. 5). The *Orionastraea placenta* band occurs 12 m above the lava. The limestones rest on the vesicular upper margin of a flow which is 5 m thick. The central portion of the flow is characterised by a non-vesicular dolerite and a vesicular base rests on a lower flow. This has a highly vesicular and slightly hematised upper margin which grades downwards into a thick sequence of non-vesicular dolerite.

Lathkill Dale witnessed an unusual mining venture in the 1850's when it was claimed that gold had been discovered in auriferous pyrite associated with the weathered top of the Conksbury lava (Grigor-Taylor, 1972). Auriferous pyritic clay was also supposedly assayed from the weathered top of the Alport Lower Lava in Wheels Rake Shaft. All that remains of the ambitious venture are overgrown hollows and spoil heaps of basaltic fragments at SK209.661.

The Conksbury Bridge Lava is not encountered west of Over Haddon but may equate with a thick wayboard in Mandale Mine (SK196.662). The Lathkill Lodge Lava, according to Shirley



Text-fig. 8: Correlation of lavas in the Millclose Mine - Alport - Lathkill Dale areas.

(1950) is 27 m beneath the Conksbury Bridge Lava (text-fig. 8). At the type locality some 5 m of lava are visible and contain marmorised limestone fragments. Traced in a westerly direction a rapid attenuation may be observed. Farey (1811) noted that the Lathkill Dale Vein Sough commenced in lava into which the vein persisted.

Bakewell Area

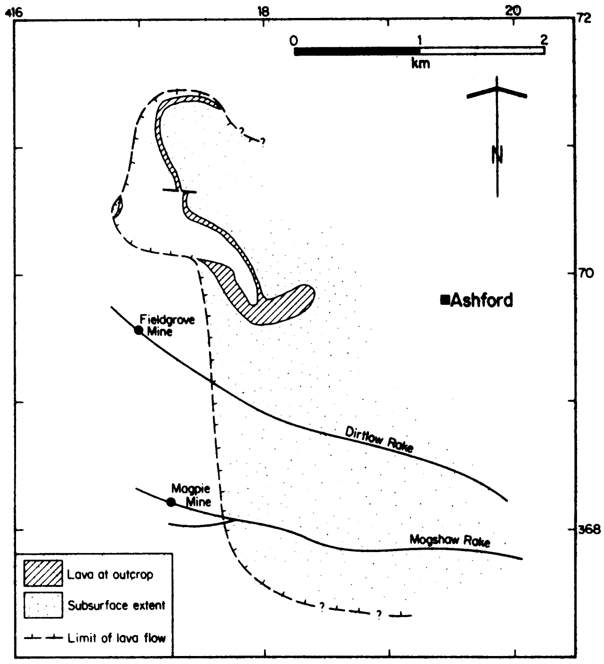
The subsurface extent of the lavas towards Bakewell is unknown due to the paucity of mines and borehole data. The Institute of Geological Sciences (1977b) report two vents, at Ditch Cliff (SK211.670) and adjacent to the Monyash road, at SK207.684. These are minimal in extent and exposure. Officers of the Institute, in noting a lava (the Endcliff flow) to the north of Bakewell at a stratigraphical horizon some 25 m beneath the *Orionastraea placenta* band, have correlated it with the Conksbury Bridge Lava. The Cracknowl 'vent' of Bemrose (1897, 1904) has been reinterpreted as a faulted segment of the same lava (Inst. Geol. Sci. 1977b).

Shacklow Wood and Lees Bottom Lavas

To the west of the Alport-Bakewell area, a number of lavas have been located at outcrop, in mines and boreholes in the general vicinity of Sheldon (text-fig. 5). A number of these lavas may correlate with the Lathkill Dale/Bakewell units.

Two flows, the Shacklow Wood and Lees Bottom Lavas (basalts) - are known from outcrops in Monsal Dale and Shacklow Wood. These units were equated by Butcher and Ford (1973) with the Millers Dale Upper and Lower Lavas, but have been subsequently considered (Inst. Geol. Sci., 1976a) to occur at stratigraphically higher horizons in the Brigantian succession.

The Lees Bottom Lava is exposed at the foot of Taddington Dale and a flow front is located in a southerly direction. It has not been reported from the Magpie Mine area nor from the head of Monsal Dale to the north. Information in the Ashford/Great Longstone area is minimal and hence its distributional limits are problematical.



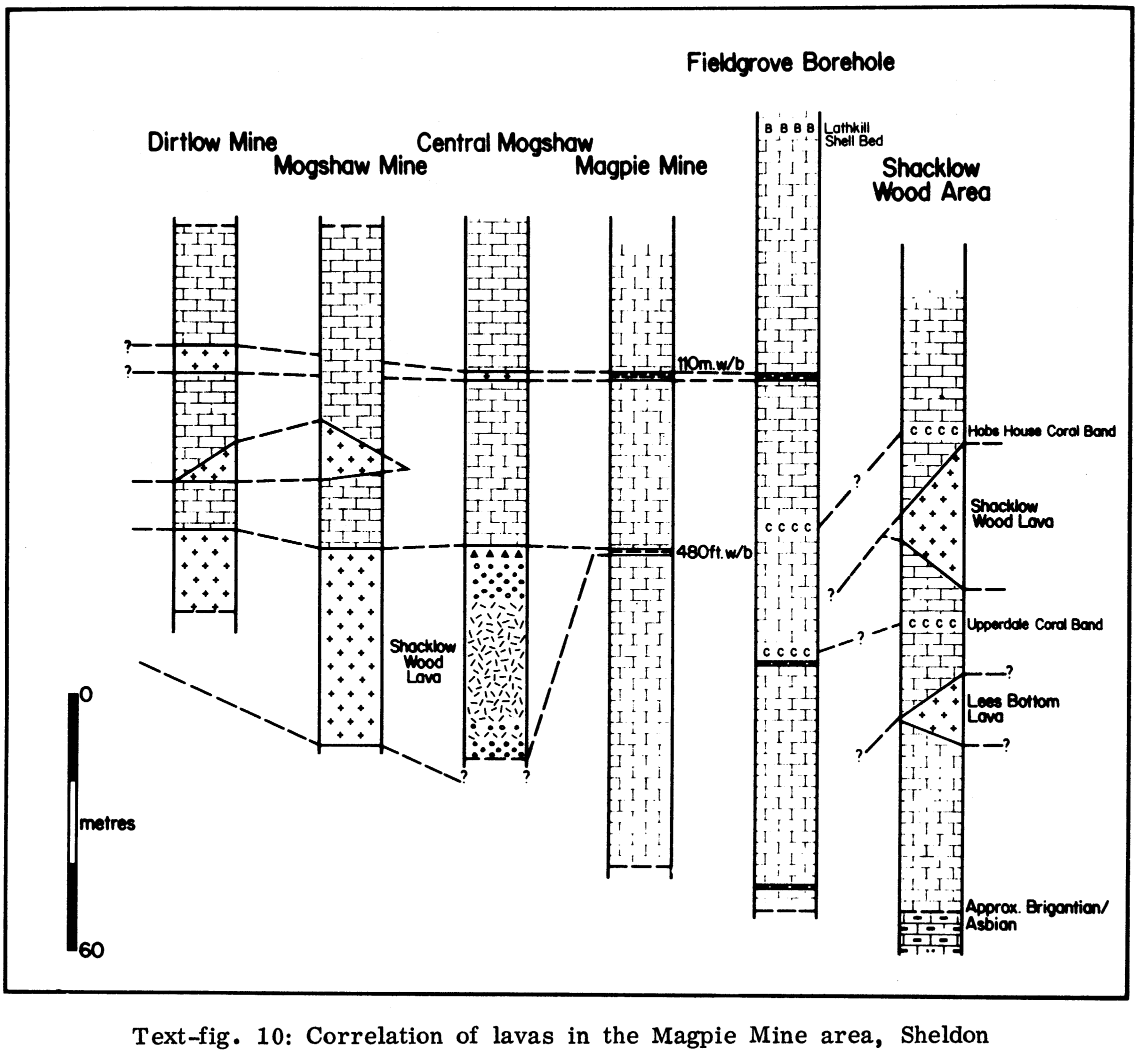
Text-fig. 9: Geographical distribution of the Shacklow Wood Lava, stippling denotes subsurface extent and density denotes certainty.

The Shacklow Wood Lava is exposed in Taddington Dale (text-fig. 9). Near Fin Cop (SK173.704) it is 11.5 m thick and at Black Rock corner (SK177.700) some 18 m are exposed. At this latter locality a vesicular upper surface rapidly grades into a sequence of non-vesicular dolerite. The coarseness of the central flow led Bemrose (1907) to regard it as intrusive - his New Bridge Sill. A more recent description of the area has been given by Miller (1980).

Magpie Mine Area

Magpie Sough intersects the Shacklow Wood Lava over a distance of 457 m, where it is folded into a shallow syncline and so faulted that the base is not exposed. Butcher (1975) described the top as having a spheroidally weathered surface associated with yellow clay and overlain by pyritous limestones. According to Butcher & Ford (1973) Sheldon Shaft (SK177.688) exposed 42 m of lava above sough level, while it was absent at Magpie Mine Shaft (SK172.682), 700 m to the south.

True Blue Mine (SK177.680) to the east of Magpie Mine intersected the base of the Shacklow Wood Lava in a rise 26 m above the Magpie 560 ft. (170.7 m) level (Varvill, 1959). Considering the horizontal attitude of the strata in the area, the thick wayboard at the 480 ft. (146.3 m) level in Magpie Shaft may be the lateral equivalent of the Shacklow Wood Lava seen in the True Blue rise (text-fig. 10). Varvill (1959) equated a clay, intersected at the bottom of the True Blue Shaft, as the top of the lava. If this interpretation had been correct,



Text-fig. 10: Correlation of lavas in the Magpie Mine area, Sheldon it would have given a thickness of 40 m for the lava. However as Worley (1978) indicated, this clay cannot be equated with the weathered top of the Shacklow Wood Lava, but is more probably the lateral equivalent of a thick wayboard (over 1.5 m) seen in the Redsoil Shafts at depths of between 104 and 110 m.

North of Magpie Mine, the Shacklow Wood Lava diminishes (at outcrop) in the vicinity of Shacklow Wood only to reappear further to the west. At (SK168.705) a small isolated exposure of vesicular lava may represent a lobate flow front (text-figs. 5 & 9). Fieldgrove Engine Shaft (SK170.695) exposed a thick clay at 110 m on the southern, upthrown side of the fault. A recent borehole (Cox & Bridge, 1977) at SK173.695 close to Fieldgrove Shaft, failed to intersect the Shacklow Wood Lava, but proved a number of wayboards. In the same borehole, a 0.55 m pyritic clay with included limestone clasts at 82 m, most probably correlates with the 110 m wayboard in Fieldgrove Shaft. It is not possible to equate a specific wayboard with the Shacklow Wood Lava, but the most obvious equivalents are a group of wayboards between 149 and 157 m. The tentative identification (Cox & Bridge, 1977) of marker horizons in the area, indicates that the Shacklow Wood Lava may equate with stratigraphically higher but less obvious wayboards. A number of marker horizons, the Lathkill Shell Bed and the *Orionastraea placenta* band, can be traced into the area enabling a comparison to be made of the relative stratigraphical horizon of the Lathkill Dale/Monsal Dale Lavas (text-figs. 5,8 & 10).

East of Magpie Mine

To the east of Magpie Mine three toadstones are recorded. Farey (1811) referred to the 'chance' toadstones in Mogshaw Mine while Green *et al.* (1887) noted old mining records as showing three toadstones at Dirtlow Mine (SK188.687). A section at the eastern end of Mogshaw Rake (dated 1840) depicts two toadstones inclined to the east, with the thinner, upper toadstone decreasing westwards (Bagshawe Coll. Sheffield City Library - B.C. 598).

Additional information has been provided by recent exploration drilling which intersected the lower toadstone. The hole failed to penetrate the base of the lower toadstone but proved a minimum thickness of 54 m. Non-vesicular holocrystalline basalts, comparable with the exposures at Black Rock corner, are now correlated with the Shacklow Wood Lava. The upper lava of the Mogshaw Mine section, was not evident; however a pyritic clay and thin basalt are recorded some 36 m above the lava. This horizon may equate with the '110 clay' intersected in the Magpie Mine area.

The mining manuscripts of Dirtlow Mine upon which Green *et al.* (1887) based their account (Bagshawe Coll. B.C. 604,605) depict three toadstones. The 'lower toadstone' is the thickest and correlates with the lower toadstone of Mogshaw Mine and the Shacklow Wood Lava. The 'middle lava' of the Dirtlow sections is depicted as occurring 10 m above the Dirtlow Mine Lower Lava and as dying out to the west. This can be correlated with the Upper Toadstone of the Mogshaw section which has indications of a similar attenuation to the west. It was not located in the recently drilled Mogshaw Rake Borehole located in the central part of Mogshaw Rake to the west of Mogshaw Mine (text-fig. 10). The 'upper lava' of the Dirtlow sections is some 36 m above the top of the 'lower lava' (Shacklow Wood Lava - text-fig. 10). This fact strongly suggests a correlation with the tuff/lava (?) encountered 36 m above the Shacklow Wood Lava in the Mogshaw borehole. A volcanic horizon at a similar stratigraphical level is not depicted on the Mogshaw Mine section but attenuation trends suggest that it may only be a thick wayboard in this area and would not be marked on a section as 'toadstone'.

Extrapolation of the evidence provided by the Fieldgrove Borehole places this 'upper lava' below the Lathkill Shell Bed close to the horizon of the Lathkill Lodge Lava. Attenuation trends, however, support the probability that it represents the continuation of local flows developed, at depth, in the Bakewell-Longstone Edge area.

The Millclose Lavas

The northward extension of Millclose Mine intersected five distinct lavas (text-figs. 2 & 8). These horizons are tentatively correlated with volcanic sequences in adjacent areas. It has been proposed (p.98, this paper) that three flows, the 144 Pilhough, the Lower 129 and 144 Pump Station toadstones, are located at the base of the Brigantian and within the Asbian Limestones. Comparable stratigraphical horizons with volcanic sequences have not been intersected to the west or north-west (Alport area). These lavas are absent in the Matlock area, but are found at similar stratigraphical horizons to the Millers Dale Lavas, in the northern region of the South Pennine Orefield.

Correlation with Alport Lavas

The Alport lavas occur within the Brigantian succession (text-fig. 8). The only comparable volcanic horizons noted in the northern part of Millclose Mine are the 103 toadstone and the 'Alport' lava of Traill (1940), who assumed that they correlated with the Alport Upper and Lower Lavas. However, as borehole data (pers. comm. by N.J.D. Butcher) indicates, the Alport Lower Lava does not extend towards Millclose Mine. This raises the question of whether the correlation of the Alport Upper Lava and Traill's 'Alport Lava' of Millclose Mine can be accepted. The Alport Upper Lava persists towards the Millclose area, but unfortunately the 'Alport Lava' was only intersected prior to the final abandonment of Millclose Mine. It was 27.4 m thick in the Pilhough Fault area, however its exact stratigraphical location was not proven. A rise in the area of No. 1 Winze south of the Pilhough Fault demonstrated the absence of any 'Alport' Lava.

Traill (1940) tentatively correlated the 'Alport' Lava of the Pilhough area with the Intermediate Tuff of Central Millclose Mine. This thin but persistent tuff horizon formed an important cap-rock to orebodies in the vicinity of No. 1 Winze. The Intermediate Tuff occurred 3.4 to 4.6 m beneath the horizon of the Matlock Upper Lava in the south of Millclose Mine. The horizon, according to Shirley (1950) was some 28-38 m below the *Orionastraea placenta* band.

In the absence of more detailed and definitive information on the stratigraphical horizon of the lavas in Millclose, the available evidence coupled with the general attenuation trends, is compatible with the following hypothesis. The 'Alport Lava' of Millclose Mine, the Alport Upper Lava of Alport and district as well as the Conksbury Bridge basalt of Lathkill Dale may all be regarded as one eruptive unit.

The 103, 144 Pilhough, Lower 129 and 144 Pump Station Toadstones

The 103 Toadstone forms another cap-rock horizon in a manner similar to the Intermediate Tuff. It was infrequently penetrated in the mine workings. In the Pilhough rise, a thickness of 3 to 6.7 m was recorded. The geographical limits of this toadstone are known in detail as it delimited the zone of step-like ascension of the orebodies to the overlying 'Intermediate Tuff'. Traill (1940) indicated that the toadstone terminated south-west of a line between Pilhough and No. 2 Winze (text-figs. 6 & 8). The emanative centre is probably in the vicinity of Rowsley (SK255.660).

The 144 Pilhough Toadstone is only recognised in Millclose Mine. Stratigraphically it occurs above the Upper 129 Toadstone in the central section of the mine. On the Pilhough Fault, it was 8.5 m thick, with a rapid attenuation to the south-east where it is represented by a wayboard.

The Lower 129 Toadstone is located some 12 m beneath the 144 Pilhough Toadstone, between No. 2 Winze and Pilhough. Traill (1940) noted that it lay on an erosion surface with attendant marmorization of the underlying limestones. It is a thin but highly variable flow varying between 3 and 8 m thick. Any attempt to deduce the direction of attenuation and hence a geographical distribution for the flow is not possible. It may correlate with the top of a flow located at a similar horizon in No. 1 Winze to the south, and 10 m below the Upper 129 Toadstone.

The lowest volcanic horizon in the basal Asbian Limestones was the 144 Pump Station Toadstone. It is 9.4 m stratigraphically lower than the Lower 129 Toadstone, and was intersected in the area of No. 2 Winze. The base of the toadstone was never exposed; however, some 15 m of lava were proved. The detailed description given by Traill (1940) of the flow front on the 144 fathom level indicates attenuating limestones with a number of wayboards abutting a 20° slope of pillowed, eroded lava which decreases in thickness towards the south-west.

North of the Pilhough Area

Despite the difficulties already outlined with respect to the correlation of the 'Millclose Lavas' with adjacent areas, a distributional analysis indicates that they are related to an Upper Asbian volcanic centre to the north-east of Pilhough. On the basis of data from the north-west of Pilhough it is suggested that this area also contains the volcanic centres responsible for the majority of the Brigantian extrusive activity at Millclose and Alport.

Three 'flows' were encountered north of Pilhough (text-fig. 8). The upper flow (52 m thick) consists of vesicular and non-vesicular units. To judge from its stratigraphical horizon this lava may correlate with the Alport Upper Lava and the 'Alport Lava' of Millclose Mine. This proposal is consistent with the observed attenuation trends. The middle lava (93 m thick) infers proximity to a vent with a comparable situation to the Low Mine sequences of the Matlock Lower Lava around Bonsall (p.89, this paper). Confirmation of this possibility is supported by the presence of a 60 m tuff sequence. Highly inclined graded tuffs, and auto-brecciated horizons intercalated with thin basalt flows underlie the uppermost 33 m of vesicular/non-vesicular flow units. It is proposed that this represents the flanks of a feeder cone similar to the situation outlined by Ramsbottom *et al.* (1962) for an interpretation of comparable horizons in the Ashover boreholes.

A minimum thickness of 58 m has been indicated for the lower lava which, unlike the middle and upper units, is characterised by the absence of pyroclastic material and the presence of thick coarsely crystalline doleritic centres to the individual flows. These horizons cannot be equated with individual lavas in the Pilhough area. One of the thick lava/tuff sequences may correlate with one or all of the 'Pilhough flows'. In the absence of detailed palaeontological classification of the intercalated limestones, the erection of correlatable horizons is not possible. The expanded volcanic sequence does, however, reconfirm the statement that Rowsley may be regarded as a volcanic centre concealed beneath Namurian shales.

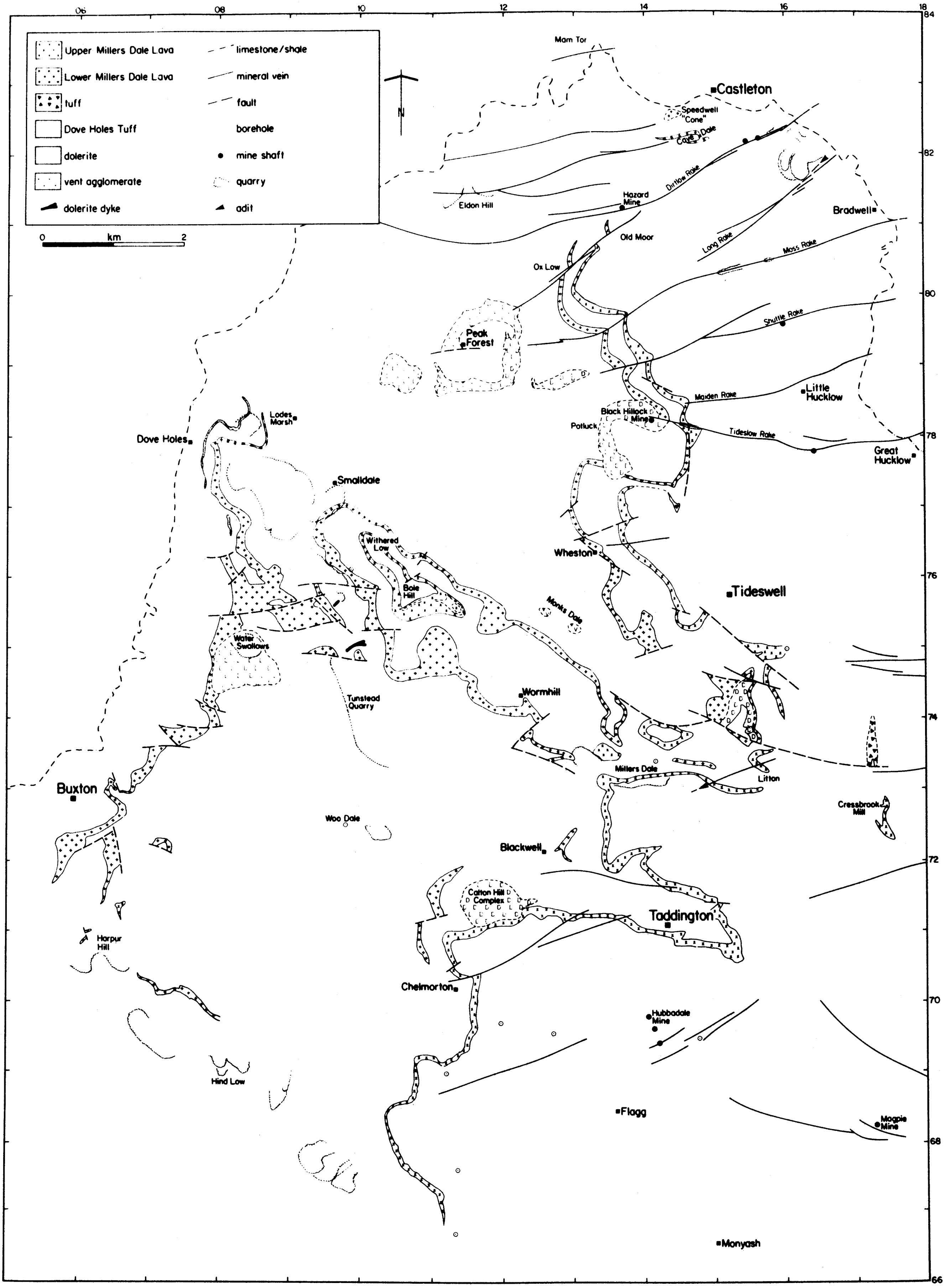
3. The Castleton - Buxton - Tideswell Region

Introduction

Two extensive lavas, the Miller's Dale Upper and Lower Lavas, dominate the igneous horizons in the north western part of the South Pennines. Additional volcanic strata include the Ravensdale Tuff and the Dove Holes Tuff. The region is unusual in that a large number of sills are located within the limestone sequence; the Waterswallows, Peak Forest, Potluck and Mount Pleasant Sills constitute this assemblage. Possibly the Waterswallows Sill is the most well known and the Peak Forest Sill occurs at the lowest stratigraphical horizon, while the remaining sills are of minimal extent and exposure, as are the Monks Dale and Peter Dale vents.

The region also contains one of the most frequented igneous localities in the whole of the South Pennines, The Calton Hill Complex. Unfortunately this locality was never fully documented and is now the site of a refuse tip, however two typical exposures are preserved as Sites of Special Scientific Interest (S.S.S.I.). Although not unique to the South Pennines the region also contains two dykes near ICI's Tunstead Quarry. These are poorly exposed, and as they are located on private land, are difficult to examine and sample.

Included within this subdivision of the South Pennines is the Castleton area, and so complex are the igneous deposits of this geographically restricted area, that it is described



Text-fig. 11: General Map of the Igneous horizons in the Buxton - Tideswell area (excluding Castleton) in a separate section. The Pindale Tuff and the Cave Dale Lava together with the Speedwell 'vent' are possibly the best known igneous horizons. The Speedwell 'vent' in particular has resulted in a considerable number of publications, far beyond the number normally produced by such a small exposure. It has recently been the subject of a complete reappraisal with the result that it is now considered to be a littoral cone. (Cheshire & Bell, 1977).

Pre-Asbian Extrusive Activity

The Woo Dale Borehole

The Woo Dale Borehole (SK 4099.3726) described by Cope (1949 & 1973) encountered 'volcanics' at a depth of 275.6 m. The upper 26.4 m of the 33 m sequence consists of highly inclined tuffs overlain by horizontal limestones and resting on sub-alkaline lavas (Cope, 1979). Although thought to be pre-Carboniferous, the age of the volcanic sequence has always been doubtful and Cope (1949) initially considered them to be part of the Pre-Cambrian basement, however K-Ar isotopic age dating (Cope, 1979) has indicated a minimum age of 383 ± 6 m.a. (Devonian) for the tuffs.

The Ravensdale Tuff

The oldest Carboniferous igneous rocks in the northern (Tideswell) area, the Ravensdale Tuff, was initially described by Bemrose (1894, 1907), while Sargent (1925) noted analcite infilled vesicles in some of the lapilli. Shirley & Horsfield (1940) placed the Tuff in the D_1 (Asbian) limestones. The bedded tuff sequence may be correlated with similar horizons in the Litton Dale Borehole (SK 160.750) where Stevenson *et al.* (1971) noted that the Tuff was 29.6 m below the base of the Millers Dale Lower Lava, and borehole chippings indicated that a 13.7 m sequence of tuffs and thin lava flows may be present. Further to the west, a Severn-Trent Water Authority's borehole in Millers Dale (SK 142.733) failed to intersect igneous horizons in the 300 m of limestones beneath the Millers Dale Lower Lava. A 'black calcareous shale' logged 30 m below the base of the Lava may represent the last vestige of the Ravensdale Tuff (text-figs. 11 & 14).

The Millers Dale Lower Lava

The lava outcrops from Buxton to Doveholes, around Wormhill and Tunstead east of Great Rocks Dale and forms an inlier in Millers Dale. Towards Tideswell it is intruded by the Tideswell Dale Sill. It can be traced northwards over Tideswell Moor as far as Ox Low, while in the Castleton area local pyroclastic and extrusive activity may have occurred contemporaneously.

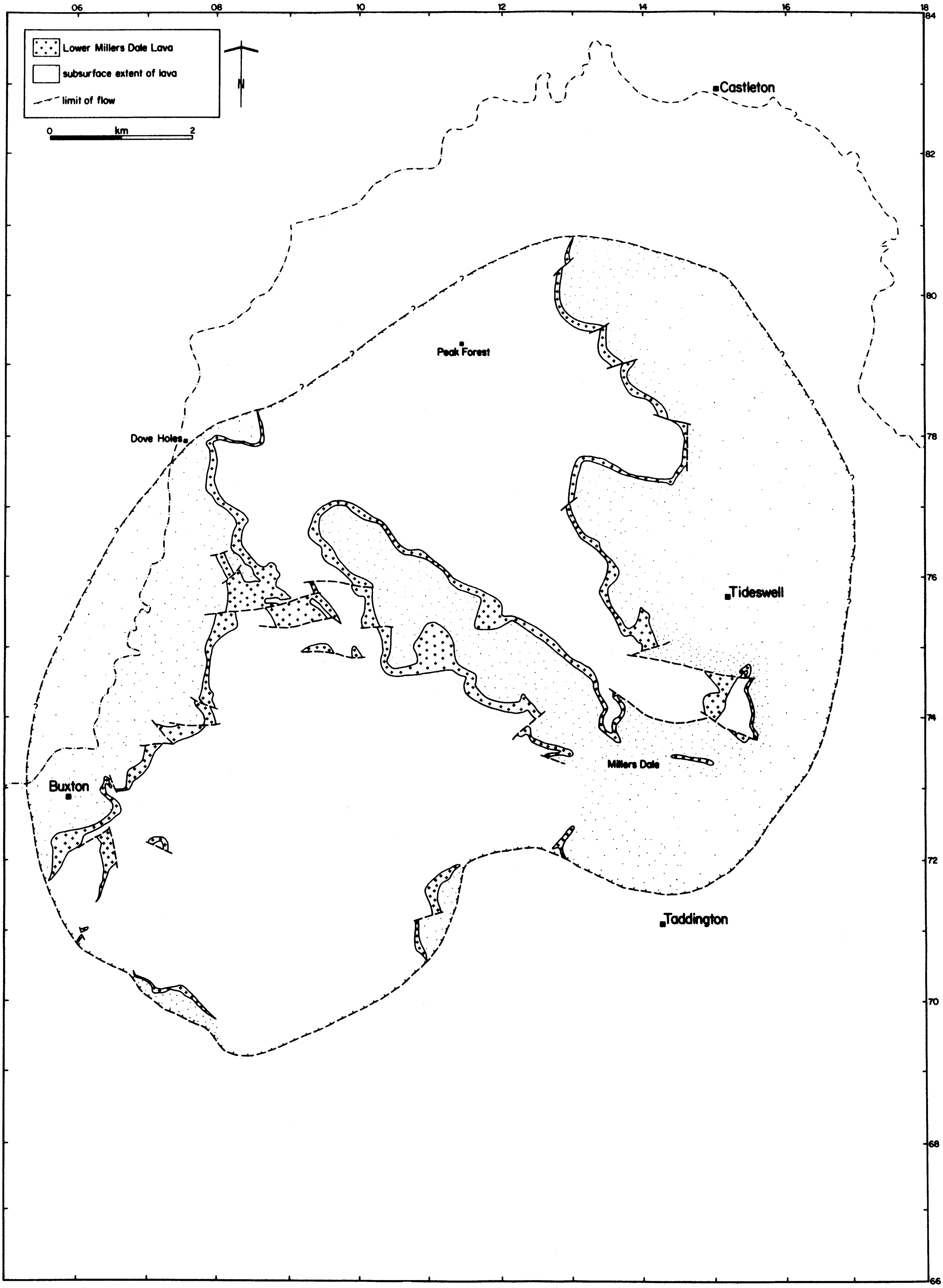
Stratigraphically the lava occurs in the Asbian Limestones and where present it subdivides the Bee Low Limestones into the Upper Millers Dale Beds and the Chee Tor Beds.

Buxton-Taddington Area

East of Buxton, the Millers Dale Lower Lava is 9 m thick but decreases in thickness and terminates south-west of a line from Grindlow (SK 055.717) to Hind Low (SK 082.690) (text-figs. 11 & 12) where a number of flow fronts are complicated by faulting. Walkden (1972) recorded a lenticle of weathered toadstone in the Hind Low quarries, at the horizon of the Lower Lava. This rapidly degenerates into a wayboard and the southern limit of the flow is defined by a number of isolated exposures near Calton Hill (SK 118.715) and Blackwell Dale (text-fig. 12).

Farey (1811) noted that the Millers Dale Lower Lava was present in Horsesteads Mine (SK 142.716) near Taddington, however it is absent in Cressbrook Dale, and this fact enables an approximate eastern limit to be defined.

The top of the lava is exposed below Raven's Tor in Millers Dale (SK 150.733) where it forms a small domed inlier and the full sequence (20.7 m) was proved in the Severn-Trent Water Authority's Millers Dale Borehole.



Text-fig. 12: The geographical distribution of the Lower Millers Dale Lava

Great Rocks Dale/Wormhill - the Waterswallows Sill (Cover, plate 2)

To the north of Buxton the Waterswallows Sill has been intruded at the junction between the limestones and the Millers Dale Lower Lava. The olivine dolerite sill lacks the coarse ophitic texture common to many of the Derbyshire intrusives and Moseley (1966) interpreted the evidence as indicating that Waterswallows was the site of a vent infilled with 'massive basalt'. Subsequently K-Ar isotopic age dating of the dolerite by Stevenson *et al.* (1970) indicated a mean intrusive age of 311 ± 6 m.a. They refuted Moseley's proposition of a vent and supported Bemrose's (1907) interpretation of a sill intruding the lava.

In the 1960's, I.C.I. undertook a feasibility study to the east of Great Rocks Dale in order to ascertain the suitability of the lava for use as a roadstone aggregate. Boreholes at SK 103.755 and SK 099.761 intersected the lava and showed a northerly attenuation over a distance of 600 m, where the lava decreased from 29.9 m to 22.8 m. It is divisible into three extrusive events with a tuffaceous upper unit while the two lower and relatively thicker units display coarse holocrystalline central flows with fresh augite. Sections of the lava are exposed in three small quarries at SK 098.761, near Buxton Bridge which were opened as part of the feasibility study.

The Millers Dale Lower Lava extends from the north-west of Tunstead Quarry, through an intensely faulted area towards Doveholes. Its furthest extent in this direction, is in the region of Lodes Marsh (SK 086.784) while the western extremity of the lava is undefined and may occur beneath the adjacent Namurian strata. The top of the unit was intersected west of Tunstead Quarry (SK 100.740) in boreholes at SK 075.767 and SK 078.763 (Stevenson *et al.*, 1971).

Great Rocks Dale Dykes

Two NE-SW trending dykes, described by Stevenson *et al.* (1971) in Great Rocks Dale, are exposed at SK 097.757 and SK 101.751. The northerly dyke, now minimally exposed, was described by Cope (1933) as being 3.7 m wide and highly weathered. The adjacent limestones illustrate marmorization while Cope noted xenoliths of dolomite and sandstone and suggested that the latter were derived from basement formations. Xenoliths of a similar lithology have also been noted (Smith *et al.*, 1967; p. 92 this paper) from the Ashover Tuff and the Grange Mill Vents. The southerly dyke is distinguished from the northerly one being partly amygdaloidal and excessively altered. They are named by the Institute of Geological Sciences as the Buxton Bridge Dykes.

Wormhill-Ox Low

At Wormhill the Lower Lava (30 m thick) contains zeolite and calcite filled amygdales whilst the olivines and pyroxenes have been replaced and the ilmenite altered to leucoxene. The Lava is exposed in a road cutting at Wormhill (SK 123.741) and thins to the north, where in Smalldale (SK 165.814) it is 9 m thick.

Tideswell Dale (plate 3, plate 4, fig. 2)

The Lava has been intruded by the Tideswell Sill and the two are visible in the old roadstone quarry in Tideswell Dale (SK 155.738). This locality, now a picnic site in the Peak Park, has been described by numerous authors, Wilson (1870), Geikie (1897), Bemrose (1899), Sargent (1917) and Wilkinson (1967). The Sill is transgressive and where it is in contact with the underlying limestone, has resulted in marmorization. Wilson (1870) stated that a baked columnar clay preserved beneath the vesicular lava was a volcanic mudflow. Geikie (1897) was the first to recognise the intrusive origin of the 'crystalline basalt'. The quarry exposes an 18 m thick sill in which Bemrose (1899) recognised five distinct zones characterised by a coarse central, and finer grained outer margins. Sargent (1917) considered the altered vesicular lava underlying the sill to have 'spilitic affinities' an observation based on an alkali content in excess of 6%. The type of alteration he described is typical of the vesicular margins of numerous toadstones in the South Pennines and is a reflection of the complex deuteric and hydrothermal alteration these lavas have undergone rather than any primary 'spilitic' magma. Wilkinson (1967) describing the lavas, exposed in three roadside quarries (SK 154.743) at the entrance to the Picnic Site, stated that a non-vesicular lava, with microphenocrysts of andesine and augite, is in contact with a highly altered vesicular lava. Original pyroxene is absent and only a few olivine pseudomorphs remain in flow-orientated feldspar laths and microlites which are oligoclase in composition. He stated that the soda content is about 4%.

The full sequence of the Lower Lava was proved in the Litton Dale Borehole (SK 160.750) (Stevenson *et al.*, 1971). A sequence of 24 m of lava and tuff were subdivided by a 3.7 m limestone horizon, into an upper 20.3 m unit, and a lower 3.7 m one. The lava thins rapidly to the east and is not seen in Cressbrook Dale.

To the west of Tideswell, in the vicinity of Wheston, the Lava is approximately 27 m thick. Two vents with vent agglomerate are located in Monks Dale and in Peter Dale. Bemrose (1907) and Stevenson *et al.* (1971) recognised the southerly (SK 130.753) and northerly (SK 126.755) occurrences, respectively. The coincidence of these vents with the area of maximum development for the Lower Lava suggests that they may represent the eroded roots of the vents and cones that were the main extrusive centres.

North of Wheston, the Lava is 10.7 m thick at Wall Cliff (SK 140.774). On Tideswell Moor, opencast workings for fluorspar in White Rake, provide an exposure in which the Millers Dale Upper and Lower Lavas are faulted in juxtaposition. The Lower Lava is exposed on the southern wall of the opencast site near Tides Low (SK 146.782) and shows an upper flow unit, with highly vesicular margins, resting on 3 m of limestone which in turn overlies a lower less vesicular but blocky lava. In the Tideswell Moor area the lava has been partly intruded by the Potluck Sill (Walters, 1980).

North of Tideswell Moor, the Lower Lava is poorly exposed at the surface but has been intersected in shafts and mine workings, over Bradwell Moor. At outcrop, it can be traced as far as Conies Dale (SK 131.807), where at Cop Round it is 9 m thick. The northern limit is a weathered horizon 1.8 m thick at a depth of 22.9 m in Hazard Mine Shaft (SK 137.813) 275 m to the west, a 0.6 m thick clay horizon at a depth of 3.6 m in Wham Shaft, may equate with the Lower Lava.

Recent exploration of mine shafts on Moss Rake (Bradwell Moor) has located the upper surface of the Millers Dale Lower Lava. In Kitty Cross Shaft (SK 154.803) the exact thickness is not known, but can be demonstrated to be less than 11 m. At Rake Head Mine (SK 143.800) Green *et al.* (1887) noted 11 m of the lower toadstone. The eastern extent of the Lava is difficult to define, but in all probability it does not extend far beyond Kitty Cross Shaft. Information with respect to its presence in and around Hucklow is not available for neither mines nor boreholes have intersected the stratigraphical horizon of the Millers Dale Lower Lava.

The Dove Holes Tuff

The Dove Holes Tuff was first recognised by Green *et al.* (1869). It has a patchy development, rests on a strongly potholed surface, and reaches a maximum thickness of some 2 m. The Tuff may initially have had the form of a low angle mound related to a vent, but now exhibits greater weathering than similar structures in the Derbyshire area. Stratigraphically it occurs approximately 15 m above the Millers Dale Lower Lava.

Outcrops of the Tuff occur around Batham Gate and Bibbington, northeast of Tunstead Quarry. It is exposed in Holderness Quarry (SK 084.782) as a 1.8 m thick unit, it decreases to 1.1 m thick in a southerly direction and is not located south of Dove Holes. It is exposed east of Peak House (SK 080.766) and was proved to be 1.5 m thick in a borehole near Batham Gate (SK 075.767) although additional boreholes in the general vicinity failed to indicate the Tuff. A borehole at Batham Gate (SK 078.763) is of interest in proving an additional lower tuff horizon 2.3 m thick, only 3.4 m above the Millers Dale Lower Lava (Stevenson *et al.*, 1971) (text-fig. 14).

Tuff sequences in the Upper Asbian are not recorded at outcrop away from the intensely quarried Great Rocks Dale area, but a lenticle of tuff occurs at a similar stratigraphical horizon to the Dove Holes Tuff in Station Quarry, Millers Dale (SK 134.734). This tuff is not associated with a palaeokarst surface which suggests that in the main area of pyroclastic activity around Dove Holes, a highly localised uplift and karstification episode preceded volcanicity (Walkden, 1977).

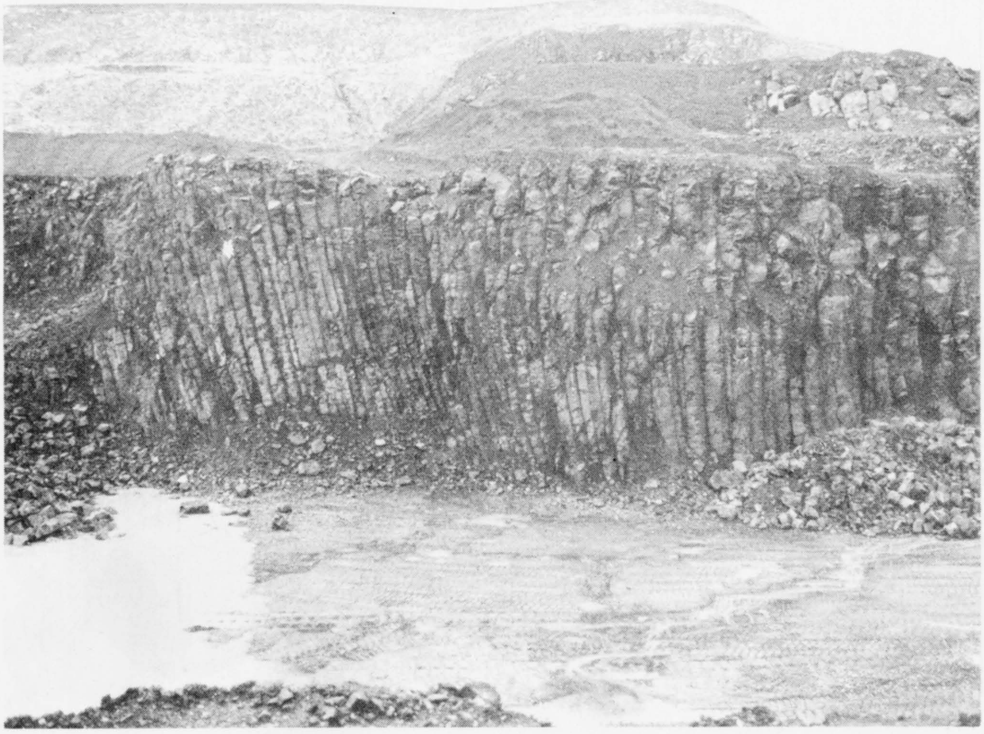


Fig. 1: Waterswallows quarry, Buxton. The Waterswallows Sill is an olivine-dolerite showing vertical columnar structure; face since removed. (Photo: M.G. Lodge, December 1980).

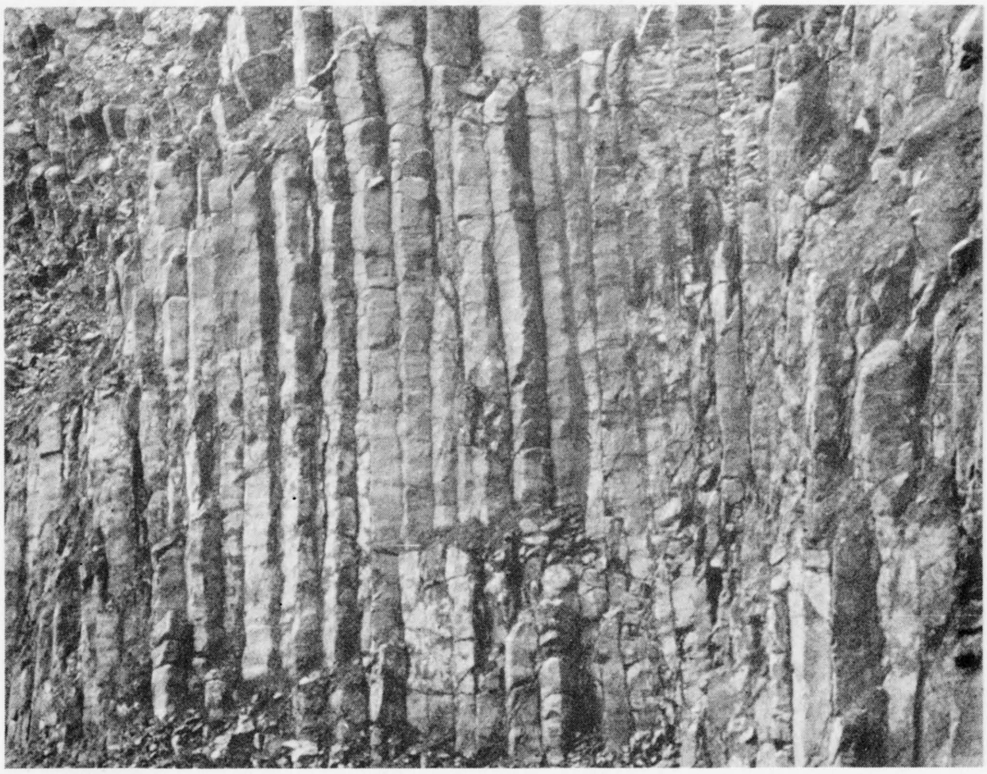


Fig. 2: Close-up of the columnar structure seen in Waterswallows Quarry. (Photo: M.G. Lodge.

Fig. 1: Millers Dale Lower Lava, Tideswell Dale.

Fig. 2: Close up right-hand side of Fig. 1, showing spheroidal weathering of lava.

The Millers Dale Upper Lava

The Millers Dale Upper Lava (text-fig. 13) can be traced from Earl Sterndale (SK 112.670) northwards to Calton Hill, around Taddington and along the south side of Millers Dale to Litton Mill (SK 160.730). Three small exposures of vesicular lava and vesicular lava in tuff occur in the foot of Cressbrook Dale, at the same stratigraphical horizon and may be a continuation of the Lava. North-west of Millers Dale the Lava forms a cap to Knot Low (SK 134.736) and outcrops around Withered Low (SK 102.764) and Bole Hill (SK 108.767) in the Wormhill area. North of Millers Dale the Lava continues through Tideswell towards Wall Cliff (SK 139.773) where it is replaced locally by a tuff sequence. On Tideslow Moor and northwards to Conies Dale the Lava is poorly exposed but has been intersected by a number of mines. It finally dies out south of Dirtlow Rake.

For the majority of its extent the Millers Dale Upper Lava occurs at the Asbian/Brigantian boundary. In the Millers Dale area a complex interplay of penecontemporaneous subsidence, folding, erosion, and vulcanicity has given rise to a locally preserved Brigantian limestone sequence beneath the Lava - the Station Quarry Beds (Cope, 1937; Walkden, 1977).

Chelmorton-Taddington Area

The southerly attenuation of the Millers Dale Upper Lava is defined from recent boreholes reported by the Institute of Geological Sciences (1977b). Previously, information on the Lava came from old mining records and workings at Hubbadale Mine, which intersected it at a depth of 57 fathoms (104.2 m) in Devonshire Shaft (Worley, 1978b). The records indicate that the southerly dipping lava may have formed a sole to some of the rich pipe deposits in the area.

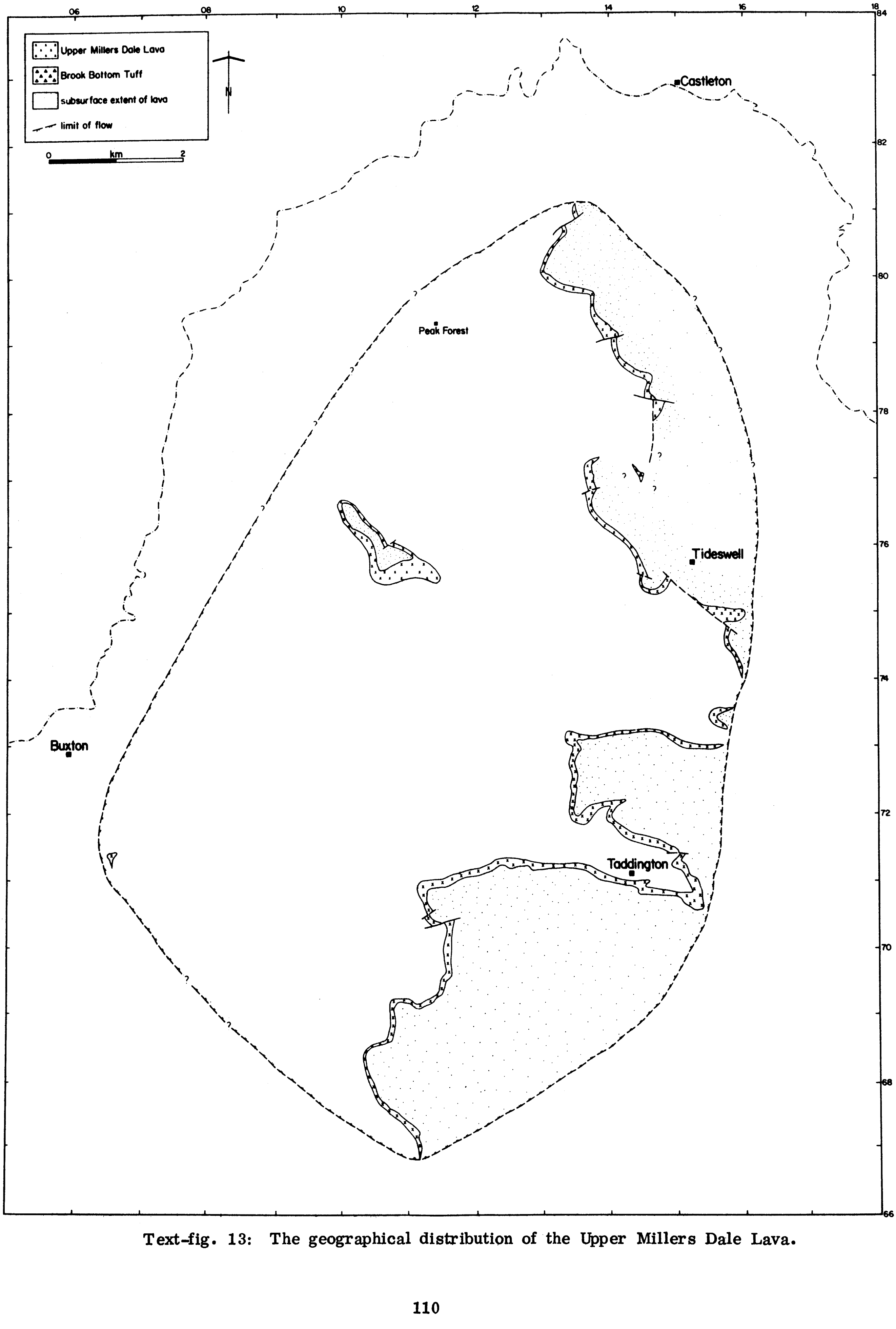
A number of wayboards occur above the Lava. The 'Great White Wayboard' lies 19 m above the Lava and may be the vestige of a lava developed at this horizon to the east, i.e. the Lees Bottom Lava (p.99, this paper). Cox & Bridge (1977), from borehole evidence, confirmed mining records reporting a thick clay horizon 22 m above the weathered amygdaloidal top of the Millers Dale Upper Lava.

To the north of Hubbadale the Lava outcrops around Taddington and Calton Hill where it is intimately associated with the complex intrusive and extrusive sequences (dolerites, tuffs and agglomerates). Between Taddington and Calton Hill the Lava is 15 m thick, while at Taddington (SK 152.711) Cope (1937) recorded a temporary exposure showing a 35° east-facing lava flow-front.

Calton Hill Complex (SK 120.718) (Plate 4, fig. 1)

Calton Hill was recognised by Bemrose (1910) as the site of a vent for the extrusion of the Millers Dale Upper Lava which had subsequently been intruded by a dolerite. He also noted unaltered olivine/pyroxene nodules in the dolerite. The only detailed description of the complex was given by Tomkeieff (1928) who recorded agglomeratic sequences beneath the Upper Lava. The intrusive analcite-dolerite has, in common with a number of Derbyshire sills, invaded a line of weakness along the Lava and large blocks of vesicular lava have been stoped into the dolerite. The roadstone quarry, operated by Derbyshire Stone Ltd. and later by Tarmac, was enlarged subsequent to Tomkeieff's account and a greater complexity of events revealed. Unfortunately no additional general studies were made. Hamad (1963) and Donaldson (1978) investigated the 'peridotite' nodules in the analcite-dolerite and found them to be olivine-orthopyroxene-clinopyroxene-spinel xenoliths, i.e. typical spinel lherzolites in basalts of upper mantle origin.

Subsequent silica-rich hydrothermal activity at Calton Hill (Mueller, 1954; Ford, 1967) gave rise to veining and quartz lined vugs. A zonation of the vugs is apparent, with a central vuggy quartz passing into a zone of calcite on quartz and finally a calcite-barite zone. The pattern suggests an ascension of siliceous fluids via the vent feeder. Prominent fibrous veins are also very common and as at Ible were once thought to be asbestos. They have been shown to consist of clays (saponite) probably replacing a fibrous chlorite (Sarjeant, 1967; Curtis, 1976).



Text-fig. 13: The geographical distribution of the Upper Millers Dale Lava.

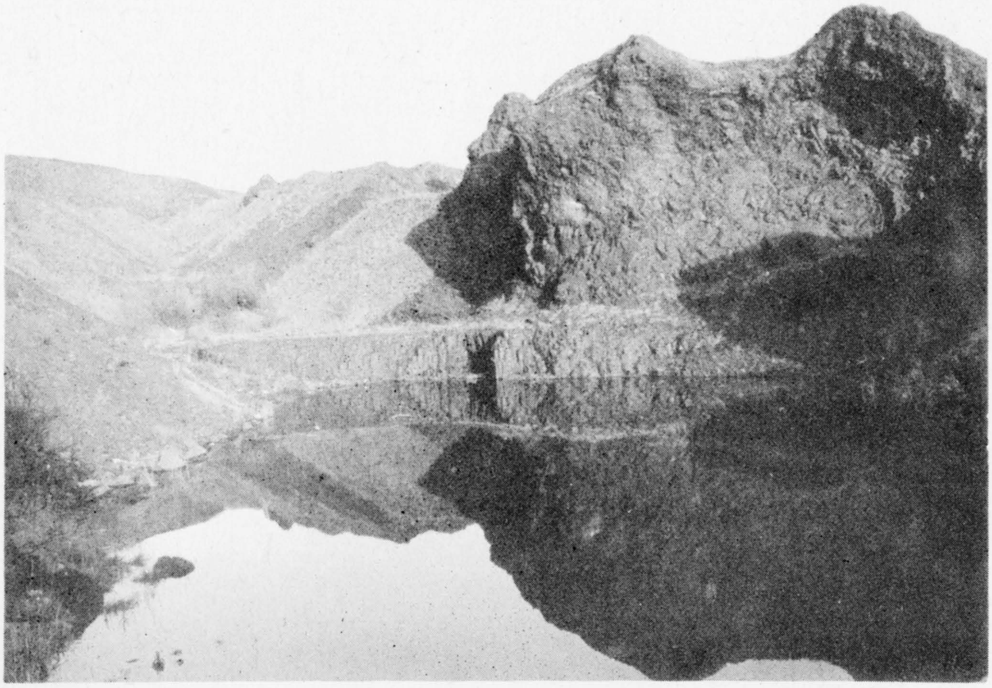


Fig. 1: Calton Hill Site of Special Scientific Interest. Reflection in water of basaltic columns and agglomerate bluff.

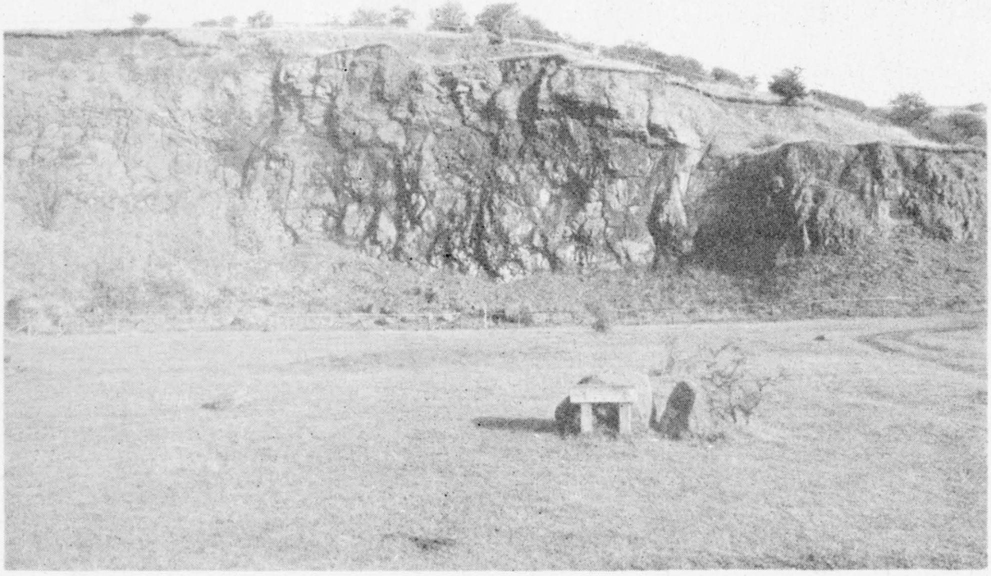


Fig. 2: Tideswell Dale Quarry picnic site. Millers Dale Lower Lava and Dolerite.

Millers Dale

The Upper Lava is exposed in a number of quarries in Millers Dale (SK 134.731). Bemrose (1894, 1907) noted a continuous exposure of the complete sequence of igneous rocks in the Lime Works Quarry (SK 140.730). It was 35 m thick and capable of subdivision into at least two distinct extrusive events, a 5.2 m thick sequence of tuffs with a thin amygdaloidal basalt was overlain by a thick lava (text-fig. 14). Although Bemrose's section is no longer visible, two small quarries (SK 134.731 and 134.730) to the west of the old lime works are clearly in the thick lava sequence and expose 10 m of non-vesicular, holocrystalline basalt with spheroidal weathering. A similar exposure is observed in quarries on Knot Low (SK 134.736) to the north of the dale where Sargent (1917) noted 'spilitic affinities' for the altered, vesicular lower portions of the flow. The maximum development of the Millers Dale Upper Lava is 35 m.

East of the Lime Works the Lava forms a prominent feature above the disused railway line as far as Litton Mills. It is exposed in the adit of Maury Mine (SK 150.731) where a vein persists into the Upper Lava and produces a zone of intense bleaching and argillisation. Farey (1811) recorded the extraction of lead ore from within the Lava and mineralised lava including galena and sphalerite may be found on the old mine dumps. The Lava terminates in a flow front above Litton Mills in the railway embankment near to Litton Tunnel entrance. The rapid attenuation of the Lava was noted by Green *et al.* (1867) but was subsequently interpreted as a fault by Bemrose (1907). Cope (1937) considered it to be a flow front and this was supported by Walkden (1977) who demonstrated a complex relationship between the exposed flow front, flows within the Upper Lava and the local preservation of the Station Quarry Beds.

Bemrose's division into an upper major flow and a lower thinner unit enables the flow front at Litton Mills to be equated with the more extensive upper flow. Each extrusive event was accompanied by a measure of uplift, erosion and folding. At Litton Mills, the upper flow has over-ridden the thinner lower flow. The strong brecciation, palagonitisation and crude stratification seen in the flow front suggest the entry of the lava into shallow water giving a flow front breccia (Jones & Nelson, 1970). The bentonitic clay exposed above the Litton Tunnel entrance exhibits a relict vitroclastic texture in contrast to the typically amorphous bentonitic clays seen in the limestone sequence (Walkden, 1972). This implies that it is the lateral equivalent to the flow front breccia.

Cressbrook Dale

The lava which outcrops at the horizon of the Millers Dale Upper Lava in Cressbrook Dale (SK 174.727) is difficult to reconcile with the geographical distribution of the Millers Dale Upper Lava (text-fig. 13). The partial distributional analysis given by Butcher & Ford (1973) has been invalidated by the Institute of Geological Sciences' officers (1976) who considered that the Shacklow Wood Lava of the Sheldon area (p.100 this paper) lies at a stratigraphically higher horizon than the Millers Dale Upper Lava. Walkden (1977) inferred a deep embayment in the distribution of his 'lower extrusive phase' to accommodate the lava at Cressbrook Dale. It is more probable that this lava which the authors refer to as the Cressbrook Mill Lava represents the western edge of one of the flows from the Longstone Edge area that lies at the same horizon as the Millers Dale Upper Lava.

Wormhill-Harpur Hill

The Upper Lava outcrops on Withered Low and on Bole Hill where the Institute of Geological Sciences' officers (1976a) have mapped limestone intercalations. It thins to the north decreasing from 30 m at Bole Hill to between 3-4.5 m on Withered Low.

The western limit cannot be defined in detail for basal Brigantian strata are not present in the Great Rocks Dale area, and where they are present around Dove Holes, the Lava is absent. This fact implies a limit to the flow in the Great Rocks Dale/Waterswallows area. Likewise the Lava is absent around Buxton and Hind Low to the south, but it is present at Harpur Hill (SK 066.713) and allows a limit to be defined as shown on text-fig. 13.

Tideswell-Dirtlow Moor Area

The flow front above Litton Mills can be traced north towards Tideswell. At the junction of Tideswell and Litton Dales, the Millers Dale Upper Lava is 18 m thick. The Litton Dale Borehole (SK 160.750) located 350 m further east proved only 3 m of weathered lava. To the north-west of Tideswell, the Lava continues as far as Wall Cliff (SK 139.773). In a faulted area with minimal exposure, the Lava is the lateral equivalent to a bedded tuff sequence - the Brook Bottom Tuff of Bemrose (1907). This tuff may represent a small cone against which the lava thins, analagous to the situation at Grange Mill (p. 93 this paper) but on a smaller scale.

The geographical distribution of the Millers Dale Upper Lava (text-fig. 13) is asymmetrical with respect to the position of the known vent at Calton Hill. This implies an additional feeder vent associated with the northern outcrops. The disappearance and reappearance of the lava at Wall Cliff may be a reflection of the interplay between these source areas for the Lava.

The Upper Lava is exposed in White Rake opencast site (SK 146.782) on Tideswell Moor. A minimum thickness of 15 m of weathered lava is observed on the northwall with marmorized limestone inclusions up to a metre in diameter included in the Lava. The Tideswell Moor area is remarkable for the persistence of mineral veins which cut lava flows, for altered and mineralised blocks of lava occur in the spoil from a number of mines (Walters, 1980).

North of Tideslow Farm (SK 154.782) the Lava is poorly exposed, but has been proved in a number of mines and its outcrop is displaced by rake veins. It forms a feature around Cop Round (SK 126.797) where it is some 6 m thick (Moore, 1903) and finally dies out in the region of Old Moor Mine south of Dirtlow Rake (SK 136.811).

Bradwell-Little Hucklow Area

The Millers Dale Upper Lava underlies part of Bradwell Moor and is 9.1 m thick in a shaft on Moss Rake, near Rake Head Mine (SK 143.800). Green *et al.* (1887) noted a toadstone 3.7 m thick at a depth of 87.8 m near this locality which was referred to as 'the clay' in mining records and correlated with the attenuating Upper Lava. Likewise in the Hucklow area, the Lava cannot be accurately defined. A toadstone 45 m thick at a depth of 95 m in Shuttle Rake Mine (SK 160.796) occurs stratigraphically higher than the Upper Lava and its thickness suggests a correlation with the Cressbrook Dale Lava of the Eyam area. Within the Bradwell-Hucklow area the stratigraphical horizon at which the Millers Dale Upper Lava may occur has not been penetrated and hence conclusions cannot be formulated, with respect to its north-eastern extent.

The Peak Forest Sill

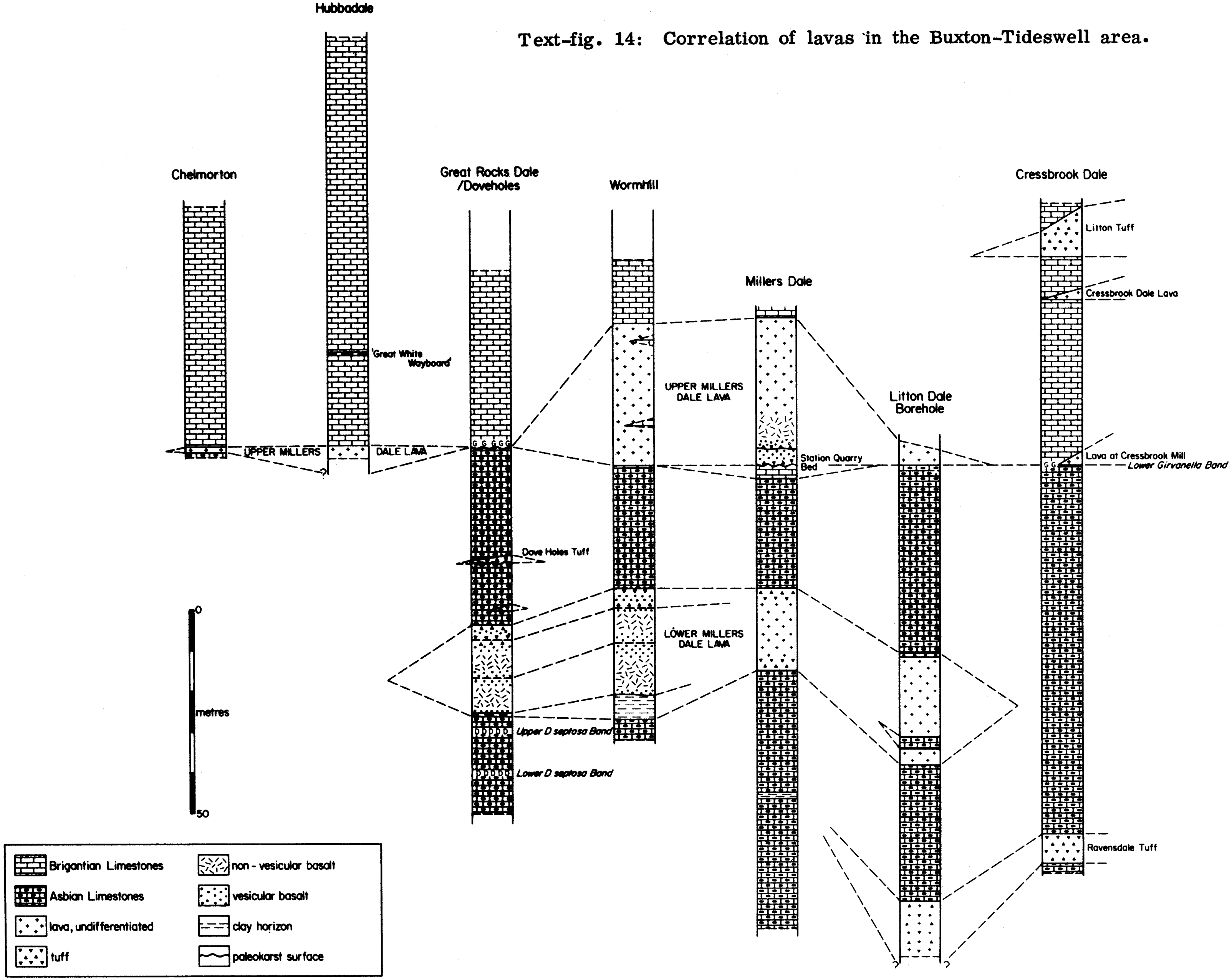
The Peak Forest Sill is a non-vesicular coarse olivine dolerite intruded in the axis of the Peak Forest Anticline. It was first described by Geikie (1897) and its upper contact phenomena were noted by Barnes (1902a and b). The base is not exposed hence a thickness is not known. The exposure, by Mill Cottage in Dam Dale (SK 116.788), shows the attendant marmorisation of the overlying limestones for 10 m from the contact the limestones are strongly dolomitised. The fine grained sub-ophitic dolerite has undergone extensive silicification and calcitisation. Additional localities are located at Damside Farm (SK 115.787), Backlane Farm (SK 107.789 and SK 107.790) and Newhouses Farm (SK 111.785). Text-fig. 11 illustrates the geographical distribution of the sill.

The Potluck Sill

The Potluck Sill, described by Bemrose (1907) occupies much of Tideswell Moor. Exposures are minimal, with the only occurrence at Pittle Meer (SK 136.783). Additional evidence for the geographical extent of the sill is to be found in the debris around old mine shafts and workings.

Green *et al.* (1887) state that Black Hillock Shaft (SK 141.782) proved 600 ft. (183 m) of

Text-fig. 14: Correlation of lavas in the Buxton-Tideswell area.



'toadstone' and the base was not reached. Stevenson *et al.* (1971) proposed that the shaft probably followed a feeder to the sill. A more detailed account of the locality, as recorded in mining documents, has been presented recently by Walters (1980). Stevenson *et al.* (1971) wrote that the Sill is a coarse ophitic olivine-dolerite, gave a modal analysis and a petrological description.

Mount Pleasant Sill

Initially described in 1907, Stevenson *et al.* (1971) noted that Bemrose did not appreciate its full extent. They reported ploughed igneous debris near Batham Gate (SK 126.786 and SK 130.787) as well as similar material further east (SK 131.788).

The sill appears to show an alignment along the line of Shuttle Rake and Faults, south of Hernstone Lane Head (SK 120.787). It has been suggested (Stevenson *et al.*, 1971) that Shuttle Rake exercised considerable influence on the intrusion of the Sill, but this is impossible to substantiate given the extent of exposure.

The Castleton Area

The igneous horizons were first noted by Faujas de St. Fond (1797) in Nunley's Mine, Pindale (SK 158.823). Green *et al.* (1887) reported 12 fathoms (21.9 m) of toadstone in Dirtlow Mine (SK 155.822) and a 'light greenish variety of the toadstone' beneath the 'Yoredale Shales' at Pindale (or Ashtons) mine (SK 164.825). The Cave Dale Lava and Speedwell 'vent' were described by Geikie (1897) and Bemrose (1894, 1907).

Holkerian igneous activity was advocated by Stevenson *et al.* (1971). In reporting the log of the Eldon Hill Borehole (SK 113.816) they recorded 30.5 m of tuffaceous material, 68.6 m below the top of the Woo Dale Beds. Ford (1952) noted a thin clay horizon at a similar stratigraphical horizon in Speedwell Cavern. Hudson & Cotton's (1945a) paper on the Alport Borehole (SK 136.911) indicated 'basinal' facies of the S_2 (Holkerian) as containing 6 m of dark limestones and mudstones with tuffaceous bands and fragments of eroded tuff. This horizon, 110 m below the top of the Holkerian limestones, may equate with the Eldon Hill Tuff.

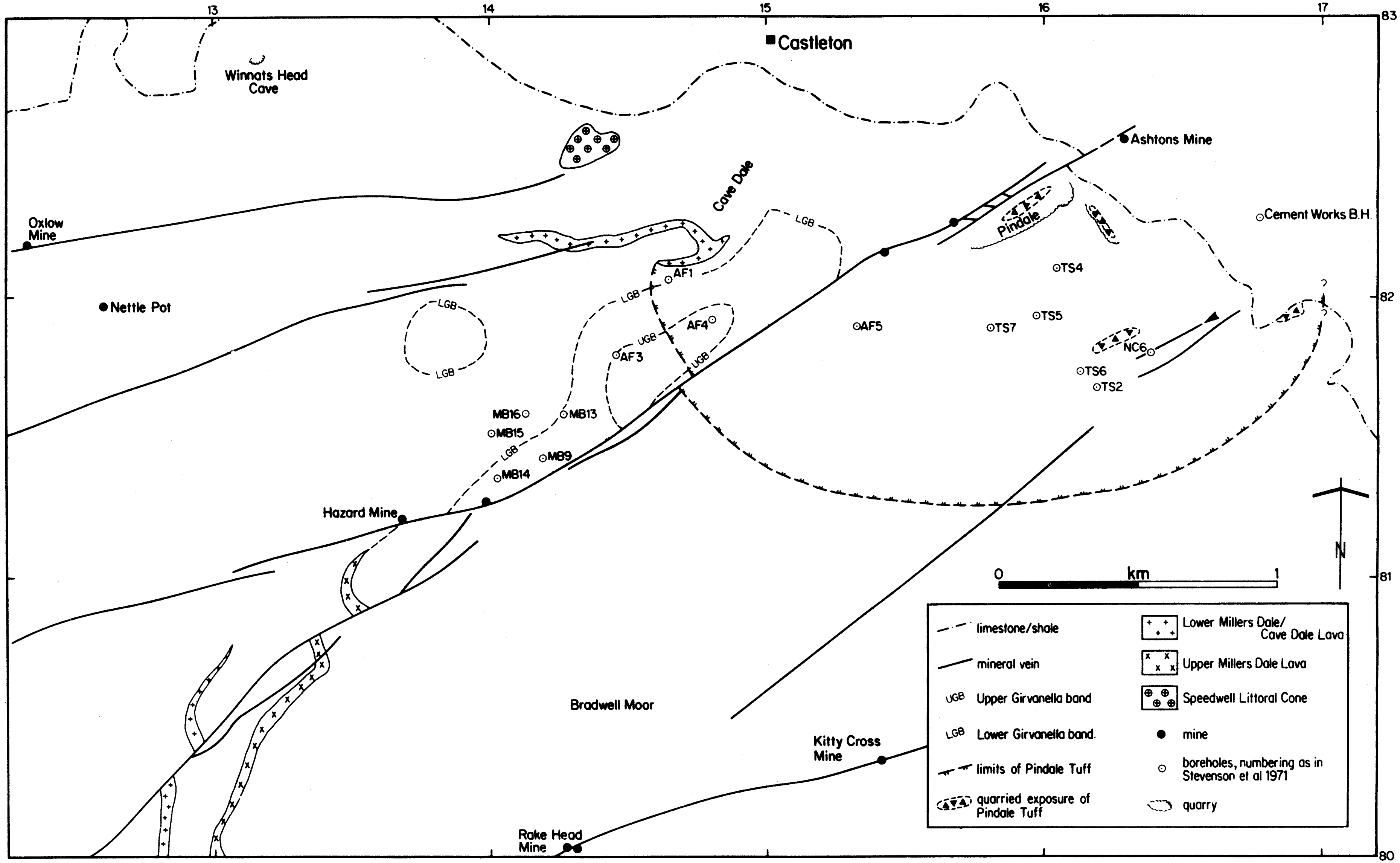
Lower Asbian igneous activity has been intersected in a number of boreholes, and at least two distinct episodes are evident. In the Eldon Hill Borehole, Wright (1979) noted a 3 m thick basalt at a depth of 12 m (i.e. 70 m above the base of the Asbian). This places it below the lowest *Davidsonia septosa* band and hence below the horizon of the Millers Dale Lower Lava. Exploration boreholes on Bradwell Moor have, according to Jefferson (1979, and pers. comm.), intersected a thin tuff at a similar horizon. These two occurrences may be part of the same minor Lower Asbian eruption, however lack of intervening information makes this a very speculative correlation.

To the west of the Blue Circle Group's limestone quarry at Hope, borehole core logs have delineated the eastern limit of a thick tuff sequence stratigraphically beneath the 'Pindale Tuff' (text-fig. 16). It grades downwards into a coarse agglomerate, locally associated with vesicular basalt. The extrusive centre was probably on the Bradwell Moor area.

The igneous activity, spanning from the Holkerian to the Brigantian (S_2 to D_2) is characterised by pyroclastic deposits. The result is a complex palaeogeographic interplay between the volcanics and the back reef, fore reef and basinal calcareous shale facies. The extrusive activity here is unrelated to the contemporaneous proximal events centred on Millers Dale to the south.

The Pindale Tuff

Quarry exposures and the interpretation of numerous borehole logs from the ground to the south of Pindale have demonstrated the presence of a major tuff and volcanic cone - the Nunlow Tuff of Shirley & Horsfield (1940) or the Pindale Tuff of Stevenson *et al.* (1971). Shirley and



Text-fig. 15: A detailed geographical distribution map of igneous horizons in the Castleton area.

Horsfield considered that it was located at the base of the D_2 (Brigantian) limestones, but Eden *et al.* (1964) demonstrated that the horizon is D_1 (mid-Asbian) in age and is hence at a similar stratigraphical horizon to the Millers Dale Lower Lava.

The Pindale Tuff was exposed in the lower bench of Blue Circle's Hope Cement Works Quarry as an elongate mound-like structure according to Shirley & Horsfield (1940). It marked the site of a WNW-ESE aligned volcanic cone. The exposure, with a maximum dilation of 20 m, illustrated a central coarse ungraded agglomerate with included limestone fragments, while the extremities, with 30° marginal dips, were finer grained and well sorted. Stevenson *et al.* (1971, plate V) illustrated a generalised isopach map of the Pindale Tuff, which inferred the presence of a second unexposed volcanic cone to the north of the quarry. Their interpretation was based on a 65 m thick tuff sequence intersected in borehole TS4 (text-fig. 15). Subsequently D.P. Jefferson (pers. comm.) has proved the presence of a major fault between the quarry and borehole TS4 and postulates that fault repetition may explain the unusual thickness of tuff encountered in that borehole rather than a hypothetical second cone structure.

The southerly limit of the Pindale Tuff is defined in detail (text-fig. 15) and indicates that both the Millers Dale Lower Lava and the Pindale Tuff are either absent or represented by a thin tuffs/clay horizons on Bradwell Moor.

Stevenson *et al.* (1971) indicated that the Millers Dale Lower Lava is stratigraphically above the Pindale Tuff in the Michill Bank area to the west of Hope Cement Works Quarry. The attenuated lava is traced in boreholes as a thin (0-2 m) weathered tuff horizon east of Hazard Mine Shaft (SK 137.813) whilst in borehole AF1 (Stevenson *et al.*, 1971, plate IV) the tuff, noted as a 'clay parting', is recorded some 7 m above the Pindale Tuff and is 10 m above the Cave Dale Lava in Roger Cliff (Cave Dale).

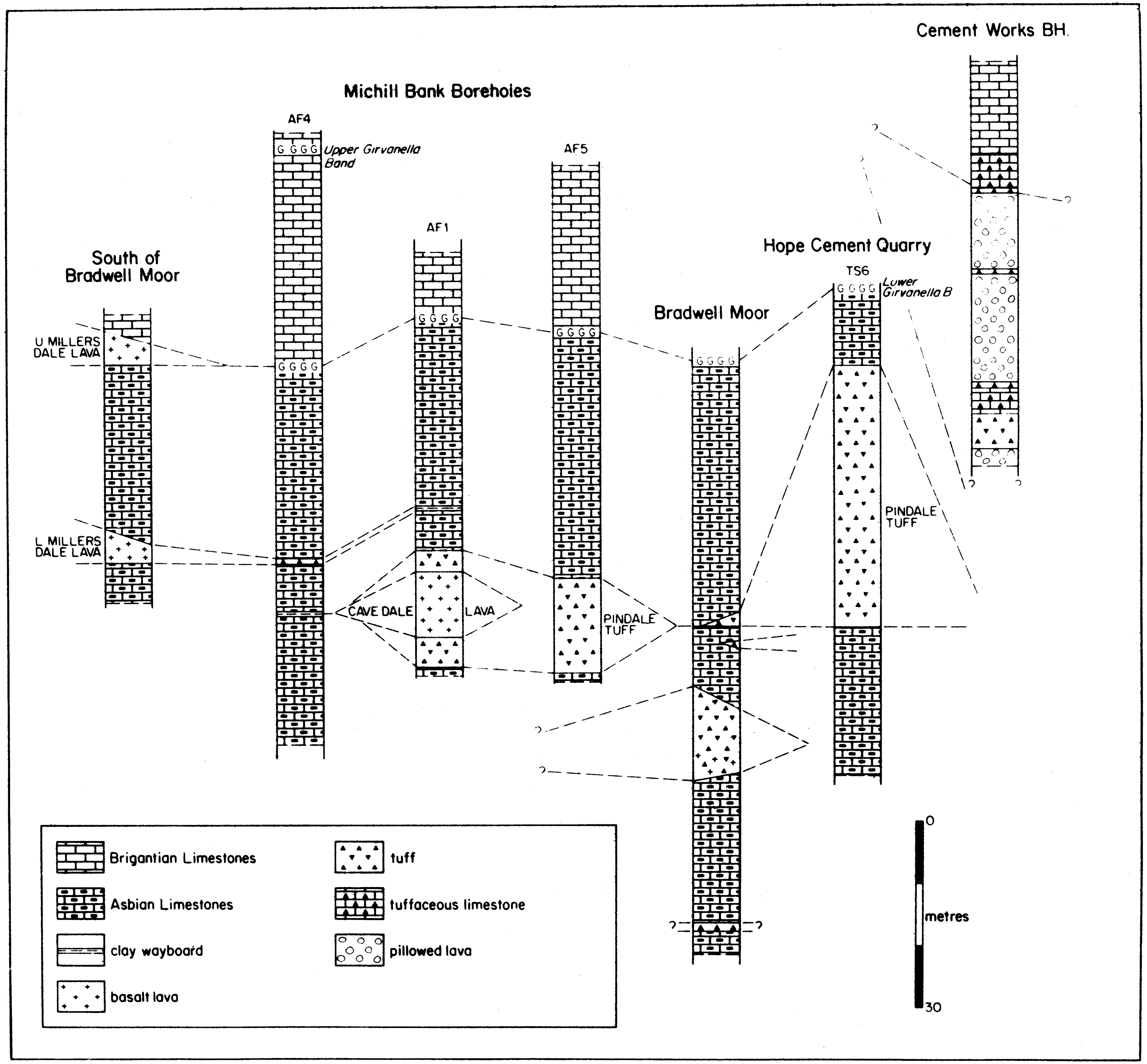
The Cave Dale Lava

The amygdaloidal Cave Dale Lava is exposed near the head of Cave Dale (SK 148.822) where a 7.6 m section is visible. Shirley & Horsfield (1940) proposed that the lava was at the same stratigraphical horizon as the Millers Dale Lower Lava. However, as they considered that the Cave Dale and Millers Dale Lower Lavas were part of the same flow, they attributed the absence of lava in the Dirtlow Moor area, S.W. of Cave Dale, as due to the effects of a postulated D_1 (mid-Asbian) erosional episode. Stevenson *et al.* (1971) refuted this proposition and from evidence provided by borehole cores, showed that the Cave Dale Lava was a flank eruption of the main cone, from which the Pindale Tuff was ejected.

The Cave Dale Lava is traced at outcrop for a short distance (700 m) to the west of Cave Dale. A number of wayboards in the mines and caves around Castleton may represent the lava's lateral extent. A 0.3 m weathered clay in Winnat's Head Cave is located at the same stratigraphical horizon as the Cave Dale Lava. Nettle Pot (SK 126.819) exposes two clay horizons, the first at a depth of 45 m is 1.0 m thick and the second thinner horizon is 8 m lower in the succession. Ford (1952) referred to these horizons as 'clay beds with amygdales' and implied they were decomposed lava. The upper horizon occurs to the NW where it is exposed in Oxlow Mine (SK 125.822). Subsequently, Ford (1977) considered that these 'clays' represent 'flows in the Cave Dale Lava'. The Millers Dale Lower Lava, it is proposed, may extend as far as Nettle Pot and another explanation is that the two clay horizons are the remnants of both the Cave Dale and Millers Dale Lower Lavas.

Speedwell Littoral Cone

The outcrop of 'igneous material' near Speedwell Cavern (SK 143.825) has been the subject of a number of publications. It was interpreted as a vent by Geikie (1897, p.16), Bemrose (1907, pp.250-1), Shirley & Horsfield (1940, p.294), Wilkinson (1967, p.49) and Stevenson *et al.* (1971, p.301). Broadhurst & Simpson (1973) however, suggested that it represented a fragmented portion of Cave Dale Lava Flow which had spilled over the dry apron reef slope. This interpretation has been supported by Cheshire & Bell (1977) who demonstrated the hyaloclastic nature of the 'agglomerate' and considered it to have been



Text-fig. 16: Correlation of lavas in the Castleton area.

formed in the tidal zone at the foot of the reef slope. This interpretation would imply an emergence of some 100 m in the mid-Asbian. The 'vent' is now considered to be a littoral cone.

Brigantian Activity

Fearnsides & Templeman (1932) described the sequence in the Hope Cement Works borehole (SK 1678.8228) which intersected pillow lavas and tuffs 21.3 m below the base of the Namurian. Three vesicular pillow lavas, the lowest not penetrated, totalled 28.3 m in thickness and were separated by 13.1 m of tuff and tuffaceous limestone. Fearnsides & Templeman considered that the sequence was unable to be correlated with adjacent volcanic horizons and stated that they represented an unexposed vent in the vicinity. Eden *et al.* (1964) regarded the sequence as equivalent to the Pindale Tuff and hence implied an unconformable junction between the lava and the succeeding limestones. This hypothesis was rejected by Stevenson *et al.* (1971, p.113) who pointed out that the overlying limestones (with a Brigantian fauna) contained tuff bands and tuffaceous partings which suggested an association between the limestones and volcanics. They stated that the igneous rocks are upper P_1 (upper D_2) or P_2 in age and lie near an unexposed eruptive centre. This interpretation is supported by logs of the Alport (SK 136.911) and Edale Boreholes (SK 108.849) described by Hudson & Cotton (1945b). Both showed extensive tuff horizons in lower Brigantian 'basinal' facies. It is proposed that the pyroclastic components of the pillow lava sequence in the Hope Cement Works, Alport and Edale Boreholes are all of the same extrusive event.

The tuff in the Alport Borehole consists of altered palagonite, carbonated shards and glass fragments, indicative of submarine eruptions. It is interesting that the only record of a major pillow lava sequence amongst the Derbyshire volcanics should be associated with deep water 'basinal facies' strata.

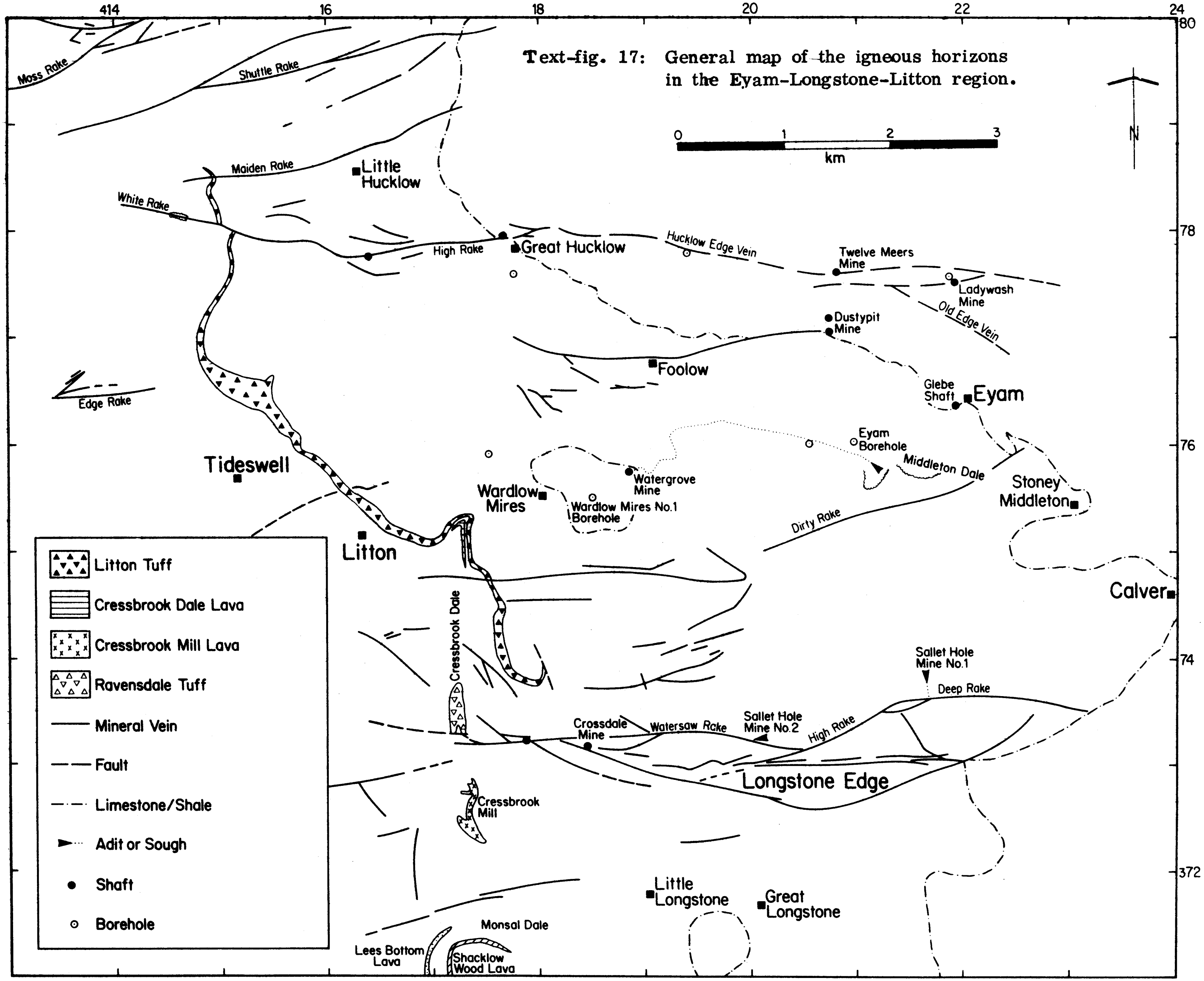
4. The Eyam-Longstone-Litton Region

The igneous rocks (lavas and tuffs) in the north-eastern part of Derbyshire are poorly represented at outcrop (text-fig. 17). They have been intersected in numerous mines and boreholes from which it is inferred that they are of considerable sub-surface extent. Indeed many of the units are better developed than the lavas and tuffs in the Matlock and Millers Dale areas.

The Cressbrook Dale Lava and the Litton Tuff are well documented horizons; however a further three major tuff horizons (the Longstone Edge Upper, Middle and Lower Tuffs) are recorded here for the first time and an extensive lava, the Cressbrook Mill Lava, is separated from the Cressbrook Dale Lava.

Stratigraphical Complexities

Brigantian limestones (Monsal Dale and Eyam Limestones) dominate the surface stratigraphical succession where typical exposures are seen in Eyam Dale (Stevenson *et al.*, 1971). Information with respect to the underlying horizons and especially the complete Asbian succession has been provided only by the Eyam Borehole (Dunham, 1973) located to the north of Middleton Dale (SK 2096.7603). A 162 m succession of 'normal massif facies' limestones was intersected in the 1851.0 m deep borehole, which compares favourably with 160 m of Asbian limestones and volcanics intersected by the Severn-Trent Water Authority's borehole and surface exposures in Millers Dale (p.113, this paper). However, the lavas present in Millers Dale are not developed around Eyam. For example, a coarse tuff (18.6 m thick) at a depth of between 256.8 and 275.4 m and a thin (0.63 m) tuff at 286 m, both within the upper Asbian succession of the Eyam Borehole (Dunham, 1973) are not exposed in the Eyam area. They represent localised activity, which postdated the extrusion of the Millers Dale Lower Lava to the west.



Text-fig. 17: General map of the igneous horizons in the Eyam-Longstone-Litton region.

In contrast to the Asbian succession, the Brigantian Monsal Dale Beds illustrate complex facies and thickness variations related to the development of contemporaneous downwarping with respect to the more stable areas of Longstone Edge to the north and Monyash-Sheldon to the south. This palaeogeographical interplay and facies variation introduces complexities in the attempted correlation of relatively localised volcanic sequences, as palaeontological marker horizons are not well developed. (Shirley & Horsfield, 1945).

The major facies change, which effects the Lower Monsal Dale Beds, particularly below the horizon of the Cressbrook Dale Lava, is an area of subsidence in the Eyam-Calver area. Thus, some 60 m of limestone are present beneath the Cressbrook Dale Lava in Cressbrook Dale and 54 m of limestone beneath the same lava in the Ladywash Borehole (SK 218.776) while 109 m were proved by the Eyam Borehole. Above the horizon of the Cressbrook Dale Lava the main areas of subsidence are centred on Wardlow Mires and Great Longstone (text-fig. 17).

Stevenson *et al.* (1971) reported some 120 m of Monsal Dale Beds above the Cressbrook Dale Lava in Wardlow Mires No.1 Borehole. These limestones decrease in thickness to 100 m in Cressbrook Dale and the Littonfields Borehole (SK 175.759). To the east 70 m are recorded in Dustypit Mine Shaft (text-fig. 17), 70 m in the Middleton Dale area and 60 m in the Ladywash Borehole. Hucklow Edge No.1 and 2 Boreholes penetrated 62.5 m according to Stevenson *et al.* (1971). Further to the west, in the region of Great Hucklow, these limestones thicken to approximately 80 m. The major part of this variation is the result of subsidence in the Wardlow Mires area during the deposition of the Lower Monsal Dale Limestones above the Cressbrook Dale Lava and below the Upper Girvanella band; differential subsidence had largely ceased prior to the deposition of the Lower Shell Bed (text-fig. 18).

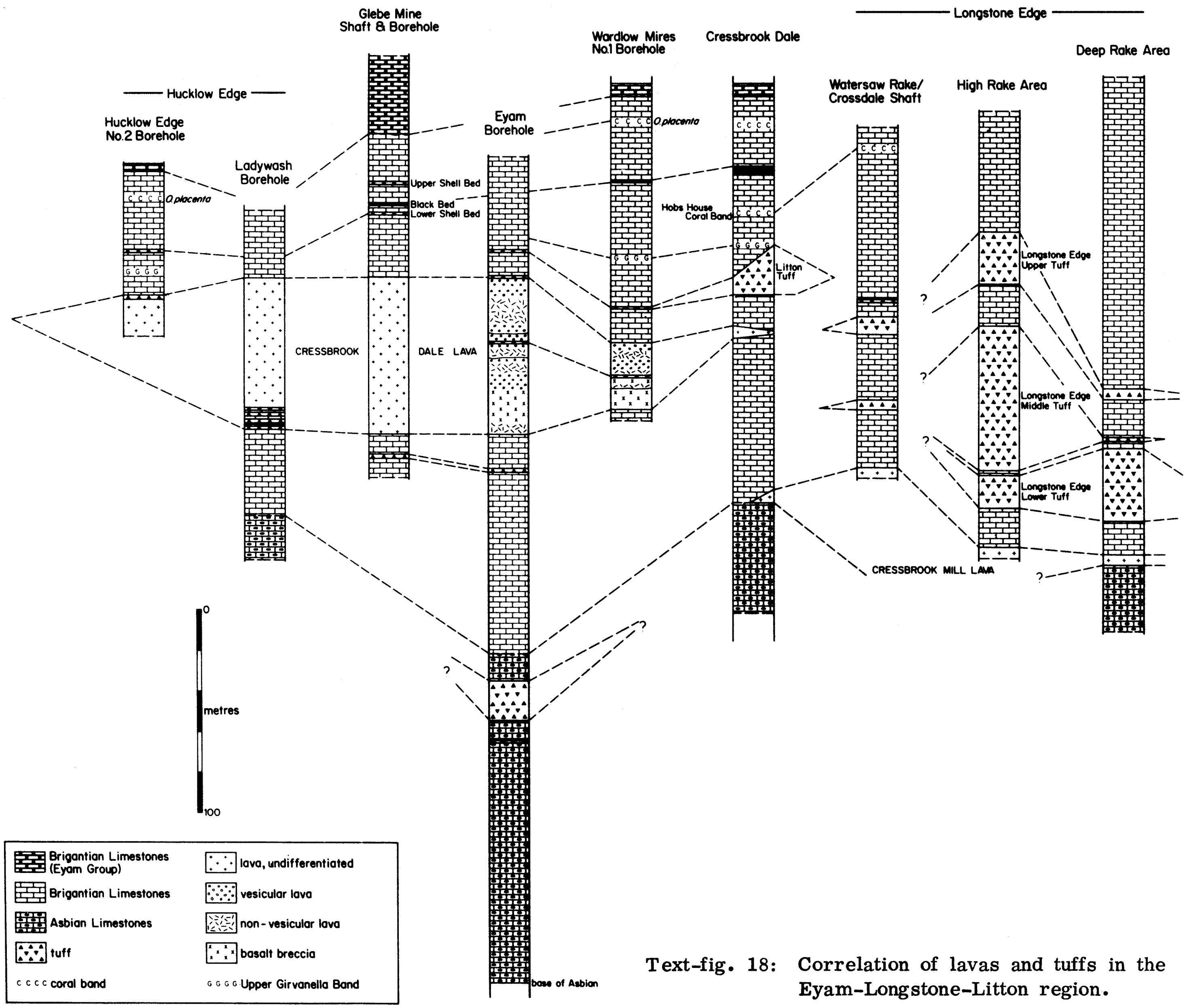
Within this stratigraphical framework the region can be divided into two areas each characterised by extrusive centres. The Eyam-Litton-Hucklow area including the Litton Tuff and the Cressbrook Dale Lava, and Longstone Edge which has complex tuff sequences.

The Cressbrook Dale Lava

The Lava has a restricted, poorly exposed outcrop near the head of Cressbrook Dale where it is 10 m thick and occurs 5 m below the horizon of the Litton Tuff. The Lava thins to the south-east and is absent in a shaft on Wardlow Sough Mine (SK 176.748) some 300 m away. It does not outcrop around Tideswell nor extend into the Longstone Edge area.

In a north-easterly direction it has a considerable sub-surface development. The Littonfields Borehole (SK 175.759) indicated that the Cressbrook Dale Lava was 33.8 m thick, and the Wardlow Mires No.1 Borehole proved a total thickness of 33.5 m. The Lava attains its maximum recorded thickness in the Eyam area, the evidence being provided by a number of boreholes. Dunham (1952) reporting a borehole to the north of Glebe Mine shaft, indicated that the Lava was 76.2 m thick with a 1.5 m thick volcanic horizon 10 m below the base of the Lava. More recently the Eyam Borehole proved the Cressbrook Dale Lava to be 76.6 m thick with a corresponding tuff (1.55 m thick) 14 m stratigraphically lower (Dunham, 1973). Additional confirmation that the Lava attained its maximum development in the Eyam area was provided by the Ladywash Borehole which intersected a 63.4 m thick lava underlain by the 10.7 m thick sequence of thin tuffs, clays and pyritic limestones (Schnellmann and Willson, 1947). The Derwent Water Authority's borehole near the west end of Middleton Dale (SK 205.760) intersected 50 m of lava overlain by a 1.5 m thick tuff, but did not pass through the flow.

Examination of the Wardlow Mires No.1 and the Eyam Borehole cores of the Cressbrook Dale Lava have enabled the internal flow structures to be elucidated (text-fig. 18). The predominant features are breccias in the lower part of the unit, and comparable with the 'auto-breccias' or 'flow breccias' described from the Haddonfields and Ashover area (p.103, this paper, and Ramsbottom *et al.*, 1962). They consist of oxidised angular fragments of either vesicular or non-vesicular basalt set in a matrix of silica and chlorite. The breccias interdigitate with non-brecciated lava flows. In the Eyam Borehole the lower breccia sequence is 22 m thick, while 17 m are developed in the Wardlow Mires area. Core samples indicate the presence of similar breccias in the Ladywash Borehole.



Text-fig. 18: Correlation of lavas and tuffs in the Eyam-Longstone-Litton region.

In a north-westerly direction towards Great Hucklow only the uppermost part of the Cressbrook Dale Lava has been encountered in a number of old lead mines (Farey, 1811) and boreholes, all of which indicate an easterly dip of the upper surface. The Hucklow Edge No.1 Borehole penetrated 3.6 m into vesicular lava with an overlying 2.6 m tuff. Hucklow Edge No.2 Borehole drilled 19.8 m of lava below a 1.4 m thick tuff sequence. Around Great Hucklow the lava was encountered in Milldam Mine and the Derwent Water Authority's borehole (SK 178. 776) was sunk through 1.8 m of tuff and into 2.0 m of lava.

The overall variations in thickness together with their geographical distribution imply an emanative centre for the Cressbrook Dale Lava in the area to the south of Eyam. However, closer examination of the available information indicates that extrusion may have been beneath Hucklow Edge to the west of Ladywash Mine for Slater's Engine Borehole at Foolow (SK 193. 777) proved that the Lava was 72 m thick (J. Hedges, pers. comm.). The Lava is overlain by only 0.75 m of tuff in the Eyam Borehole and rests with a sharp irregular base on a thin (0.5 m) tuffaceous limestone sequence. When traced northwards towards Ladywash Mine, the basal tuffaceous limestone increases in thickness as does the overlying tuff. In the Twelve Meers Mine region (text-fig. 17) the overlying tuff is coarse and poorly sorted with abundant limestone clasts and is interbedded with fine pyroclastic debris with high angle graded bedding. This observation may imply the proximity of a pyroclastic cone marking the eruptive centre of the Cressbrook Dale Lava.

The westerly extent of the Cressbrook Dale Lava beyond Milldam Mine is uncertain. During the sinking of High Rake Shaft (SK 163.778) at least 133.5 m of 'toadstone' were penetrated, leading to the abandonment of the shaft at a depth of 219.5 m (p.119, this paper). The top of this toadstone lies very close to the stratigraphical position of the Cressbrook Dale Lava. The 133.5 m of toadstone may be due to the intrusion of a dolerite sill into the Cressbrook Dale Lava at this locality, in a situation similar to the Tideswell Dale, Bonsall, Waterswallows and Calton Hill sills. The nearby Black Hillock Mine shaft penetrated 183 m of the Potluck Sill and its associated feeder (Walters, 1980). Another possibility is that the 'toadstone' represents a tuff-mound unrelated to the Cressbrook Dale Lava. A thickness in excess of 130 m indicates a substantial cone structure and this would have to thin rapidly to be absent at outcrop over a distance of less than 2 km. Such a situation is not improbable if it is compared with similar changes in thickness of some of the tuff horizons of Longstone Edge. On Tideswell Moor a distinct tuff horizon stratigraphically below the Litton Tuff may equate with a tuff sequence at High Rake shaft (Walters, 1980).

The implication of this alternative hypothesis is that the Cressbrook Dale Lava rapidly attenuates west of Milldam Mine shaft. In support of this proposition, Green *et al.* (1887) stated that when the top of the lava was traced west of the shaft it was found to be absent from its projected position 'if it had had the same dip as the enclosing limestones'.

North of High Rake, Green *et al.* recorded a 45 m thick toadstone at a depth of 95 m in Shuttle Rake Mine (approx. SK 160.795). This places it at approximately the same stratigraphical horizon as the Cressbrook Dale Lava but again it is difficult to reconcile with the proposed position of the emanative centre. In the absence of further borehole information the igneous stratigraphy of the Great Hucklow area must remain speculative. The subsurface presence of igneous horizons in addition to the Cressbrook Dale Lava is a distinct possibility.

The northern and eastern extent of the Cressbrook Dale Lava cannot be defined. In all probability it extends beneath the Namurian cover to the north of Hucklow Edge and into the Abney Syncline. Likewise the eastern boundary may coincide with the valley of the River Derwent, between Grindleford and Calver, and as it has not been encountered in the Longstone Edge area it is inferred that the southern boundary is beneath Middleton Moor.

The Litton Tuff

The Litton Tuff can be traced from Tideswell Moor through Litton and Cressbrook Dale to Wardlow Hay Cop (SK 180.738). It attains its maximum thickness in excess of 30 m to the north-east of Litton, where temporary exposures (Stevenson *et al.*, 1971) of an agglomerate which included bombs, indicate proximity to the vent. At outcrop in Cressbrook Dale it decreases in thickness northwards from 12.8 m to 7.6 m, a trend confirmed by the Littonfields Borehole where 3.2 m of fine grained tuff overlie 0.9 m of tuffaceous limestone. In the Wardlow Mires No.1 Borehole 0.5 km from the proposed source area the Litton Tuff is a 0.76 m thick unit illustrating small scale graded bedding (Stevenson *et al.*, 1971, p.124). The Tuff is separated from the Lower Girvanella Band by 24.2 m of oolitic limestone which Stevenson *et al.* related to the effects of sedimentation against the upstanding cone structure. In profile the Tuff represents a low-angle tuff-mound with peripheral slopes in the region of 1°.

In the Hucklow Edge area the Litton Tuff might be expected to be present in a highly attenuated form as a thin, fine-grained tuff or a wayboard, but it has not been detected in either the Hucklow Edge No.1 or No.2 Boreholes. Green *et al.* (1887) recorded a thick clay horizon 3.7 m above the Cressbrook Dale Lava in Milldam Mine as 'hot unlike decomposed toadstone''. The Great Hucklow Borehole (SK 178.776) intersected a 0.3 m thick 'ashy shale' also 3.7 m above the Lava. This horizon lies at a similar stratigraphical position and may well correlate with the attenuated Litton Tuff.

In the Eyam area the Litton Tuff has been correlated with a 1.1 m thick fine-grained tuff 12 m above the Cressbrook Dale Lava in the Eyam Borehole (Dunham, 1973). A thin tuff only 12 m below the horizon of the Lower Shell Bed (text-fig. 18) in Burnt Heath Mine shaft, on Middleton Moor, has also been correlated with the Litton Tuff by Worley (1978). These suppositions may be incorrect for the Eyam area is nearer to Longstone Edge than Litton and it is now becoming evident that major tuffs are located in the Longstone Edge area with which these tuffs may correlate.

Longstone Edge

The mining and exploration boreholes located on the 5 km of Longstone Edge have indicated numerous igneous horizons of which only one is seen at surface. The area has been and is one of the most actively exploited areas of Derbyshire for Laporte Industries Ltd. are mining fluorspar from Sallet Hole No.1 Mine. At the time of writing detailed information for the area is minimal and this account must be regarded as no more than an introduction to the complexities of the area.

Mining documents of the 18th and 19th centuries recorded an unsuccessful attempt to drive a level from Coombs Dale (Sallet Hole Level) in 1780. It encountered a toadstone. Wager's Level was then driven north into Longstone Edge to work veins beneath the toadstone (Willies, 1976). More recent information has been provided by Ineson (1967 & 1970) and Butcher (1976) with borehole information provided by Laporte Industries Ltd.

The igneous activity is dominated by Brigantian pyroclastic eruptions giving rise to low angle tuff mounds with peripheral slopes of between 2° and 5°. Occasionally these tuff mounds exceed 90 m in thickness but illustrate rapid thinning where limestone intercalations interdigitate and result in a complex relationship between extrusion and sedimentation. The correlation of the major tuffs with their lateral attenuated representatives, that is thin tuffs and wayboards, is extremely difficult as no detailed palaeontological correlation of marker horizons is available and the Monsal Dale Limestones show a strong easterly increase in thickness.

Three major tuffs have been intersected (text-fig. 18) and are designated the Longstone Edge Upper, Middle and Lower Tuffs. The Upper Tuff was intersected in Sallet Hole Mine No.1 adit where it proved a maximum development of some 30 m. The same horizon is 5 m thick at the eastern end of Longstone Edge (Red Rake) and of similar thickness at the west end in the High Rake area. Petrographic details were given in Ineson & Mitchell (1973). The Middle Tuff is centred further west at High Rake where 90 m are recorded; it likewise attenuates in both an easterly and westerly direction, in the former direction at Deep Rake it is 0.7 m thick and it may extend into the Watersaw Rake although a positive correlation is not possible (text-fig. 18). In general terms the western segment of Longstone Edge does not contain major developments of tuff. The Lower Tuff, for which information is at present minimal, appears to be thickest (> 35 m) beneath the Deep/Red Rake area (text-fig. 18).

The lowest igneous horizon so far penetrated is a thin but extensive lava. Crossdale Mine Shaft (SK 184.732) at the west end of Watersaw Rake encountered lava at depth of 110 m while Farey (1811) noted a toadstone in Robinstye Mine in Hay Dale. These two occurrences are the lateral equivalent of the lava exposed near Cressbrook Mill (text-fig. 17) located at the horizon of the Millers Dale Upper Lava. Walkden (1977) postulated a deep embayment in the geographical outline in order to incorporate this locality in the overall extent of the Millers Dale Upper Lava. This suggestion is not substantiated for it is proposed that this lava, now termed the Cressbrook Mill Lava, is part of a separate flow centred in the Longstone area. The Lava, at the Asbian-Brigantian boundary, can be tentatively correlated with similar material intersected in boreholes located in the central and eastern part of Longstone Edge (text-fig. 18). Although only 4 m thick in the Deep/Red Rake area information provided by Mr. J.D. Hedges indicates that 'a substantial thickness' is present beneath the central area of Longstone Edge.

Additional information with respect to the geographical extent of these igneous horizons beneath Longstone Edge is not available. They have not been recorded at outcrop in the Little Longstone-Monsal Dale area to the south and they are largely absent to the north in the Eyam Borehole. Farey (1811) noted toadstone in High Fields Sough located to the north of Coombs Dale. The tuff horizons in the Eyam Borehole and Burnt Heath Shaft may well be the attenuated equivalents of the tuffs beneath Longstone Edge. This suggestion implies the complex interfingering of the attenuated Longstone Edge Tuffs and the Cressbrook Dale Lava and Litton Tuff beneath Middleton Moor, a statement which at present cannot be substantiated.

Conclusions

The correlation of the igneous horizons in Derbyshire, and in particular the South Pennine Orefield, has indicated a greater complexity than had been previously proposed for more than thirty major lavas and tuffs have been recognised.

In the Matlock, Wirksworth, Ashover and Crich region the Bonsall Moor area is providing detailed information with respect to the form and attitude of the igneous horizons as well as the influence they have had on the near surface mineralisation. The opencast sites and exploration boreholes for fluorspar have intersected the Matlock Upper Lava and the Winster Moor Lava on Bonsall Moor and have shown that the stratigraphical horizon of the Winster Moor Lava is equivalent to the Upper 129 Toadstone of Millclose Mine. These two units are located in the Asbian-Brigantian boundary.

To the south, in the Middleton-by-Wirksworth area the Winster Moor Lava is absent, whilst the Matlock Lower Lava rests directly on the Asbian limestones. This junction is marked by a palaeokarstic surface indicative of an emergent and erosional period which is equivalent, in the Bonsall Moor area, to the limestone succession between the Winster Moor and Matlock Lower Lavas.

The overall geographical distribution and thickness variations indicate that the main eruptive centre from which the Matlock Lower Lava was emitted is likewise located on Bonsall Moor in the vicinity of Low Mine. The easterly extent of both the Matlock Upper and Lower Lavas may, in part, contribute to the thick sequence of volcanics proved at Ashover. However until detailed palaeontological zonation of the intercalated limestones is undertaken, definitive statements are not possible.

In this southern region the authors conclude that the Grange Mill Vents and the Shothouse Spring Tuff represent localised volcanicity which although contemporaneous with the extrusion of the Matlock Lower Lava, was unrelated to it.

The maximum development of the Matlock Upper Lava (36 m) is in the vicinity of Cawdor Quarry, Matlock.

Further north in the Alport-Bakewell-Taddington Region, of the 7 major lavas recorded in Millclose Mine, only 3; the Matlock Upper Lava, the Upper 129 Toadstone and the 'Alport' Lava can be correlated with lavas at outcrop. The remaining 4 (the 103, the Pilhough, the Lower 129 and the 144 Pump Station Toadstones) represent localised flows beneath the Namurian cover, which were extruded from a volcanic centre in the Rowsley area.

This region has a proliferation of locally named lavas which were thought to be separate horizons. We now conclude, however, that the 'Alport' Lava of Millclose Mine, the Alport Upper Lava, the 'Haddonfields Upper Lava' and the Conksbury Bridge Lava are one and the same eruptive unit. Likewise, but less definite, the Alport Upper Lava is equivalent to both the Lathkill Lodge and the Bradford Dale Lavas. We can find no evidence to support the proposition of a vent in the vicinity of Wheels Rake Shaft on Long Rake Shaft.

A tentative conclusion for the area between Long Rake and Bakewell based on the extrapolation of known igneous horizons in surrounding areas, implies the presence of thick and complex igneous deposits. Unfortunately, there are no exploration boreholes nor old mines situated in this area to confirm or disprove this statement.

In the Castleton-Buxton-Tideswell Region the Millers Dale Lower Lava (30 m thick) occurs in the vicinity of Wormhill and this implies a genetic relationship with the vents in Monks Dale and Peter's Dale, and secondarily that the geographical distribution of the Millers Dale Upper Lava is asymmetrical with respect to a single extrusive vent at Calton Hill. This observation combined with additional information suggests that a second extrusive vent may be present beneath Tideswell Moor. Although the area between Castleton, Bradwell and the villages of Little and Great Hucklow is known to contain a number of volcanic horizons these cannot be correlated with those of adjacent areas, for insufficient details of the stratigraphical succession are available, due to the lack of deep boreholes. The opposite case occurs around Castleton and that area is best regarded as a distinct volcanic centre unrelated to that centred on Millers Dale. Igneous activity, dominated by the extrusion of tuffs, occurred over a period of 20 million years, that is, from the Holkerian to the Brigantian. Pillow lavas associated with 'basinal facies' limestone-shale sequences indicate dominant subaqueous extrusion as opposed to the largely subaerial extrusion associated with the volcanicity in the 'shelf areas'. Six igneous units are recognised in the Castleton area. Pillow lavas occur at the highest stratigraphical horizon and are underlain by the northern limit of the Millers Dale Lower Lava, the Pindale Tuff and Cave Dale Lava, the Bradwell Moor tuffs, and a basalt beneath Eldon Hill Quarry. An agglomerate in Holkerian limestones is the lowest unit proved in the Castleton area, and this, as with other horizons beneath the Pindale Tuff/Cave Dale Lava, cannot be followed laterally to any great extent.

The study of the north-east region of Derbyshire, Eyam-Longstone-Litton, was hampered by 'restricted' information. Sufficient information is available, however, for it to be concluded that the Cressbrook Dale Lava was extruded from the central part of Hucklow Edge rather than to the south of Eyam, as had been previously inferred.

The lava exposed at Cressbrook Mill is not part of the Millers Dale Upper Lava, but is the western edge of a thin but extensive flow traced beneath Longstone Edge, the Cressbrook Mill Lava. Although the limestones beneath Longstone Edge have not been palaeontologically sub-divided it is thought that the Cressbrook Mill Lava is located at the Asbian-Brigantian boundary.

The Longstone Edge area contains a complex Brigantian volcanic sequence dominated by three major tuff horizons, called the Longstone Edge Lower, Middle and Upper Tuffs. Contrary to previous opinions these tuffs are not considered to be the lateral equivalents of either the Litton Tuff or the Cressbrook Dale Lava.

The stratigraphical horizons and geographical distribution of the Derbyshire igneous rocks are important as they effect the hydrology of the limestone area, giving rise to perched water tables. They likewise have had an important influence on the localisation and form of a number of orebodies (Trail, 1940; and Walters & Ineson, 1980).

Although the Matlock and Millers Dale areas were regarded as the main extrusive centres, the present study has shown that virtually the whole of the eastern part of the South Pennine

Orefield is underlain by substantial volcanic sequences as suggested by Ford (1977, p.65). Individual volcanic centres with pyroclastic cones, volcanic breccias and lavas often exceed 100 m in thickness.

It is concluded that the surface exposures represent the western edge of a Lower Carboniferous igneous province, that extends to the east beneath the Namurian cover.

The igneous activity in Derbyshire illustrates a wide range of basaltic rock types with minor geochemical and petrographic variations. Extrusive bodies include lavas, tuffs, autobreccias and cones which have a stratigraphical range from the Upper Holkerian to Upper Brigantian (S_2 to D_2), i.e., 20 m.y. However, the major phase of activity occurred in the Lower Brigantian. These deposits cannot be considered to be minor in extent or volume for ten lavas have an areal extent in excess of 10 km^2 and maximum thicknesses of approximately 100 m, with volumes in the order of 4 km^3. Intrusive bodies, genetically related to the basaltic volcanism, include vents, sills and dykes. Isotopic age determinations on the sills indicate a Namurian age of emplacement.

The correlations proposed are the best obtainable in the light of available evidence and until a full and comprehensive correlation of the limestones is undertaken, this paper must be regarded as erecting tentative conclusions in certain areas. The value of this exercise is not only in the reconstruction of the past volcanic environments, but may also help mineral operators to locate additional deposits.

Acknowledgements

The authors would like to thank the following people, companies and organisations for information, access to mines, mine plans, documents, borehole data and detailed discussions with respect to the location, thickness, stratigraphical horizon and composition of the various igneous horizons:

Derbyshire Records Office and Sheffield City Libraries
Dr. N.J.D. Butcher and Dresser Minerals International Inc.
Mr. J.D. Hedges and Laporte Industries Limited
Mr. P.H. Dagger and Imperial Chemical Industries Limited
Dr. D.P. Jefferson and the Blue Circle Industries Limited
Mr. L.H. Dowse and Severn-Trent Water Authority
Mr. H. Cowley and Derbyshire County Council
National Coke Carbonising (Minerals) Limited
Members of the Peak District Mines Historical Society Limited
Mineral tributors, farmers, landowners, etc.

Drs. I.P. Stevenson and J.I. Chisholm of the Institute of Geological Sciences kindly commented on the manuscript, while information from a detailed log of the Eyam Borehole by I.P. Stevenson is published with the permission of the Director of the Institute of Geological Sciences.

National Coke Carbonising (Minerals) Limited, co-sponsored with NERC, the Research Studentship for which Mr. Walters is particularly grateful.

Special thanks are extended to Messrs D. Nash, J. Rieuwerts and M.G. Lodge, for detailed field information and finally, Dr. T.D. Ford's contribution in comments and correlation details as well as critically reading the manuscript is duly acknowledged.

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References

ALSOP, J. 1845. On the toadstones of Derbyshire. *Rep. Brit. Assn. for 1884, Section C*, pp.51-52.

ARNOLD-BEMROSE, H.H. 1894. On the microscopical structure of the Carboniferous dolerites and tuffs of Derbyshire. *Q. Jl. geol. Soc. Lond.*, vol.50, pp.603-644.

ARNOLD-BEMROSE, H.H. 1894a. A Note on Crich Hill, Derbys. *Arch. Nat. Hist. Soc.*, vol.16, pp.44-51.

ARNOLD-BEMROSE, H.H. 1899. On a sill and faulted inlier in Tideswell Dale (Derbyshire). *Q. Jl. geol. Soc. Lond.*, vol.55, pp.239-250.

ARNOLD-BEMROSE, H.H. 1907. The toadstones of Derbyshire. Their field relations and petrography. *Q. Jl. geol. Soc. Lond.*, vol.63, pp.241-281.

ARNOLD-BEMROSE, H.H. 1910. On olivine nodules in the basalt of Calton Hill, Derbyshire. *Geol. Mag.*, vol.7, pp.1-4.

BAND, S. 1976. Lead mining in Ashover: A preliminary survey. *Bull. Peak Dist. Mines Hist. Soc.*, vol.6, pp.129-139.

BARNES, J. 1902a. On a metamorphosed limestone at Peak Forest. *Trans. Manchr. geol. Soc.*, vol.27, pp.317-321.

BARNES, J. 1902b. Further observations of the changes brought about by the intrusion of igneous matter into the Carboniferous limestone at Peak Forest. *Trans. Manchr. geol. Soc.*, vol.27, pp.366-369.

BROADHURST, F.M. & SIMPSON, J.M. 1973. Bathymetry on a Carboniferous reef. *Lethaia*, vol.6, pp.367-381.

BUTCHER, N.J.D. 1975. The geology of Magpie sough and mine. *Bull. Peak Dist. Mines Hist. Soc.*, vol.6, pp.65-70.

BUTCHER, N.J.D. 1976. Some aspects of structure and fluorite mineralisation in the Southern Pennine Orefield. Unpublished Ph.D. Thesis. University of Leicester, 218pp.

BUTCHER, N.J.D. & FORD, T.D. 1973. The Carboniferous limestone of Monsal Dale, Derbyshire. *Mercian Geol.*, vol.4, pp.179-195.

CHESHIRE, S.G. & BELL, J.D. 1977. The Speedwell vent, Castleton, Derbyshire. A Carboniferous littoral cone. *Proc. Yorks. geol. Soc.*, vol.41, pp.173-184.

COPE, F.W. 1933. A tholeiite dyke near Buxton, Derbyshire. *Geol. Mag.*, vol.70, pp.414-422.

COPE, F.W. 1937. Some features in the D_1 - D_2 limestones of the Miller's Dale region, Derbyshire. *Proc. Yorks. geol. Soc.*, vol.23, pp.178-195.

COPE, F.W. 1949. Woo Dale Borehole near Buxton, Derbyshire. *Abstr. Proc. geol. Soc. Lond.*, 1446, p.24.

COPE, F.W. 1973. Woo Dale borehole near Buxton, Derbyshire. *Nature* (*Phys. Sci.*), vol.243, pp.29-30.

COPE, F.W. 1979. The age of the volcanic rocks in the Woo Dale Borehole, Derbyshire, *Geol. Mag.*, vol.116, pp.319-320.

COX, F.C. & BRIDGE, D. McC. 1977. *The limestone and dolomite resources of the country around Monyash, Derbyshire.* Description of 1:25,000 resources sheet, SK 16, HMSO, Lond. 137pp.

CURTIS, C.D. 1976. 'Unmixed' Ca^{2+}/Mg^{2+} saponite at Calton Hill, Derbyshire. *Clay Minerals*, vol.11, pp.85-89.

DONALDSON, C.H. 1978. Petrology of the uppermost upper mantle deduced from spinel lherzolite and harzburgite nodules at Calton Hill, Derbyshire. *Contrib. Mineral Petrol.*, vol.65, pp.363-377.

DUNHAM, K.C. 1952. Fluorspar. 4th Edit. *Mem. geol. Surv.*, *Spec. Rep. Miner Resour. Gt. Br.*, 143pp.

DUNHAM, K.C. 1973. A recent deep borehole near Eyam, Derbyshire. *Nature* (*Phys. Sci.*), vol.241, pp.84-85.

EDEN, R.A., ORME, G.R., MITCHELL, M. & SHIRLEY, J. 1964. A study of part of the margin of the Carboniferous limestone 'massif' in the Pindale area of Derbyshire. *Bull. geol. Surv. Gt. Br.*, vol.21, pp.73-118.

FAREY, J. 1811. *A general view of the agriculture and minerals of Derbyshire*, vol.1, 532pp.

FAREY, J. 1812. On toadstones in Derbyshire. *Min. Mag.*, vol.33, pp.513-516.

FAUJUS DE ST. FOND, B. 1797. *Voyage en Angleterre ... avec la description Mineralogique ... des montagnes de Derbyshire.* Paris. English translation 1799 (Derbys. vol.ii, p.264).

FEARNSIDES, W.G. & TEMPLEMAN, A. 1932. A boring through Edale Shales to Carboniferous limestone and pillow lavas at Hope Cement Works near Castleton, Derbyshire. *Proc. Yorks. geol. Soc.*, vol.22, pp.100-121.

FITCH, F.J., MILLER, J.A. & WILLIAMS, S.C. 1970. Isotopic ages of British Carboniferous rocks. *Cr. 6th Int. Congr. Carb. Strat. Geol.* (Sheffield, 1967), vol.2, pp.771-789.

FORD, T.D. 1952. New evidence on the correlation of the Lower Carboniferous reefs at Castleton, Derbyshire. *Geol. Mag.*, vol.89, pp.346-356.

FORD, T.D. 1967. Some mineral deposits of the Carboniferous limestone of Derbyshire. In: *Geological Excursions in the Sheffield Region and the Peak District National Park.* Ed. R. Neves & C. Downie, University of Sheffield, pp.53-75.

FORD, T.D. (ed.) 1977. Limestones and caves of the Peak District. *Geo. Abstracts*, 469pp.

GARNETT, C.S. 1923. The toadstone clays of Derbyshire. *Min. Mag.*, vol.2, pp.151-157.

GEIKIE, A. 1897. *Ancient volcanoes of Great Britain.* London, vol.2, pp.8-22.

GEORGE, T.N. *et al.* 1976. A correlation of Dinantian rocks in the British Isles. *Spec. Rep. No.7, geol. Soc. Lond.*, 87pp.

GIBSON, W. & WEDD, C.B. 1913. The geology of the northern part of the Derbyshire Coalfield and bordering tracts. *Mem. geol. Surv. E. & W.*, 186pp.

GREEN, A.H., LE NEVE FOSTER, C. & DAKYNS, J.R. 1869. The geology of the Carboniferous limestone, Yoredale rocks and Millstone grit of North Derbyshire. *Mem. geol. Surv. Gt. Br.*, 1st ed. 150pp.

GREEN, A.H., LE NEVE FOSTER, C. & DAKYNS, J.R. 1887. The geology of the Carboniferous limestone, Yoredale rocks and Millstone grit of North Derbyshire. *Mem. geol. Surv. Gt. Br.*, 2nd ed., 212pp.

GRIGOR-TAYLOR, W.R. 1972. Notes on the Lathkill Gold Mine 1854-1856. *Bull. Peak Dist. Mines Hist. Soc.*, vol.5, (1), pp.43-49.

HAMAD, S. EL D. 1963. The chemistry and mineralogy of the olivine nodues of Calton Hill, Derbyshire. *Min. Mag.*, vol.33, pp.483-497.

HOPKINS, W. 1834. *On the stratification of the limestone district of Derbyshire.* Private Publication, 47pp.

HUDSON, R.G.S. & COTTON, G. 1945a. The lower Carboniferous in a boring at Alport, Derbyshire. *Proc. Yorks. geol. Soc.*, vol.25, pp.254-330.

HUDSON, R.G.S. & COTTON, G. 1945b. The Carboniferous rocks of the Edale Anticline, Derbyshire. *Q. Jl. geol. Soc. Lond.*, vol.101, pp.1-36.

INESON, P.R. 1967. Trace-element geochemistry of wallrock alteration in the Pennine orefields and Cumberland ironfield. Unpublished Ph.D. Thesis, University of Durham, 286pp.

INESON, P.R. 1970. Trace element aureoles in limestone wallrocks adjacent to fissure veins in the Eyam area of the Derbyshire orefield. *Trans. Inst. Min. Metall.* (*Sect. B, Appl. earth Sci.*), vol.79, pp.B238-245.

INESON, P.R. & MITCHELL, J.G. 1973. Isotopic age determinations on clay minerals from lavas and tuffs of the Derbyshire orefield. *Geol. Mag.*, vol.109(6), pp.501-512.

INSTITUTE OF GEOLOGICAL SCIENCES 1969. Classical areas of British geology, Sheet SK 18 and part of SK 17 (Solid & Drift) - Edale & Castleton, 1:25,000. Inst. geol. Sci. Col.

INSTITUTE OF GEOLOGICAL SCIENCES 1970. Classical areas of British geology. Parts SK 25, 26, 35 and 36 (Solid & Drift) - Matlock: 1:25,000, Inst. geol. Sci. Col.

INSTITUTE OF GEOLOGICAL SCIENCES	1975. Classical areas of British geology. Sheet SK 07 (Solid & Drift) - Buxton: 1:25,000 Inst. geol. Sci. Col.
INSTITUTE OF GEOLOGICAL SCIENCES	1975. Classical areas of British geology. Sheet SK 18 (Solid & Drift) - Castleton: 1:25,000, Inst. geol. Sci. Col.
INSTITUTE OF GEOLOGICAL SCIENCES	1976a. Classical areas of British geology. Sheet SK 17 (Solid & Drift) - Millers Dale: 1:25,000, Inst. geol. Sci. Col.
INSTITUTE OF GEOLOGICAL SCIENCES	1976b. Geological Survey map, Sheet SK 25 NW (Solid & Drift). 1:10,560, Inst. geol. Sci. Col.
INSTITUTE OF GEOLOGICAL SCIENCES	1977a. Classical areas of British geology. Sheet SK 16 (Solid & Drift) - Monyash: 1:25,000, Inst. geol. Sci. Col.
INSTITUTE OF GEOLOGICAL SCIENCES	1977b. Geological Survey map, Sheet SK 26 NW (Solid & Drift). 1:10,560, Inst. geol. Sci. Col.
IXER, R.A.	1972. Controls of mineralisation in Derbyshire. Unpublished Ph.D. Thesis. University of Manchester. 117pp.
IXER, R.A.	1975. A revision of part of the Matlock group at Masson Hill, Matlock, Derbyshire. *Mercian Geol.*, vol.5, pp.181-186.
JEFFERSON, D.P.	1979. *Guide book to the Midlands of England, field excursion guide E5.* Sixth International Clay Conference, 1978. Oxford. pp.34-39.
JONES, J.G. & NELSON, P.H.H.	1970. The flow of basalt from air into water: Its structural expression and stratigraphic significance. *Geol. Mag.*, vol.107, pp.13-19.
KELMAN, P.	1980. The geology of the Ashover Volcanics. *Merc. Geol.*, vol.8, pp.11-28.
MILLER, G.	1980. Now you see it, now you don't, or the case of the disappearing sill. *Amat. geol.*, vol.VIII (1), pp.14-18.
MOORE, S.	1903. Note on an unmapped toadstone in Derbyshire. *Geol. Mag.*, vol.10, pp.84-96.
MOSELEY, F.	1966. The volcanic vents and pocket deposits of Derbyshire. *Mercian Geol.*, vol.1, (3), pp.283-285.
MUELLER, G.	1954. Enclosures in gangue minerals. *Min. Mag.*, vol.90, pp.148-154 and 208-217.
OAKMAN, C.D.	1978. Sough Hydrology of the Wirksworth-Matlock-Youlgreave area. Unpublished M.Phil. Thesis, University of Leicester, 209pp.
PILKINGTON, J.	1789. *A view of the present state of Derbyshire*, vol.1, 469pp.

RAMSBOTTOM, W.G.C., RHYS, G.H. & SMITH, E.G. 1962. Boreholes in the Carboniferous rocks of the Ashover district, Derbyshire. *Bull. geol. Surv.* GB., no.19, pp.75-168.

SARGENT, H.C. 1912. On the origin of certain clay bands in the limestones of the Crich inlier. *Geol. Mag., vol.9,* pp.406-412.

SARGENT, H.C. 1917. On a spilitic facies of Lower Carboniferous lava flows in Derbyshire. *Q. Jl. geol. Soc. Lond.*, vol.73, pp.11-25.

SARGENT, H.C. 1925. An analcite bearing tuff in the Carboniferous limestone of Derbyshire. *Geol. Mag.*, vol.62, pp.462-463.

SARJEANT, W.A.S. 1967. Fibrous chlorites in the volcanic rocks of Derbyshire. *Mercian Geol.*, vol.3 (1), pp.85-95.

SCHNELLMANN, G.A. & WILLSON, J.D. 1947. Lead-zinc mineralisation in North Derbyshire. *Trans. Instn. Min. Metall.*, vol.485, pp.411-429.

SHIRLEY, J. 1950. The stratigraphical distribution of the lead-zinc ores of Mill Close Mine, Derbyshire and the future prospects of the area. *XVIII Int. geol. Congr. Lond.* (London, the Congress), Pt.7, pp.353-361.

SHIRLEY, J. 1959. The Carboniferous limestone of the Monyash-Wirksworth area, Derbyshire. *Q. Jl. geol. Soc. Lond.*, vol.114, pp.411-429.

SHIRLEY, J. & HORSFIELD, E.L. 1940. The Carboniferous limestone of the Castleton-Bradwell area, North Derbyshire. *Q. Jl. geol. Soc. Lond.*, vol.96, pp.271-299.

SHIRLEY, J. & HORSFIELD, E.L. 1945. The structure and ore deposits of the Carboniferous limestone of the Eyam district, Derbyshire. *Q. Jl. geol. Soc. Lond.*, vol.100, pp.289-310.

SMITH, E.G. RHYS, G.H. & EDEN, R.A. 1967. Geology of the country around Chesterfield, Matlock and Mansfield. *Mem. geol. Surv.* GB. 430pp + vii.

SPEED, P.H. 1964. The volcanic rocks of the Wirksworth area. An excursion report. *Mercian geol.*, vol.1, pp.71-72.

STEVENSON, I.P. & GAUNT, G.C. 1971. Geology of the country around Chapel-en-le-Frith. *Mem. geol. Surv.* GB., 444pp.

STEVENSON, I.P., HARRISON, R.K. & SNELLING, N.J. 1970. Potassium argon age determination of the Waterswallows Sill, Buxton, Derbyshire. *Proc. Yorks. geol. Soc.*, vol.37, pp.445-447.

TOMKEIEFF, S.I. 1928. The volcanic complex of Calton Hill. *Q. Jl. geol. Soc. Lond.*, vol.84, pp.703-718.

TRAILL, J.G. 1940. Notes on the Lower Carboniferous Limestones and toadstones at Millclose Mine, Derbyshire. *Trans. Instn. Min. Engrs.*, vol.49, pp.191-229.

VARVILL, W.W. 1959. The future of lead-zinc and fluorspar mining in Derbyshire. In: '*The Future of Non-Ferrous Mining in Great Britain and Ireland*'. Lond. Instn. Min. Metall., pp.175-232.

WALKDEN, G.M. 1972. The mineralogy and origin of interbedded clay wayboards in the Lower Carboniferous of the Derbyshire Dome. *Geol. J.*, vol.8, pp.143-160.

WALKDEN, G.M. 1977. Volcanic and erosive events in an upper Viséan carbonate platform, north Derbyshire. *Proc. Yorks. geol. Soc.*, vol.41, pp.347-366.

WALTERS, S.G. 1980. The geology of the Black Hillock or Clear-the-Way Mine, Tideswell Moor. *Bull. Peak.Dist. Mines Hist. Soc.*, vol.7, pp.327-333.

WALTERS, S.G. & INESON, P.R. 1980. Mineralisation within the igneous rocks of the South Pennine Orefield. *Bull. Peak Dist. Mines Hist. Soc.* vol.7, pp.315-325.

WATSON, W. 1811. *A delineation of the strata of Derbyshire forming the surface from Bolsover in the east to Buxton in the west.* Sheffield. 76pp.

WATSON, W. 1813. *A section of the strata forming the surface in the vicinity of Matlock Bath in Derbyshire.* Chesterfield, 19pp.

WHEATCROFT, J. 1831. Uncatalogued MS. Peak Dist. Mines Hist. Soc., Derbyshire Records Office, Matlock.

WHITEHURST, J. 1778. *An inquiry into the original stage and formation of the earth with observations on the strata of Derbyshire.* London.

WILKINSON, P. 1967. Volcanic rocks in the Peak District. In: *Geological Excursions in the Sheffield Region and the Peak District National Park.* Ed. R. Neves and C. Downie. University of Sheffield, pp.47-53.

WILLIES, J. 1976. John Taylor in Derbyshire, 1839-1851. *Bull. Peak Dist. Mines Hist. Soc.*, vol.6, pp.146-161.

WILSON, E. 1870. Altered clay bed and sections in Tideswell Dale, Derbyshire. *Geol. Mag.*, vol.VII, pp.394 & 520-523.

WORLEY, N.E. 1977. The Geology of Will's Founder Shaft. *Bull. Peak Dist. Mines Hist. Soc.*, vol.6, pp.257-262.

WORLEY, N.E. 1978a. Stratigraphic controls of mineralisation in the Peak District of Derbyshire. Unpublished Ph.D. Thesis, University of Leicester, 263pp.

WORLEY, N.E., WORTHINGTON, T. & RILEY, L. 1978b. The geology and exploration of Hubbadale Mines, Taddington. *Bull. Peak Dist. Mines Hist. Soc.*, vol.7, pp.31-39.

WORLEY, N.E. & DORNING, K.J. 1977. Carbonaceous and fossiliferous material from some Derbyshire clay wayboards. *Mercian Geol.*, vol.6, pp.145-154.

WRIGHT, A. 1979. A geochemical investigation of massive limestones of North Derbyshire. Unpublished M.Sc. Thesis, University of Sheffield. 177pp.

DATING THE TIME OF MOVEMENT OF FAULTS IN THE COAL MEASURES OF THE EAST MIDLANDS

by

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Summary

Potassium-argon dating studies of the time of fault movement, using fault gouge clay samples, suggested that geochronological information relating to dynamic metamorphism was not detectable, because the potassium-argon 'time-clock" involving argon loss had not been reset by frictional heat when a fault moved. By a delicate experimental technique which separated the samples into cleaned size-fractionated aliquots, followed by a graphical isochron method of data treatment, the date at which sedimentary diagenesis involving potassium fixation took place was determined.

Introduction

A geochronological investigation into the time of fault movement in Coal Measure strata was undertaken as part of a National Coal Board sponsored research project. The initial aim of the project was to investigate the hypothesis that by dating fault gouges it may be possible to differentiate pre-Permian from Permian and reactivated faults. This line of research was considered worth-while because the Permian is water-bearing, and if underground workings intersected a fault plane which cut the Permian aquifers, then the water could percolate into the mine workings via the fault plane, as in the Lofthouse Mine flooding when workings penetrated an old mine shaft (Calder, 1973).

It was envisaged that the formation of the fault gouge, during a dynamic metamorphic event, would have resulted in the cumulative potassium-argon 'time-clock" being completely reset by the release of pre-existing argon due to the frictional heat produced at that time. Subsequently argon would continue to be produced by the natural decay of the potassium-40 present in the clay minerals of the gouge. Radiogenic decay in the gouge would thus provide a potassium-argon date relating to the time of resetting of the potassium-argon "time-clock" by dynamic metamorphism.

Fault gouge sample collection

Sampling localities in the East Midlands Coalfield were selected by the use of colliery development plans at the Regional Offices of the National Coal Board. The majority of modern workings in the East Midlands Coalfield have been designed to avoid major faults and in most of the older workings where suitable areas had once been exposed, faults were now inaccessible due to flooding, or lack of ventilation in the roadway in question.

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pp.133-142, 1 text-fig.

There were additional problems associated with the collection of samples in accessible roadways where faults were known to occur. Not only were the faulted areas weak ground, and thus, for safety reasons, the most heavily reinforced and covered, but often the faults consisted of a zone of shattered shale, rather than a distinct fault plane with a parting of clay gouge. Only samples of true clay gouge were considered suitable for further analysis.

A further problem was encountered occasionally in the form of small faults which were drawn on the plans, but which, did not exist. The addition of these "bogus" faults to the mine plans in the days of private ownership was a common ruse for the non-payment of the full amount of royalties, that is, the faulted coal was taken tax-free. An example of such a non-existent 3.6 m fault is to be found on the Deep Hard plans of Glapwell Colliery. (SK 468669).

Despite the above difficulties 36 good clay gouges were collected from localities in the East Midlands Coalfield. (Table 1).

Initial potassium-argon dating of the fault gouges

Method

Clay, less than 2 μm in size, from the gouges was analysed for potassium using an Eel 450 Flame Photometer. The instrument underwent regular calibrations against laboratory standards in turn routinely checked with a known reference standard ("Biotite 133"). Argon was analysed in a mass spectrometer after the addition of a "spike" volume of argon-38. (Dalrymple & Lanphere, 1969). Calculations were made using the standard age equations (Aldrich & Wetherill, 1958). The data from the analyses are presented in Table 2.

Discussion of the initial potassium-argon dates

All the dates obtained from the analyses of the clay gouges were between 413 ± 5 Ma and 322 ± 4 Ma. The average result of the 36 analyses was 382 ± 5 Ma. It was apparent that the majority of the chronological information had to be reconsidered in terms of the age of the faults which cut Coal Measures strata. Few of the dates could bear a resemblance to the time of faulting, as the ages obtained were observed to be older than the chronological dates of the sedimentary rocks that the fault planes intersected.

In view of the results in Table 2, it seemed likely that the initial basic premise that the potassium-argon "time-clock" in the clay gouge could have been completely reset, either during the initial formation of the gouge, or during subsequent fault movement, was unfounded.

The second attempt to date fault movement

In view of the foregoing results, the basic premise that the potassium-argon "time-clock" was completely reset during fault movement was modified. It was suspected that the chronological information present in Table 2 was the result of a "memory" inherited from the original source area for the sediment from which the fault gouge had been generated, that is, a "memory" of the Caledonian orogeny was present in the gouge, since the sedimentary particles had been derived from Lower Paleozoic outcrops.

The variation in the data from the East Midlands suggested that the calculated dates could possibly be considered to be the result of a mixture of material, which thus resulted in a mixture of ages, that is, a mixture of orogenic material, with orogenic dates, plus an element of younger chronological information. It was suspected that some of the clay fraction included particles, which despite their small size, were still too large for their isotopic "clocks" to have been completely reset during fault movement. A more delicate clay separation technique on the gouge material was devised in order to separate a sample which contain only particles small enough to have been completely reset by argon loss during dynamic metamorphism, and which would have no "inherited memory".

Table 1: Sample Data for Selected Faults in the East Midlands

Sample	Colliery	Grid Reference	National Coal Board Reference	Throw m
K5	Cotgrave	SK 630 361	463 040/336 102	12
K8	Wrange Farm, nr. Chesterfield	SK 427 689	442 722/368 900	20.0
K10	Wrange Farm, nr. Chesterfield	SK 428 687	442 827/368 674	0.6
K12	Pit Houses, nr. Dronfield	SK 460 333	446 014/383 308	7.6
K16	Pit Houses, nr. Dronfield	SK 462 834	446 165/383 415	10.7
K21	Renishaw Park	SK 467 785	446 705/378 468	0.9
K22	Renishaw Park	SK 467 785	446 700/378 478	61
K23	Babbington	SK 533 436	453 250/343 614	73.2
K24	Babbington	SK 532 436	453 150/343 626	73.2
K26	Moorgreen	SK 501 491	450 120/349 105	9.1
K30	Newstead	SK 509 538	450 936/353 795	7.2
K33	Bentink	SK 488 543	448 765/354 812	6.4
K35	Cotgrave	SK 647 354	464 674/335 408	30.8
K37	Cotgrave	SK 645 345	464 488/334 450	4.9
K38	Bevercotes	SK 677 689	467 724/468 850	45.7
K39	Bevercotes	SK 700 735	470 020/373 543	62.5
K40	Thorsby	SK 664 727	466 427/372 686	12.2
K41	Thorsby	SK 629 671	462 888/367 121	9.1
K42	Thorsby	SK 628 673	462 785/367 320	11.0
K43	Pit Houses, nr. Dronfield	SK 461 834	446 122/383 410	10.7
K48	Whitwell	SK 539 753	453 876/375 260	27.4
K52	Blidworth	SK 636 556	463 581/355 634	11.0
K54	Warsop Main	SK 553 653	455 300/365 273	3.4
K56	Warsop Main	SK 551 656	455 111/365 684	7.6
K58	Warsop Main	SK 544 677	454 360/367 676	3.0
K60	Glapwell, nr. Chesterfield	SK 479 669	447 884/366 910	7.6
K64	Renishaw Park	SK 433 757	443 274/375 744	39.6
K68	Langwith	SK 540 718	454 030/371 780	6.1
K71	Markham (Derbys.)	SK 473 694	447 252/269 388	3.8
K72	Markham (Derbys.)	SK 467 697	446 728/369 700	6.1
K73	Markham (Derbys.)	SK 448 717	444 834/371 713	16.5
K74	Markham (Derbys.)	SK 448 719	444 760/371 888	2.1
K75	Clipstone	SK 578 635	457 749/363 465	4.3
K77	Creswell	SK 511 727	451 079/372 680	3.0
K78	Creswell	SK 605 722	450 644/372 225	33.5

Nevertheless, rather than obtain age data from the very finest of clays only (say 0.5 μm or less) the larger size clay fractions were analysed as well, in order to gain age information relating to the possible maximum size of particles which, according to the working hypothesis, should have possessed no "memory" inherited prior to the formation of the fault gouge.

Size fractionation of selected fault gouge samples

Three samples from the East Midlands were selected for size fractionation and analysis (K8, K10 and K24). These were selected in order to give as wide a range of fault types as possible.

Table 2: Potassium-Argon Fault Gouge Analyses

Sample Number	$\frac{v}{m} \times 10^{-2}$ $mm^3\ gm^{-1}$	K_2O %	% Atmos	"g"	Age (Ma)
K5	5.9803	4.42	16.1	.01354	370 ± 5
K8	3.4414	2.25	21.4	.01529	413 ± 5
K10	6.0360	4.13	13.2	.01462	397 ± 5
K12	4.4479	2.93	17.9	.01629	413 ± 5
K16	6.2075	4.36	16.1	.01423	388 ± 5
K21	6.3213	4.52	10.1	.01398	381 ± 5
K22	4.1722	3.01	12.4	.01386	378 ± 5
K23	3.6991	2.91	5.1	.01271	350 ± 5
K24	3.3418	2.48	7.9	.01348	369 ± 5
K26	6.3965	4.72	11.2	.01355	371 ± 5
K27	5.2228	3.66	17.1	.01427	389 ± 5
K30	4.2353	3.56	22.3	.01189	329 ± 4
K33	5.3434	3.73	15.4	.01433	390 ± 5
K35	5.8632	4.13	15.2	.01419	387 ± 5
K37	5.6662	4.27	15.5	.01326	364 ± 5
K38	5.5524	3.84	15.9	.01438	391 ± 5
K39	5.3320	3.71	14.5	.01437	391 ± 5
K40	5.5753	4.19	12.2	.01330	365 ± 5
K41	2.9914	2.01	22.5	.01488	403 ± 5
K42	4.1722	2.97	21.5	.01404	383 ± 5
K43	3.5562	2.59	21.9	.01373	375 ± 5
K48	5.7952	4.31	16.9	.01345	368 ± 5
K52	5.6308	4.05	17.2	.01390	379 ± 5
K54	6.1322	4.16	17.3	.01474	400 ± 5
K56	5.3032	3.84	14.2	.01381	377 ± 5
K58	6.6129	5.02	14.3	.01317	361 ± 5
K60	3.7483	3.23	23.2	.01160	322 ± 4
K64	5.6526	4.07	13.1	.01389	379 ± 5
K68	5.2942	3.79	17.0	.01397	381 ± 5
K71	4.6052	3.14	23.2	.01466	398 ± 5
K72	5.8032	3.94	21.9	.01473	400 ± 5
K73	1.5514	1.15	34.0	.01349	369 ± 5
K74	4.8899	3.34	21.3	.01464	397 ± 5
K75	6.0458	4.39	12.5	.01377	376 ± 5
K77	4.7600	3.26	20.0	.01460	397 ± 5
K78	4.8449	3.26	14.7	.01486	403 ± 5

K8 was collected from a fault with a 20 m throw from Wrange Farm Opencast Site, nr. Chesterfield. It was considered to be a typical pre-Permian fault of more than average throw.

K10, a sample of gouge from a fault with a throw of only 0.6 m had field evidence to suggest that this was a typical depositional fault, formed during sedimentation. It was anticipated that the difference in the throw of these two faults would provide information relating to any dependence of the "time-clock" resetting upon the displacement of similarly aged faults.

K24, a fault gouge collected from the Cinderhill Fault, one of the small number of large displacement faults (73 m throw) in the East Midlands Coalfield. The Fault is an excellent example of a post-Permian reactivated fault and prior to the tipping of coal-waste from Babbington Colliery at the surface, a well marked Permian fault scarp could have been observed.

Size fractionation technique

The size fractionation procedure involved the separation of the samples into aliquots. The fractions used by the author are included as suffix letters of the samples where A = 100-30 μm, B = 30-7 μm, C = 7-2 μm, D = 2-1 μm, E = 1-0.5 μm, and F was less than 0.5 μm. The larger A and B fractions were allowed to settle through a column of distilled water (Jackson, 1956) and the supernatent liquid centrifuged at various speeds in order to precipitate the finer particles. The centrifuge times for the various sizes were calculated using a modified Stokes Law equation (Hathaway, 1955) substituting the experimentally determined acceleration and deceleration times of the centrifuge used. The experimental procedure was repeated many times for each fraction in order to wash each particular size fraction clean of any smaller particles.

These fractions are analysed by the same methods as those used for the initial samples.

Results from the size fractionated fault gouges

The results from the potassium-argon analyses are presented in Table 3. It may be observed that there is a variation in the calculated age with grain size, that is, the larger size fractions give older dates than the smaller sizes. These variations were found to be similar to the variations found in size-fractionated sediments (Langley, 1978) and to the results reported by workers in the Gulf Coast of Mexico (Burst, 1969; Perry, 1974; Perry & Hower, 1970, 1972; Aronson & Hower, 1976; Hower *et al.*, 1976, 1963; Hurley, *et al.*, 1961, 1963; Weaver & Wampler, 1957, 1970; Weaver, 1958, 1965, 1967), by Hofmann, Mahoney & Giletti (1974) working on Pennsylvanian clays and by Hurley, Heezen, Pinson & Fairbairn (1963) from pelagic sediments in the North Atlantic.

The calculated ages from the size-fractionated fault gouges vary from 436 ± 5 Ma (K8B) to 351 ± 5 Ma (K8F). Clearly these dates are older than the strata in which the faults are located. Thus, taken at face value, it appears that even the delicate size fractionation technique was unable to segregate isotopic data from any particles which might have undergone argon loss during the process of dynamic metamorphism. Also, it was of considerable interest to note that the dates from K24, the post-Permian reactivated fault differed little from the dates from the other, Carboniferous faults.

Table 3: Potassium-Argon Analyses of Size Fractionated Gouges, Isochron Data

Sample Number	Ar^{40} $\times 10^{-3}$ $mm^3\ gm^{-1}$	Ar^{36} $\times 10^{-3}$ $mm^3\ gm^{-1}$	K_2O %	% Atmos	$\frac{Ar^{40}}{Ar^{36}}$	$\frac{K_2O}{Ar^{36}}$	Calculated Age (Ma)
K8B	53.03	.0259	2.79	14.9	2047.5	107.7	436 ± 5
K8C	62.48	.0279	3.44	13.0	2239.4	123.3	426 ± 5
K8D	78.78	.0390	4.38	14.6	2020.0	112.3	415 ± 5
K8E	84.82	.0384	5.21	13.9	2208.9	135.7	382 ± 5
K8F	82.76	.0272	5.85	9.0	3042.6	215.1	351 ± 5
K10C	68.51	.0395	3.62	15.9	1734.4	91.7	429 ± 5
K10D	81.44	.0370	4.95	12.5	2201.1	133.8	399 ± 5
K10E	82.90	.0359	5.16	11.9	2309.2	143.7	387 ± 5
K10F	94.89	.0689	5.80	20.0	1377.2	84.2	366 ± 5
K24C	26.66	.0242	1.32	25.3	1101.7	54.6	408 ± 5
K24D	34.27	.0323	1.72	26.9	1061.0	53.3	396 ± 5
K24E	41.94	.0354	2.28	23.8	1184.8	64.4	382 ± 5
K24F	63.13	.0377	4.04	17.5	1674.5	107.2	354 ± 5

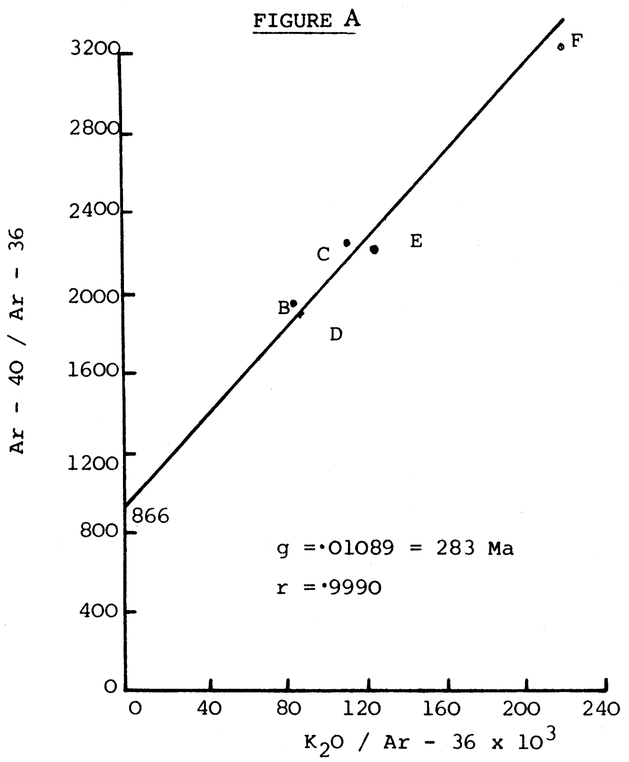
FIGURE A

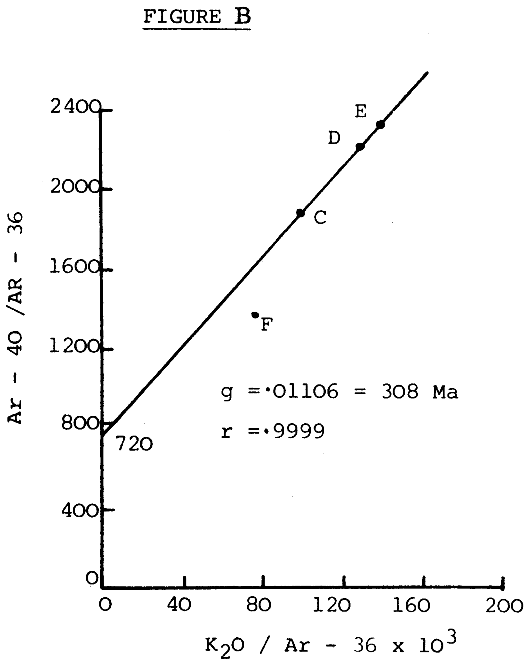
FIGURE B

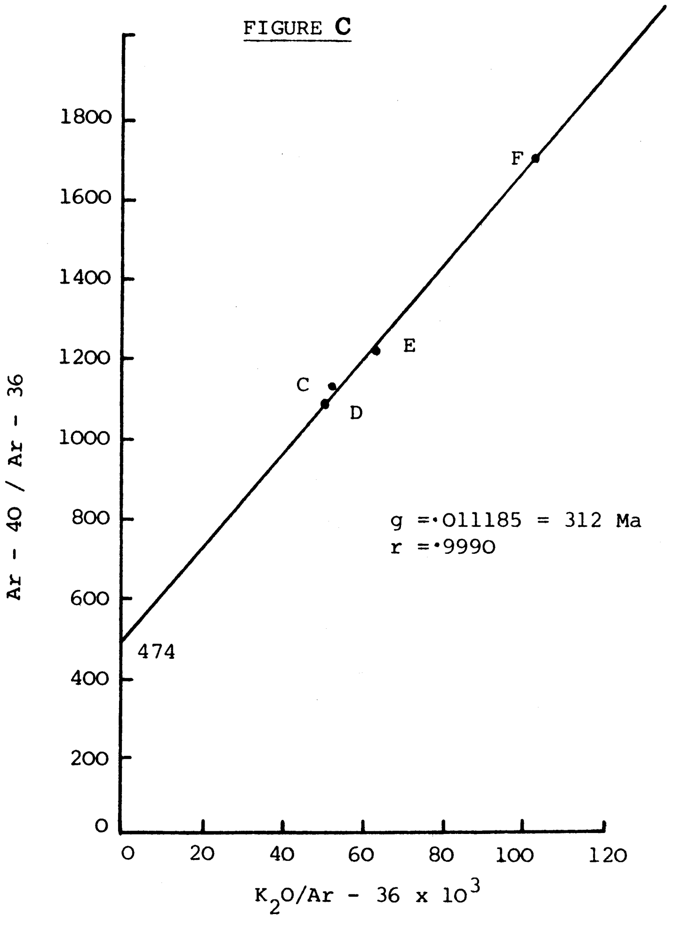
FIGURE C

Text-fig. 1: Potassium-argon isochron fault gouge

Fig. A - K8, a pre-Permian fault

Fig. B - K10, a small depositional Carboniferous fault

Fig. C - K24, the post-Permian reactivated Cinderhill fault

The isochron ages from the size fractionated fault gouges also show a marked resemblance to the isochron age from ordinary Carboniferous shale which had undergone the same analytical procedures as the fault gouges, that is, a date of 315 ± 8 Ma was obtained from Coal Measures shale, KS2, from Pit Houses Opencast Site, Derbyshire (SK 462833). (Langley, 1978).

The isochron method of data treatment

The "isochron" method of dating involves plotting a graph, Ar^{40}/Ar^{36} values against K_2O/Ar^{36} values. When joined the points form an "isochron" line, the gradient of which relates to the age of the material. This method has found application in igneous and metamorphic rocks which are thought to contain "excess" atmospheric argon of various types (Damon *et al.*, 1967). In cases where excess argon is present, the standard method of potassium-argon age calculation, which involves the use of the standard atmospheric ratio figure, normally taken to be 295.5 (Nier, 1950) is invalid (Hayatsu & Carmichael, 1970). However, the isochron method provides a way of dating which does not involve the use of this atmospheric ratio figure, and thus can be used for samples which contain excess or inherited argon relating to a previous orogenic potassium-argon "time-clock" setting events prior to weathering, transportation, deposition and/or dynamic metamorphism. Thus sedimentary or fault gouge material which contains inherited argon could be a candidate for treatment by the isochron method.

Results from the fault gouge isochrons

The isochron graphs are illustrated in text-fig. 1, A-C, for K8, K10 and K24 respectively. The dates calculated from these graphs are 283 ± 10 Ma for K8, 308 ± 6 Ma for K10 and 312 ± 6 Ma for K24. These isochron ages lie well within the expected age limits for Coal Measures strata, that is, 325 - 280 Ma. The Namurian/Viséan boundary was placed at 325 Ma on the basis of the 322 ± 12 Ma potassium-argon whole rock age obtained from the Lower Namurian Hillhouse Sill, Scotland (Francis & Woodland, 1964). A minimum potassium-argon age for the Upper Coal Measures of 308 ± 10 Ma was provided by the age of the Barrow Hill intrusion, Staffordshire, which cut sediments at the base of the Coal Measures (Fitch *et al.*, 1974). The Permo-Carboniferous boundary was placed at 280 Ma on the evidence of the 284 Ma age from metamorphosed Lower Permian Lava in the Oslo area of Norway, and Rb-Sr evidence on a number of dates from the Stephanian granites in France and Portugal (Francis & Woodland, 1964). Evidence from Britain relating to the Dartmoor granite confirmed a minimum age of 280 ± 5 Ma for the Permo-Carboniferous boundary (Kulp *et al.*, 1960).

Discussion of the isochron results

K24, the Cinderhill Fault sample is known to be a large fault, post-Permian reactivated, and yet the isochron, with a high correlation, provided a date of 312 ± 6 Ma. This age bears a close resemblance to the date obtained from a size-fractionated Coal Measures sediment, KS2, with an isochron date of 315 ± 5 Ma (Langley, 1978). These dates are too close to be the result of coincidence alone. If, however, the Cinderhill Fault gouge date related to the diagenetic age of the sediment from which the gouge was made, rather than to the time of a post-Permian reactivated fault movement, then it is apparent that, in this case, the fault movement has had little or no effect on the resetting of the potassium-argon cumulative "time-clock" during dynamic metamorphism. Fault movement produced a fault gouge, but it may be concluded that insufficient heat had been generated to reset the "time-clock" by argon loss.

K10, the small depositional fault, had an isochron date of 308 ± 6 Ma. The date, in this case, may be related to either diagenesis or fault movement. However, in consideration of the result from the much larger Cinderhill Fault, it seems that the age was more likely to be the time of potassium-fixation at diagenesis rather than fault movement. There was no reason why argon loss of a sufficient extent should have occurred in this small fault, and reset the potassium-argon "time-clock" when a fault gouge material from the larger fault (K24) was apparently unaffected.

K8 had an isochron date of 283 ± 10 Ma. Although this was a younger age than the two previous results, this still fell within the stratigraphical age range of the Coal Measures, and it seems very probable that this isochron date also relates to the time of diagenesis, rather than to the time of fault movement.

Conclusions

The initial method of dating bulk clay gouge produced only a mixture of ages which were "swamped" by the primary "time-clock" setting event which started prior to weathering, erosion and transportation of the sediment from which the fault gouge was made. The dates produced were thus Caledonian dates.

The geochronological information from the size-fractionated gouges showed a variation in age as had been observed from various sedimentary samples (Langley, 1978; Burst, 1969; Perry, 1974; Perry & Hower, 1970, 1972; Aronson & Hower, 1976; Hower *et al.*, (1963, 1967; Weaver & Wampler, 1957, 1970; Weaver, 1958, 1965, 1967; Hofmann, Mohoney & Giletti, 1974 Hurley, Heezen, Pinson & Fairbairn, 1963). Calculated dates from the delicately separated clay fractions gave only marginally more significant results than the bulk samples, in that all the fractions still gave calculated dates that were older than the stratigraphical ages of the faults.

When the data was treated by the graphical, or isochron method, the data was freed from the restraints due to the argon inherited from previous orogenic happenings. The isochron ages from the gradients of the graphs for the gouges all lay well within the expected age limits for the Coal Measures. However, the large Carboniferous and Permian Cinderhill Fault gave results which were not significantly different from the other smaller faults which were restricted to the Coal Measures strata. From the results, it was assumed that the Cinderhill Fault, with a 73 m throw had been unable to reset the "time-clock" in the fault gouge by dynamic metamorphism. Thus it was unlikely that the smaller faults would have been capable of such an isotopic event. Therefore it may be concluded that, if even large faults are incapable of producing enough frictional heat to cause argon loss, it is unlikely that smaller faults are capable of such an event. Alternatively any heat generated when a fault moves might be dissipated so quickly that the effect would be insignificant isotopically.

The chronological resemblance of the isochron ages from the fault gouges with the stratigraphical age of the strata from which the faults cut cannot be overlooked. As it was unlikely to be the result of mere coincidence that the dates fell within the 325-280 Ma age range of the Coal Measures strata, it is suggested that the dates obtained from the fault gouge isochrons related to a potassium fixation event which took place during the diagenesis of the sediment from which the clay gouge was made, and that it was this isotopic event which was detected by the isochron method of data treatment of the size-fractionated samples.

Acknowledgements

The author wishes to thank the National Coal Board who sponsored the project, in particular Mr. Elliott and his geological staff for their invaluable help underground, Dr. P.R. Ineson as supervisor, Dr. J.G. Mitchell at the University of Newcastle-upon-Tyne where the analyses were carried out, and Dr. T.D. Ford and Dr. K.R. Pollitt for all their help and encouragement.

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References

ALDRICH, L.T. & WETHERILL, C.W. 1958. Geochronology by radioactive decay. *Annual Rev. Nuc. Sci.*, vol.8, pp.257-298.

ARONSON, J.L. & HOWER, J. 1976. Mechanism of burial metamorphism of argillaceous sediment. 2. Radiogenic argon evidence. *Geol. Soc. Amer. Bull.*, vol.87, no.5, pp.738-744.

BURST, J.F. 1969. Diagenesis of Gulf Coast clayey sediments and its possible relation to petroleum migration. *Bull. Amer. Assoc. Petrol. Geologists*, vol.53, pp.73-93.

CALDER, J. 1973. *In-rush of water at Lofthouse Colliery, Yorkshire.* Dept. of Trade and Industry Report, No. C.m.n.d.5419.

DALRYMPLE, C.B. & LANPHERE, M.A. 1969. *Potassium-argon dating.* Freeman and Co.,

DAMON, P.E., LAUGHIN, A.W. & PERCIOUS, J.K. 1967. Problems of excess argon-40 in volcanic rocks: pp.463-481 in *Radioactive Dating and Methods of Low-level Counting.* Vienna, Internat, Atomic Energy Agency.

EVERNDEN, J.F., CURTIS, G.H., OBRADOVICH, J. & KISTLER, R. 1961. On the evaluation of glauconite and illite for dating sedimentary rocks by the potassium-argon method. *Geochim. et Cosmochim. Acta*, vol.23, pp.78-99.

FITCH, F.J., MILLER, J.A. & WILLIAMS, S.C. 1970. Isotopic age of British Carboniferous rocks. *Compte Rendu 6^{e} Congres Intern. Strat. Geol. Carbonif. Sheffield*, 1967, vol.11, pp.771-790.

FITCH, F.J., FORSTER, C.S. & MILLER, J.A. 1974. Geological time scale. *Reports on Progress in Physics*, vol.37(11), pp.1433.

FRANCIS, E.H. & WOODLAND, A.W. 1964. The Phanerozoic Timescale. (ed) W.B. Harland, A.G. Smith and B. Wilcock; *London Geol. Soc.*, pp. 211-232.

HATHAWAY, J.C. 1955. *Procedure for clay mineral analyses used in the Sedimentary Petrology Laboratory of the U.S. Geological Survey.* U.S. Geol. Surv., Beltsville., Md. U.S.A.

HAYATSU, A. & CARMICHAEL, C.M. 1970. K-Ar isochron method and initial argon ratios. *Earth Planet. Sci. Lett.*, vol.8, pp.71-76.

HOFMANN, C.W., MAHONEY, W. & GILETTI, L.J. 1974. K-Ar and Rb-Sr data on detrital and post-depositional history of the Pennsylvanian Clay from Ohio and Pennsylvania. *Geol. Soc. Amer. Bull.*, vol.85, pp.639-644.

HOWER, J., HURLEY, P.M., PINSON, W.H. & FAIRBAIRN, H.W. 1963. The dependence of K-Ar age on the mineralogy of various particle size ranges in shale. *Geochim. et Cosmochim. Acta*, vol.27, pp.405-410.

HOWER, J., ESLINGER, E. HOWER, M. & PERRY, A.E. 1976. Mechanism of burial metamorphism of argillaceous sediments: 1. Mineralogical and chemical evidence. *Geol. Soc. Amer. Bull.*, vol.87, no.5, pp.725-737.

HURLEY, P.M., BROOKINS, D.G., PINSON, W.H., HART, S.R. & FAIRBAIRN, H.W. 1961. K-Ar age studies of Mississippi and other river sediments. *Geol. Soc. Amer. Bull.*, vol.72, pp.1807-1816.

HURLEY, P.M., HEEZEN, B.C., PINSON, W.H. & FAIRBAIRN, H.W. 1963. K-Ar age values in pelagic sediments of the North Atlantic. *Geochim. et Cosmochim. Acta*, vol.27, pp.393-399.

HURLEY, P.M., HUNT, J.M., PINSON, W.H. & FAIRBAIRN, H.W. 1963. K-Ar age values on the clay fraction in dated shales. *Geochim. et Cosmochim. Acta*, vol.27, pp.278-284.

JACKSON, M.L. 1956. *Soil chemical analysis - advanced course.* (5th printing) published by the author, Department of Soil Science, University of Wisconsin, Madison, Wisconsin, 53706.

KULP, J.L., LONG, L.E., GRIFFIN, C.E., MILLS, A.A., LAMBERT, R.S., GILLETT, B.J. & WEBSTER, R.K. 1960. Potassium-argon and rubidium-strontium ages of some granites from Britain and Eire. *Nature*, vol.185, pp.495-497.

LANGLEY, K.M. 1978. Dating Sediments by a K-Ar Method. *Nature*, Lond., vol.276, no.5683, pp.56-57.

NIER, A.O. 1950. A re-determination of the relative abundance of the isotopes of carbon, nitrogen, oxygen, argon and potassium. *Phys. Rev.*, vol.77, pp.789-793.

PERRY, E.A. 1974. Diagenesis and the K-Ar dating of shales and clay minerals. *Geol. Soc. Amer. Bull.*, vol.85, pp.827-830.

PERRY, E.A. & HOWER, J. 1970. Burial diagenesis in Gulf Coast pelitic sediments. *Clays and Clay Minerals*, vol.18, pp.165-177.

PERRY, E.A. & HOWER, J. 1972. Late stage dehydration in deeply buried pelitic sediments. *Amer. Assoc. Petrol. Geol. Bull.*, vol.56, pp.2013-2021.

WEAVER, C.E. 1958. The effects and geological significance of potassium "fixation" by expandable clay minerals derived from muscovite, biotite, chlorite and volcanic material. *Amer. Mineral*, vol.43, pp.839-861.

WEAVER, C.E. 1965. Potassium content of illite. *Science*, vol.147, no.3658, pp.603-605.

WEAVER, C.E. 1967. Potassium illite and the ocean. *Geochim. et Cosmochim. Acta*, vol.31, pp.2181-2196.

WEAVER, C.E. & WAMPLER, J.M. 1957. Ar, illite burial. *Geol. Soc. Amer. Bull.*, vol.68, pp.1659-1682.

WEAVER, C.E. & WAMPLER, J.M. 1970. K, Ar, illite burial. *Geol. Soc. Amer. Bull.*, vol.81, pp.3423-3430.

OBITUARY

LEONARD JOHNSTON WILLS (1884-1979)

Honorary Member of the East Midlands Geological Society

When the Council of the East Midlands Geological Society inaugurated its Honorary Memberships, the principal criterion for selection for this honour was that the person concerned should have contributed significantly to knowledge of the geology of midland England. As this notice will demonstrate, Professor L.J. Wills was virtually an automatic choice; at the Annual Meeting on the 4th of February 1967, he became one of our first two Honorary Members. Much later, in 1976, the Geological Society of London followed our excellent example and he became its only British Honorary Fellow. The paragraphs that follow can only give a partial picture of a life so long and so full of scientific achievement.

Leonard Johnston Wills, known to personal friends as 'Jack" and to the scientific world at large as "LJ", was a man of the Midlands throughout his life. His paternal grandfather had founded a manufacture of edge tools at Nechells, near Birmingham; his father continued this business; and he was born in affluent circumstances in the Birmingham suburb of Erdington on the 27th February, 1884.

His interest in geology may have in part stemmed from the enthusiasms of his great uncle, Sir Alfred Wills (1828-1912). Sir Alfred was a barrister (and later a Queens Bench judge) by profession, but he was also one of the great Victorian mountaineers, making many first ascents in the Alps and helping to found the Alpine Club, of which he became third President. Sir Alfred was the author of a number of zestful accounts of his adventures (*Summer Months among the Alps*, *Wanderings in the High Alps*, etc.), all of which were to occupy honoured places in 'LJ"'s library; but he was also interested in the origin and shaping of those mountains and had translated into English one of the classic early works on their geomorphology and glaciology, Canon Rendu's *Théorie des Glaciers de la Savoie* (1840). These interests may well have been transmitted, directly or indirectly, to his great-nephew.

"LJ"'s scholastic abilities were never in doubt. He did well at his school, Uppingham, winning a scholarship to King's College, Cambridge; and his academic bent was made clear by his selection of courses, for he read Part I Natural Sciences with Part II in Geology. By the middle of 1907 he had attained a Double First, being awarded the Walsingham Medal and the Hackness Research Scholarship. Nevertheless, his comments on his education were scathing. "I learned nothing worthwhile at school," he told me. "Too much emphasis on classics. And I learned nothing worthwhile at University, either. It was only after I'd taken my degree that my education really began."

The researches that were begun in 1907, and continued for the next two years under tenure of the Harkness Scholarship, essentially determined the future course of Wills' geological career. Characteristically, they were focused close to home, on the plant and animal fossils of the Keuper sediments exposed in the building-stone quarries of the Bromsgrove district. His first paper (1907) announced these discoveries; and he was to retain interest in the continental deposits and fossils of the Upper Palaeozoic and Triassic throughout his life. Though he also wrote accounts of new ostracoderm fishes from the Downtonian, it was on terrestrial arthropods, notably the eurypterids, scorpions and pseudo-scorpions, that he became a specialist. He developed ingenious techniques for the dissection of these fossils, discovering thereby many hitherto unknown anatomical details. such as the structure of the respiratory and reproductive organs. He was concerned also with stratigraphy, in particular that of the Triassic continental sediments. He tried different methods of correlating these deposits and reconstructing the environments they represented: indeed, one of his latest papers (1976) set forth the concept of rhythmic sedimentary deposition in the West Midlands Triassic. Unfortunately the most effective tool he might have used, palynology, was developed too late to be of much service to him.

In 1909 "LJ" was elected a Fellow of King's College, an appointment he held for six years. In the same year he was appointed to the Geological Survey of Great Britain, spending four years in mapping the rocks of the Llangollen area of north Wales. Those were happy years, for in 1910 he married Maud Janet Ewing, daughter of the distinguished scientist Sir Alfred Ewing. Their son Leonard was born on the 13th October, 1911 and their daughter Penissa in 1913. In that year also, "LJ" was appointed Lecturer in Geology and Geomorphology at the University of his home town, Birmingham, under the new Head of the Department of Geology, Professor William S. Boulton.

Thus established again in the Midlands, Wills' interests progressively enlarged. He had begun with studies of the Midlands Triassic, over the next four years he had developed an interest in the Welsh Palaeozoic, and now his concerns came to embrace more recent episodes in geological history - the Pleistocene deposits of the Midlands, the advances and retreats of the glaciers across the area and the position and extent of ice-dammed meltwater lakes. One of the latter, he found, had been truly extensive, covering much of the northwest Midlands; he named it Lake Lapworth, after Birmingham's most distinguished geologist. In 1932, when Boulton retired, Wills succeeded him as Professor and Head of Department, thus becoming Charles Lapworth's direct successor.

By this time "LJ" had begun on the work which, in particular, was to earn him lasting fame - the putting-together of all available information on subsurface and surface structure with the aim of producing a sequential picture of the geological evolution of the British Isles. A series of important books resulted; *Physiographical Evolution of Great Britain* (1929), *The Palaeogeography of the Midlands* (1948), *A Palaeogeographical Atlas of the British Isles* (1951) and *Concealed Coalfields* (1956). The economic importance of this research can scarcely be overstated. The *Atlas*, with its 49 maps of Britain from the Lower Palaeozoic to the Quaternary in which tectonics, palaeogeography, sedimentary facies and glaciations were all shown, was to make Wills, as Sir Peter Kent has noted, a "household name" among petroleum geologists; and *Concealed Coalfields* was to become the bible of National Coal Board geologists. All these works included information previously unpublished; Wills was an indefatigible correspondent, adept at extracting useful information from other geologists and endearingly meticulous in acknowledging his sources in his publications.

Such research brought for him a number of honours; an Sc.D. in 1928, the award of the Wollaston Fund by the Geological Society of London in 1922, its Lyell Medal in 1936 and finally, in 1954, its highest honour, the Wollaston Medal. It is puzzling, and sad, however, that he was never elected a Fellow of the Royal Society of London - surely a deserved honour, in view of his geological achievements.

As an academic teacher, he was not always so successful. F.W. Shotton, who was a junior member of his staff from 1928 to 1936, has noted that:

> "He never had the reputation of being a good lecturer except to the brightest of his students who appreciated the quality of what he was saying. On field excursions his lean body was a bundle of energy and most students had difficulty keeping up with him. His pungent and witty aphorisms and anecdotes, so gently uttered in lecture or conversation that they could pass over the head of a listener, only became pointed when he wished to cut an obstructive student down to size - something which he rarely had to do." (1980b, p.38).

As an academic administrator, however, he was more successful: and in the four years after the war--the beginning of a happy but, alas, all too brief phase of expansion in British Universities--he established a school of geophysics at Birmingham and laid the foundation for other developments that would be carried out by his successors.

In 1949 came retirement to his home near Romsley, in the attractive area of the Clent and Lickey Hills. Within a year, he suffered a severe coronary thrombosis; yet, though this inevitably reduced his physical activity, Wills was to have another 29 years of active geological research. This was supported first by his wife and, after their happy partnership had been ended by her death in 1952, by his daughter Penissa, who kept house for her father and took care of him for 27 years. (His son Leonard died in 1976). During this time, Wills moved into a smaller house; his original home and 45 acres of beautiful land below Farley Wood, Romsley, were presented to the National Trust, for use or disposal as that authority saw fit. The Trust decided not to retain this property; but his inevitable disappointment at this decision was greatly lessened when the money from its sale brought into being the Leonard Wills Field Studies Centre in Somerset.

His research had now to be basically of an "arm-chair" sort; it was facilitated by the maintaining of strong contacts with the University of Birmingham, which had honoured him by naming him Emeritus Professor. Nevertheless he continued to do a little field work, and it was whilst examining specimens from boreholes put down by the East Worcestershire Waterworks Company that he discovered the first vertebrate footprints ever to be found in the Bunter Series of the English Midlands.

This led to my first contact with him. After reading a paper of mine on vertebrate footprints from the Nottinghamshire Triassic, he wrote to me on the 9th June, 1968, to see whether I would be interested in examining his finds. I was then spending a year at the University of Oklahoma; and it was not until some months after my return to England that I was able to respond properly to his letters. He and his daughter were involved in a car accident in November, 1968; and only in January of the following year was I eventually able to visit him and examine the footprints.

When I saw his specimens, I was not much impressed. Yes, there did appear to be imprints on a few of the slabs, but their quality seemed poor; and, in some specimens on which he claimed to see footprints, I could see nothing at all. It was more as a courtesy to a venerable geologist than from any other motive that my technician and I took the specimens back to the University of Nottingham for fuller examination. When we examined them under oblique illumination in a dark room, my astonishment was great; in every instance, the slabs did indeed bear footprints, many so extremely shallowly imprinted that I still marvel at his having perceived them in the field... A joint paper in *The Mercian Geologist* resulted (1970); and we were thereafter correspondents until 1975, when my work on English Midlands footprints came to an end.

This was only a small part of his work in these later years, however. His principal endeavours continued to be concentrated on the stratigraphy of the Triassic of the Midlands in particular and the subsurface geology of England and Wales in general. When in 1973, at the age of 89, he published a map of the buried pre-Permian formations of England and Wales, many felt this must be his last geological achievement. His heart condition was increasingly serious and he had lost the sight of one eye; surely he would spend the time remaining to him relaxing in his beautiful Worcestershire garden?

But not so; there was always something new to be learned! More and more valuable geological information was coming to light as, in the increasingly frenzied search for new British mineral resources, more and more boreholes were put down. Though, to be sure, he could no longer work for many hours a day, "LJ" continued patiently to compile data and reconstruct past topographies. Successively he published two further maps showing yet deeper levels. The first showed how the surface would appear with Upper Devonian and later formations removed (1975) and the second depicted the pre-Devonian formations. His work came to culmination when, in 1978, the Geological Society of London published a *Memoir* setting forth his interpretations of the data provided by these maps. By then, Wills was 94!

There was a last celebration when, on his 95th birthday, "LJ" was presented by the University of Birmingham with a special medal recognising his services to that University and to science. He died eleven weeks before his 96th birthday could be celebrated, on December 12th, 1979.

Acknowledgements

I am indebted to Miss Penissa Wills and to Dr. Isles Strachan for their assistance in assembling material for this notice.

References

ANON. 1920. Wills, Right Hon. Sir Alfred. In *Who was who. A companion to "Who's Who" containing the biographies of those who died during the period 1897-1916.* London: A. & C. Black (p. 769).

CLARK, RONALD 1953. *The Victorian mountaineers.* London: Batsford, 232pp.

KENT, Sir PETER 1980. L.J. Wills. *Nature*, vol.285, no.5761, p.177-178.

SHOTTON, F.W. 1980a. Professor L.J. Wills. *The Times*, London, January 5th.

SHOTTON, F.W. 1980b. The late Emeritus Professor L.J. Wills. *University of Birmingham Gazette*, vol.32, no.3, p.38-39.

WILLS, ALFRED (transl.) 1874. *Theory of the glaciers of Savoy by M. le Chanoine Rendu. To which are added the original memoir; and supplementary articles by P. G. Tait and John Ruskin. Edited, with introductory remarks, by George Forbes.* London, Macmillan, 216p.

W.A.S. Sarjeant

Emeritus Professor Leonard J. Wills in the garden of his home near Romsley, Worcestershire, Tuesday 7th January 1969.

(Photo: W.A.S. Sarjeant)

BOOK REVIEW

'A Manual of New Mineral Names 1892-1978', edited by P.G. Embrey and J.D. Fuller, 467 + x pp. British Museum Natural History, 1980. Printed by Oxford University Press. £24.00

This excellent book is really an etymological dictionary of those mineral names which have appeared, at the rate of about fifty per year, since 1892, the date of publication of the sixth edition of Dana's comprehensive 'System of Mineralogy". It has been compiled from thirty 'Lists of New Mineral Names', which were prepared by L.J. Spencer and M.H. Hey and published at the end of each volume of the Mineralogical Magazine. The 'System of Mineralogy' and 'A Manual of New Mineral Names 1892-1978' complement one another and together provide the only complete up-to-date list of mineral names.

Happily Dana, Spencer and Hey, shared and held firmly the view that one purpose of any concern about mineral nomenclature was to avoid confusion of names. Moreover they were also in agreement that the means of avoiding confusion were in the establishment of internationally recognised names based on the Roman alphabet, free from linguistic variants and the "recognition under proper restrictions of the law of priority".

The Commission on New Minerals and Mineral Names of the International Mineralogical Association has largely been the instrument whereby new mineral names are approved and most editors of reputable earth-science journals now require the Commission's approval before allowing a new name to be published. In spite of the improving situation there are still many mineral names of doubtful validity in circulation. Embrey and Fuller's manual enables us to assess their status. It contains mineral names spanning the whole range of respectability and significance; valid mineral species; artificial species; inadequately described species; synonyms; errors, variants, mistranslations and mistransliterations; unnecessary and undesirable names for gemstones, rocks and artificial products; improved names and corrected spellings; and other entries. The only exclusions appear to be trade names for artificial species and phonetic back transliterations from the Cyrillic alphabet for names that had Roman originals.

Each entry is concise and informative; each contains reference to the source material and many have instructive comments. For the working mineralogist the manual is indispensible, for the less seriously involved it is stimulating and rewarding. Reading between the lines is great fun, for example, "Goodletite is an unnecessary rock name: the limestone matrix of Burma ruby"; the reference identifies the miscreant who wants to call limestone something else. Let that be a lesson to us all.

The Manual is pleasant to use; the variety of types, the composition of the entries and their spacing make reference easy. Drs. Embrey and Fuller are to be congratulated in providing us with a volume which combines style and taste with scholarship and unquestionable authority.

R. B. Elliott

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THE MERCIAN GEOLOGIST

Journal of the East Midlands Geological Society

The journal first appeared in December 1964 and since that time 29 parts, comprising 7 volumes have been issued; the last, Vol.8, No.1, in November, 1980. The Mercian Geologist publishes articles especially on the geology of the Midlands of England, but other articles have been published which are of current interest to geology generally. Contents include original papers, review articles, biography, bibliographies, excursion reports, book reviews and the Secretary's report on Society activities.

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March 1981, pp.81-162, plates 2-5