DINANTIAN EXTRUSIVE ACTIVITY IN THE SOUTH PENNINES

by

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Summary

Dinantian extrusive activity in the South Pennines (Derbyshire) occurred in the form of a number of small volcanoes. Basaltic magma emanated from central vents recorded in the vicinity of Hopton, Bonsall, Bakewell, Taddington and Litton and inferred around Ashover, Millclose Mine, Eyam and Castleton. Lava flows and sills associated with boss-like tuff cones and sheet deposits are related to phreatomagmatic activity. The extrusive activity may have occurred on an emergent carbonate platform, however, the interplay of sedimentation and emergence peripheral to the central areas of extrusion and uplift, gave rise to complex stratigraphical sequences.

Introduction

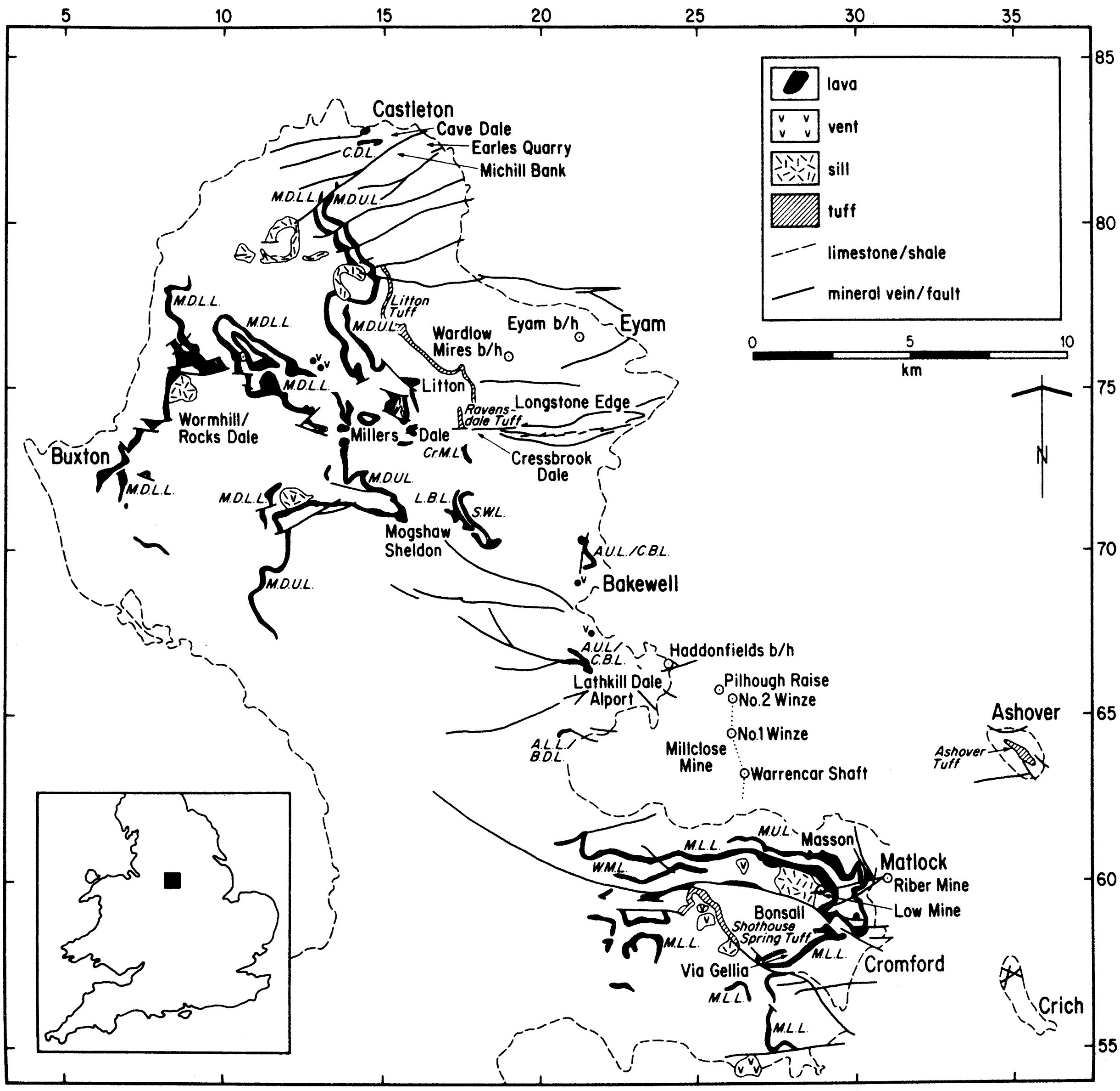
The Dinantian limestones of the South Pennines contain contemporaneous lava flows and tuff horizons together with sills, vents and rare dykes. Arnold-Bemrose (1894; 1907) provided detailed accounts of the petrography and field relationships, while Geikie (1897) enumerated the rock types. Stratigraphical complexities and subsurface distribution of the igneous rocks have been provided by Traill (1940) and Shirley (1950), general compilations by the Institute of Geological Sciences (Smith *et al.*, 1967; Stevenson & Gaunt, 1971) as well as 1:25,000 maps (Inst. geol. Sci., 1969; 1970; 1975a and b; 1976a and b; 1977). Kelman (1980) described the volcanics at Ashover while Walters and Ineson (1981) reviewed the distribution and correlation of these horizons. Text-figs. 1 and 2 show this distribution and correlation.

The terms 'lava' or 'tuff' have been, and still are, used to denote a mappable stratigraphical unit, i.e. the Miller's Dale Upper Lava or the Litton Tuff. The individual 'lavas' may contain separate lava flows as well as pyroclastic material and, in some cases, thin sedimentary intercalations. Walters and Ineson (1981) illustrated their circular to ovate outlines and indicated that the most extensive units have diameters of between 10 and 12 km with a maximum thickness of 100m. In profile they are comparable with the small basaltic shield volcanoes described by MacDonald (1972). In extent and volume they are less than, for example, the Icelandic eruptions which may extend to a diameter of 30 km and a height of 1000m, and are more comparable to the small shield eruptions centred on the Faroes which Noe-Nygaard (1968) designated as 'scutulum type'. These have a maximum diameter of 20 km and a maximum height of 250m.

As no general synthesis of the extrusive igneous activity centred on the South Pennines has been produced since Arnold-Bemrose's papers, and as recent mining and exploratory boreholes have provided new information, this paper describes the various styles of extrusive activity and erects palaeoenvironmental reconstructions.

Lavas

Nichols (1936) and Walker (1970) classified lava flows, on the basis of their internal structures and relationships, into composite, simple, compound and multiple types. A composite 'lava' is capable of subdivision into a number of distinct flows, or sets of flow units, each separated by an appreciable time interval which was sufficient for the onset of weathering or resumption of sedimentation, or marked by a period of pyroclastic activity. Simple lava flows occur as extensive flood-like extrusions and each flow is divided into an upper and a lower vesicular margin with a massive interior. If a simple flow is overlain by another lava, the whole assemblage is composite. Compound lavas are identified by having 'flow units' comparable to simple flows, the individual

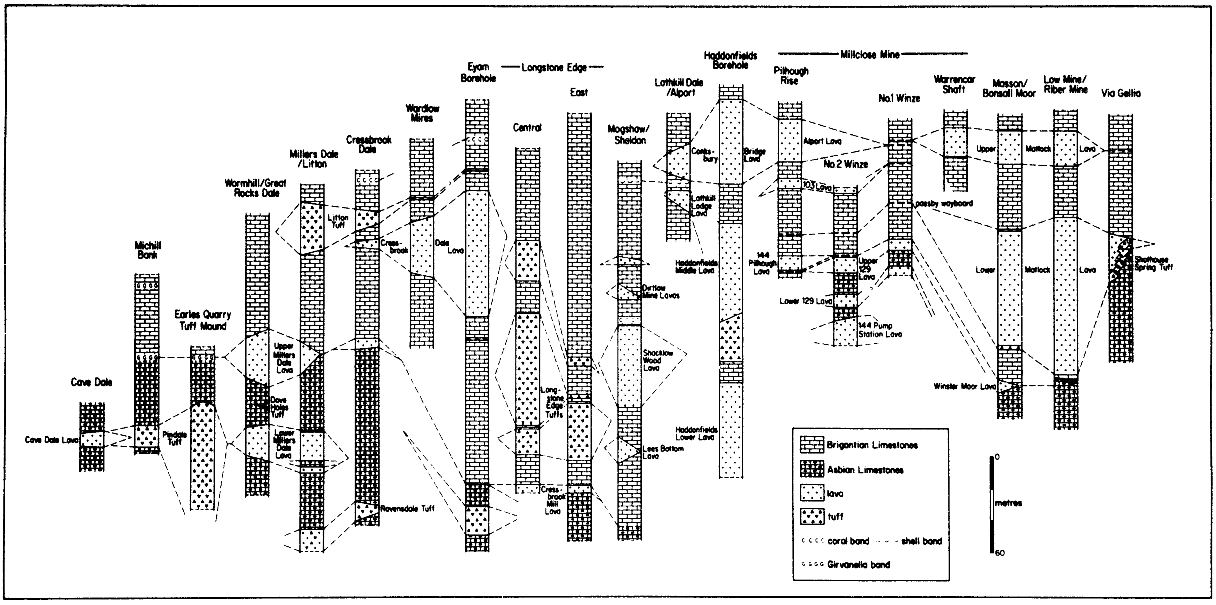


Text-fig.1. Distribution of the igneous horizons in the South Pennines.

units however are not laterally extensive. The controlling factor in differentiating simple and compound lavas is the effusion rate (Walker, 1970) where simple flows result from the more rapid effusion of material, while in compound lavas the time interval between successive units is only sufficient for a skin to form on the lower unit before it is inundated. Multiple flows are a variant of compound flows in which the time interval is such that no discrete divisions are evident, however the units are recognised by variations in the concentration, shape and size of the vesicular horizons.

The Eyam Borehole (Dunham, 1973) and the Wardlow Mires Borehole (Stevenson & Gaunt, 1971) intersected the Cressbrook Dale Lava which is poorly exposed at outcrop. Variations in the vesicular nature of the lava (text-fig. 3) indicate that it is a compound lava, for sharp contacts between highly vesicular and haematised lava as well as a 0.1m thick tuff, divides the lava into two effusive episodes.

In contrast, the Miller's Dale Lava and the Matlock Lava (text-fig. 1) are composite lavas where the 'simple' individual flow units rarely exceed 10 m in thickness. In the thinner flows rapid cooling has preserved a vesicular central zone, while in thicker flows the slower cooling has given rise to coarse holocrystalline centres characterised by fresh granular augite with a subophitic texture. An example of this type of lava is the Miller's Dale Lower Lava, the internal structures of which are shown in text-fig. 4. Boreholes at SK 103754 and SK 099762 intersected



Text-fig.2. A correlation of the igneous horizons in the South Pennines.

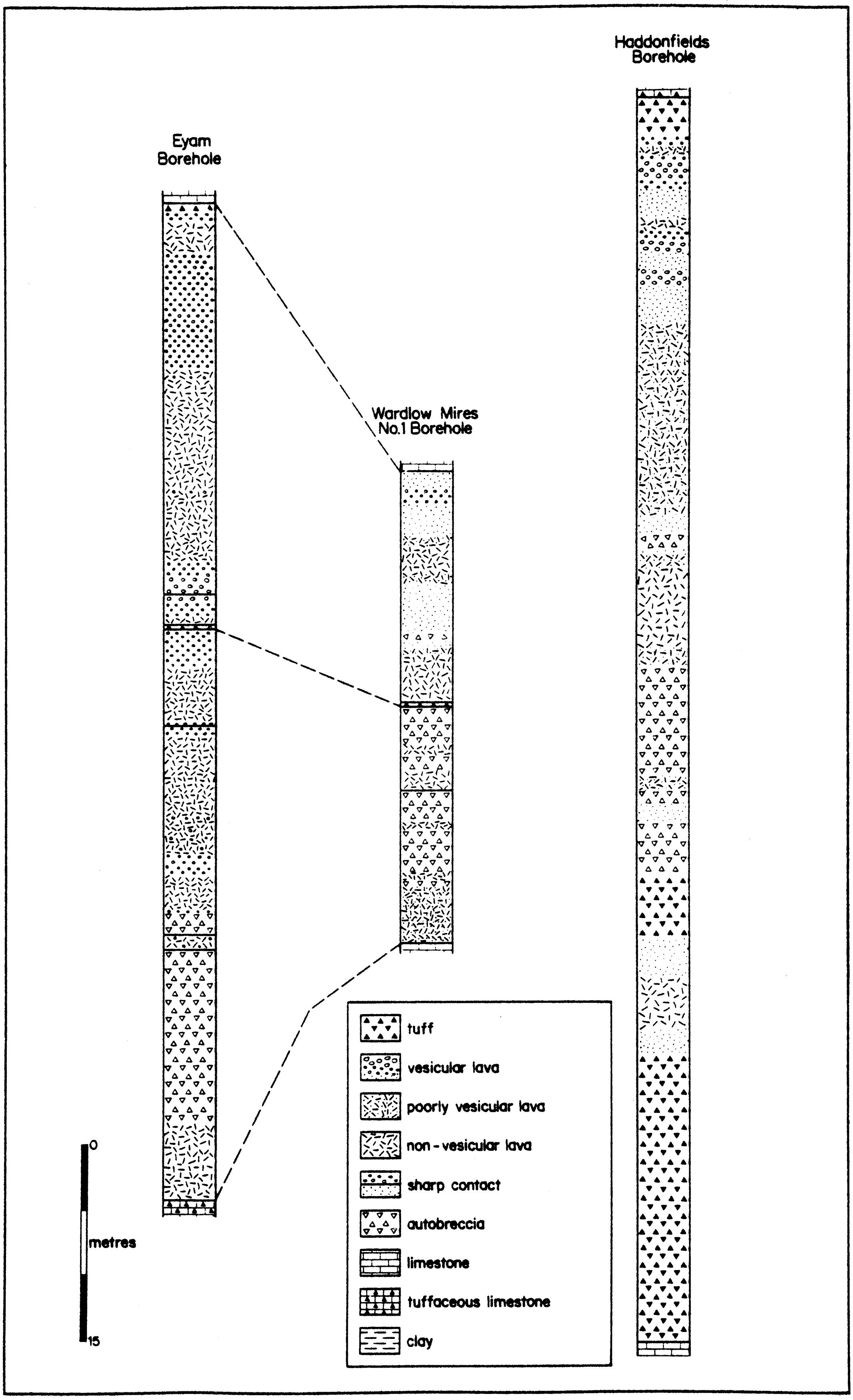
the lava and the cores showed that it is divisible into three extrusive events with a tuffaceous upper unit, while the two lower and relatively thicker units display coarse holocrystalline centres. The three flows exhibit uniform petrography in both the vesicular and the non-vesicular types. Pseudomorphed olivine microphenocrysts are set in a medium grained groundmass with occasional resorbed plagioclase phenocrysts and rare clinopyroxene microphenocrysts. Interstitial relict glass altering to clay aggregates occurs and results in a texture similar to that shown by the Haddonfields Lower Lava (text-fig. 3). Sections of the lava are exposed in three small quarries at SK 098761, near Buxton Bridge.

The Matlock Lower Lava is another example of a composite flow. The Bonsall Basalt Quarry (SK 284575) and Groaning Tor Adit (SK 283572) expose a flow unit approximately 12 m thick. The lava reaches its maximum thickness in the Masson Hill area (text-fig. 1) where a series of boreholes on Great Rake proved 99 m of lavas and tuffs (Walters, 1981). Three flows, characterised by vesicular upper and lower surfaces and separated by ash or decomposed clay, were recognised. The lower two units contain marmorised limestone and angular basaltic fragments with an agglomeratic texture. The upper unit is exposed in the opencast site on Masson Hill which has been described by Dunham (1952) and Ixer (1975).

Limestone and ash intercalations

Thin limestone and ash layers occur between flow units. Stevenson and Gaunt (1971) reported a 12 ft (3.7 m) limestone separating two flow units of the Miller's Dale Lava encountered in the Litton Dale Borehole (SK 160750). In an opencast site near Tides Low (SK 146782) the Lower Lava shows an upper flow unit, with highly vesicular margins, resting on 3 m of limestone which in turn overlies a lower but less vesicular blocky lava flow. Similar intercalations have been recorded in the Miller's Dale Upper Lava on Bole Hill (SK 108757) by the Institute of Geological Sciences (1976a) while Arnold-Bemrose (1894) reported coarse ash layers in a section of the lava at the Miller's Dale Lime Works Quarry (SK 140730) that enabled him to subdivide it into at least two units.

These examples are distinguished from the penecontemporaneous deposition of limestone with lava at the edge of a flow as described by Smith *et al.* (1967, p.18) for the Matlock Lower Lava. In that ash and limestone intercalations are not present in compound or multiple lava flows (Walker, 1970), certain lavas in the South Pennines are classed as composite flows, a suggestion initially made by Stevenson and Gaunt (1971).



Text-fig.3. Borehole sections of the Cressbrook Dale Lava in the Eyam, Wardlow Mires No.1 and Haddonfield Boreholes.

Breccias and pseudobreccias

Breccias were recorded by Ramsbottom *et al.* (1962) in the cores of the Ashover Borehole and by Walters in Ineson (1981) in the cores of the Eyam, Wardlow Mires No.1 and Haddonfields Boreholes (see text-figs. 1 and 3). The lateral extent of these breccias is not known in detail. The Haddonfields (No.11) Borehole (SK 237658) penetrated volcanics, in which breccias associated with the 'Middle Lava' overlie a sequence of inclined and graded tuffs (text-fig. 2). Walters and Ineson (1981) used this and Traill's (1940) information from Millclose Mine to suggest that in the vicinity of Rowsley a major volcanic centre may be concealed beneath the Namurian cover.

The breccias show characteristics of subaerial autobrecciation (Parsons, 1969), where friction or internal disruption of a flow produces 'monolithologic autoclastic volcanic breccias with angular, lithic unsorted fragments, usually with a central zone or lens of non-brecciated materials'. In the South Pennines the fragments are composed of either non-vesicular basalt which has been iron-stained and altered or occasionally shows evidence of chilling. The clasts are ill-sorted, and in the Cressbrook Dale Lava (text-fig. 3), the majority of the fragments do not exceed 50 mm in diameter but blocks up to a metre across are present. There is no fine grained material between the blocks and the voids are infilled with silica and chlorites while reaction rims between matrix and blocks are not seen (see plate13; fig. A). An additional feature of these breccias is that they interdigitate with unbrecciated, non-vesicular lava and appear to be related to areas of maximum lava development and local cone structures. As brecciation of a lava is a function of temperature, viscosity and strain rates as well as the rate of degassing and extrusion (MacDonald, 1972), these conditions may not have prevailed adjacent to all extrusive centres and as such breccias are not a ubiquitous feature. They are not developed, for example, adjacent to the 'central vent' of the Matlock Lava in the Masson Hill area (Walters & Ineson, 1981).

(Additional care must be taken in the interpretation of brecciated structures for 'pseudobreccias' can be produced by either the irregular iron-staining of a lava or the development of a fine net-like veining of a lava adjacent to mineral veins (see plate13; fig. B). In these instances their true origin may be determined by field relationships and transitional types within the aureole of a vein.)

Lava fronts

The slopes of the flanks of a scutulum-type activity are calculated assuming a gradual thinning of each lava flow. Although field and borehole core evidence indicates such thinning, at a number of localities lavas terminate abruptly and a flow front may explain this feature. Traill (1940) described the 144 Pump Station flow front at Millclose Mine as having pillow structures and a 'slaggy' appearance, features typical of subaqueous extrusion. Additional localities have been cited at Taddington (Cope, 1937) and near Middleton Limestone Mine (Smith *et al.*, 1967) as well as the Litton Mill flow front of the Miller's Dale Upper Lava exposed in the disused railway cutting above Litton Mill (SK 157729) and described in detail by Walkden (1977). He noted that the lava was palagonised, crudely stratified, finely brecciated in places and while not fresh, did not show features analogous with ancient weathering. As Walkden recorded (1977, p.358), the structure was similar to that of a flow front breccia formed as a result of lava entering water and shattering (Jones & Nelson, 1970). The chilling and brecciation was sufficient to halt the flow of lava and give rise to a steep flow front.

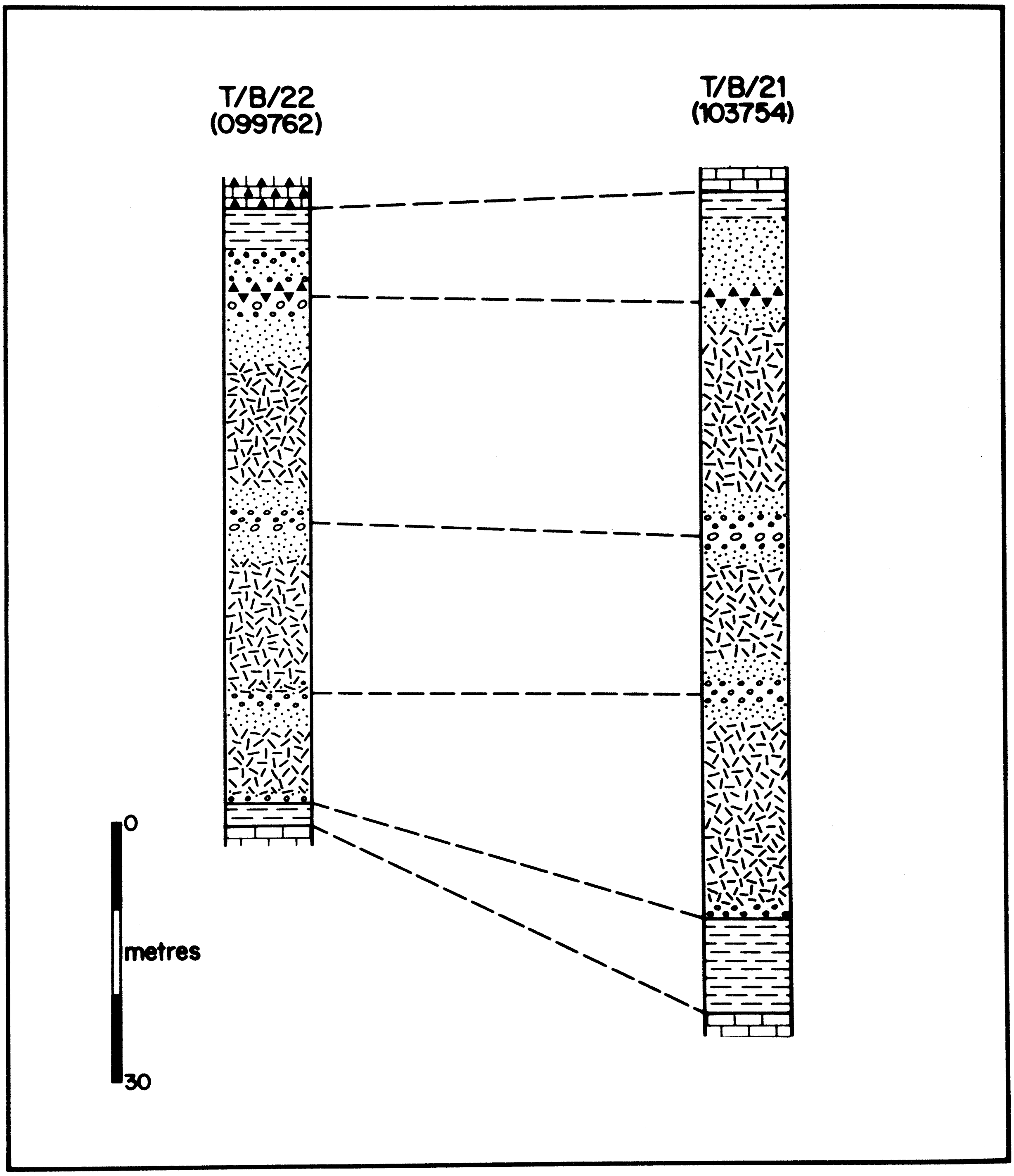
Pyroclastics

Each effusive phase contains a small but significant proportion of pyroclastic material. The lavas were either preceded and/or followed by explosive activity that resulted in extensive ash falls. As the ash deposits invariably cover a greater area than the lavas, they have enabled Walters and Ineson (1981) to suggest the correlation of lava horizons into adjacent areas. In this respect they used the Shothouse Spring, Ravensdale, Dove Holes, Pindale, Litton and Longstone Edge Tuffs which are the most extensive units.

The Dinantian stratigraphical sequence in the South Pennines is interspersed with numerous thin clay horizons which are commonly referred to as 'clay wayboards' (Walkden, 1972). They often represent emergent periods marked by palaeokarst surfaces bearing a cover of atmospheric dust-derived fossil soil (Walkden, 1972; 1974). Walkden (1972) and Somerville (1979) have demonstrated that they are typical K-bentonites derived from the degradation of volcanic ash.

Cones

The accumulation of ash around a vent forms an ash cone. The ash readily decomposes to a clay or to palagonite. If the ash cones are cemented together by the deposition of a secondary cement between the ash grains or by palagonisation, they are called tuff cones. Ash and tuff cones may resemble cinder cones, however, in the former the ejecta is thrown out at a lower angle and accumulates at greater distances from the vent than in cinder cones. They therefore have broader and lower profiles than cinder cones. MacDonald (1972) states that



Text-fig.4. Sketch sections of the Miller's Dale Lower Lava intersected in I.C.I. Boreholes T/B/21 and T/B/22 located near Tunstead, Buxton (for key see text-fig.3).

very broad steep-sided tuff cones are sometimes referred to as "tuff-rings". Although not formed at vents, littoral cones may resemble vent structures, however, they are formed by steam explosions where lava flows enter water. They are common along the shorelines of volcanic islands.

Tuff cones have been inferred or recognised at Ashover (Ramsbottom *et al.*, 1962; Kelman, 1980), Low Mine near Masson Hill (Arnold-Bemrose, 1907; Smith *et al.*, 1967), Prospect Quarry (SK 245574) near

Grangemill and in the Rowsley area (Walters & Ineson, 1981). In the northern area, the Pindale Tuff Cone has been described by Shirley and Horsfield (1940), Eden *et al*, (1964), Stevenson and Gaunt (1971) and Walters and Ineson (1981). Additional localities are located at Brook Bottom (Arnold-Bemrose, 1907; Walters & Ineson, 1981), Black Hillock Mine on Tideswell Moor (Walters, 1980), near to the Wardlow Mires No.1 Borehole (Stevenson & Gaunt, 1971) as well as beneath Longstone Edge (Walters & Ineson, 1981).

The cones contain devitrified lapilli-tuff and vitric tuff (shards). With an increase in the proportion of ash with respect to lapilli, graded tuff bedding becomes pronounced as shown in plate13; fig. C. Fragments of limestone (plate13; fig. D) derived from the vent walls are commonly associated with the coarser tuffs and an example was quoted by Shirley and Horsfield (1940) of a limestone block in excess of 1 m in diameter in the Pindale Tuff. Cinder fragments are bounded by fractured surfaces and often grade into pumice, while elongate vesicular lapilli, in possessing deformed vesicles, indicate they were fluid when ejected (see plate14;fig.A). Elliot in Ramsbottom *et al.* (1962) and Ixer (1975) reported that the lapilli were preserved in a green devitrified glass which was either relict palagonite or a clay chlorite mineral. With particular reference to the lapilli in the Pindale Tuff, euhedral pseudomorphed and partly pseudomorphed phenocrysts, in a devitrified matrix, represent plagioclase, olivine or augite. These pseudomorphs may occur as individual fragments in the tuff matrix and form a crystal-ash component. Another characteristic feature of the tuffs is the preponderance of devitrified shards indicative of a highly explosive eruption (see plate 14 ; fig. B).

Walker and Croasdale (1970) described tuffs from the subaerial Strombolain/Hawaiian eruptions and the shallow marine 'Sturtseyan type'. They indicated that achnelithic lapilli are typical of the subaerial eruptions while accretionary lapilli and large scale graded bedding characterise the shallow marine eruptions. The tuffs in the South Pennines show none of these features. The fragmentation is probably a result of phreatomagmatic activity which resulted from the interaction of the magma in the vent with the groundwater. The explosive nature of the ejecta is not in keeping with the quiet effusive activity associated with the main phase of shield construction.

A number of cone structures are characterised by the total absence or subordinate nature of lava. Typical examples are the Shothouse Spring/Grangemill Vents, Ravensdale Tuff, Litton Tuff and the Pindale Tuff (see text-figs. 1 and 2). These cones and their ejecta either occurred independently of a major extrusion episode or formed positive areas around which the lava flowed (Walters & Ineson, 1981).

The Grangemill Vents (Smith *et al.*, 1967) are spatially related to the Shothouse Spring Tuff. The tuff, at the horizon of the Matlock Lower Lava (text-fig. 2) in the Grangemill area, increases in thickness as the Matlock Lower Lava thins around the vents. The tuff may well have enveloped the lower ground around the cones formed by the vents.

The Litton Tuff is one of the largest cone structures in the area with a diameter of 6 km and a height in excess of 30 m. In profile it resembles a low angle basaltic tuff cone produced by high level phreatomagmatic activity. Stevenson and Gaunt (1971) noted that in the vicinity of the inferred vent (i.e. near Litton) a greater proportion of coarse ejecta, cinder and bombs occur. The extremities of the cone, intersected in the Wardlow Mires Borehole are repesented by a sequence of silty horizons deposited in shallow water.

The Pindale Tuff, outlined by exploratory drilling (Stevenson & Gaunt, 1971), indicates the presence of an elongate cone which may have attained a height of 30 m. The steep profile of the cone suggests that phreatomagmatic interaction was not as important as in, for example, the Litton Tuff Cone. Peripheral to the vent/s, coarse unsorted tuff pass into graded tuff, while to the north of the cone a flank eruption emitted the Cave Dale Lava. Cheshire and Bell (1977) reported that a tongue of the subaerial Cave Dale Lava entered shallow sea-water and formed a littoral cone at the site of the so-called Speedwell Vent in Castleton (SK 143 825).

Extrusion — Subaerial or Submarine

Since the lavas were first described by Geikie (1897) and Arnold-Bemrose (1894; 1907) statements or detailed arguments have proposed that they are either subaerial or submarine. Francis (1970) regarded the lavas as submarine flows while Ford (1977) said they were subaerial. Stevenson (in Chesire & Bell, 1977) stated that all the lavas were formed in a marine environment and were both preceded and followed by limestone deposition. The most detailed examination, discussion and conclusion was by Walkden (1977, p.357-8) who proposed a subaerial extrusion for the Miller's Dale Upper Lava at Litton Mills.

It is proposed that extrusive activity occurred on an emergent platform, and as such a variety of environments existed. Marginal to the platform, true pillow structures were noted and deep water facies are evident (Fearnsides & Templeman, 1932). Stevenson and Gaunt (1971) provided evidence of lavas banded with calcareous tuffs of submarine origin and implied that during the initial stages of extrusion, emergence could not be demonstrated. It was evident, however, in the upper parts of the thicker flows which may have built up above sea-level.

Walkden (1974 & 1977) has demonstrated that emergence of the platform was not always associated with extrusive activity. He noted that they are marked by potholed surfaces, crustiform textures and 'wayboard' clays. Lavas often overlie these erosional surfaces and an example was given by Traill (1940, p.204) from Millclose Mine. Likewise, the erosional surface beneath the Miller's Dale Upper Lava in Miller's Dale (Cope, 1937 and Walkden, 1977) relates to an extensive emergent period in the basal Brigantian. The Miller's Dale Lower Lava in Great Rocks Dale also overlies a strongly potholed surface infilled with 'wayboard' clay.

Further support that lavas were extruded on an emergent fully lithified carbonate platform is the absence of calcareous 'injection breccias' at the base of the individual flows. Injection breccias have been described by Strogen (1973) in Ireland, where the Carboniferous Lavas have been extruded into shallow littoral environments. The flow of lava onto an unlithified carbonate base creates steam generation and baking which results in the injection of the lime muds into the lava and the attendant brecciaion of the lava. In a section of the Cressbrook Dale Lava in the Eyam Borehole (text-fig.3) the base of the lava does not show any of the characteristic features typical of such palaeoenvironments. The presence of 'pipe-vesicles' characteristic of the flow of lava over a 'wet surface' has only been observed in the basal part of the Conksbury Bridge Lava at Conksbury Bridge.

Although extrusion may be coincidental with widespread emergence, on a local scale, the interplay between sedimentation, emergence and volcanicity was finely balanced. The transition from sedimentation to emergence is marked by tuffs with phreatomagmatic features, for example, at Low Mine (Walters & Ineson, 1981) and at Ashover (Ramsbottom *et al.*, 1962) the thin limestone intercalations demonstrate this interplay. Emergence in the central vent areas, with peripheral and periodic inundations of the lava, is illustrated by the Miller's Dale Lower Lava in the Wormhill/Great Rocks Dale area. Walters and Ineson (1981) proposed that the lava was extruded in this area, and although capable of being separated into distinct extrusive episodes (text-fig. 4), it does not contain limestone intercalations nor exhibit weathered 'boles'. Towards the periphery of the flow, limestones 3 to 4 m thick occur between the individual flows and have been located in the Litton Dale Borehole and in White Rake Opencast site (SK 146782).

The cessation of an extrusive episode, usually marked by pyroclastic activity, was followed by rapid subsidence, inundation and renewal of carbonate sedimentation. The overlying limestones exhibit thin transitional lithologies of tuffaceous limestone but only where the preceding pyroclastic activity is well developed. These horizons probably indicate a more gradual subsidence and inundation.

Conclusions

Structural, stratigraphic and palaeoenvironmental reconstructions indicate:—

1. The lavas are either composite lavas with two, three or more simple flow units or compound lavas. Multiple flows have not been recognised in the area.
2. Extrusion of lava occurred onto either a fully emergent lithified carbonate platform or an unconsolidated ash surface. In only one example, the Conksbury Bridge Lava, can extrusion have been onto an unconsolidated lime mud.
3. Volcanic breccias are recorded next to tuff cones and/or areas with the thickest lava flows. However, as they are not ubiquitous to these areas, they cannot be used to indicate the proximity of an extrusive centre.
4. Lava fronts may indicate a sub-aqueous or a sub-aerial environment or a flow entering water.
5. Tuffs and tuff cones may be related to lava outpourings or are independent of them. The fragmentation of the tuffs is due to phreatomagmatic activity.
6. The size and profile of the volcanic units compares with scutulum type activity, constructed from either a small number of individual effusive episodes or one proximal event of fluid magma. The emanative centre was a single or small number of vents.
7. Field evidence in support of these conclusions is the symmetrical outline of the lava and tuff deposits, the rarity of dykes and the correlation of known vent structures with areas of maximum 'lava' development.

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Explanation of plates 13 and 14

Plate13, Fig. A

Volcanic breccia, Cressbrook Dale Lava. Poorly sorted, angular clasts of partly chilled lava. Note absence of fine grained interstitial material. The dark matrix is silica and spherulitic chlorite intergrowths. Locality: Wardlow Mires No.1 Borehole (SK 18507553).

Plate13, Fig.B

Pseudobreccia developed in intrusive dolerite, Peak Forest. Note that fine, net-like, veining in proximity to a mineral vein has produced a texture resembling a breccia or pyroclastic rock. Locality: Near Blacklane Farm, Peak Forest (SK 102783).

Plate13, Fig.C

Graded tuff with inclined bedding from the central cone associated with the extrusion of the Cressbrook Dale Lava. Locality: Exploration Borehole, Hucklow Edge.

Plate13, Fig.D

Coarse poorly sorted analcite-tuff, with abundant inclusions of limestone fragments. Locality: as Plate13; Fig. C.

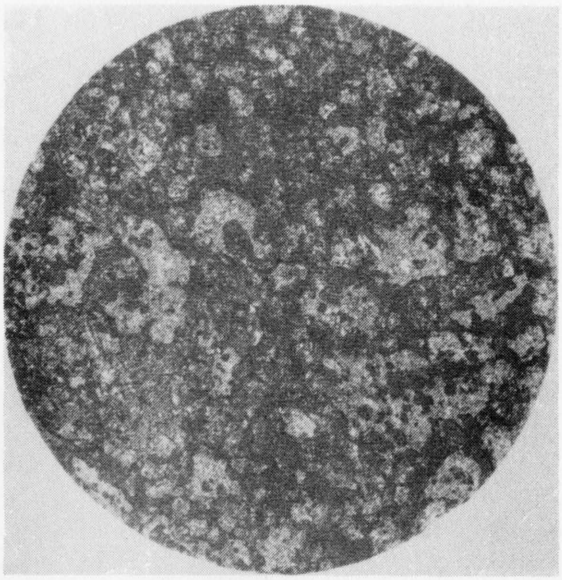
Plate14, Fig.A

Photomicrograph of deformed vesicular lapilli from the coarse tuff of Plate13; Fig.D. Large lapilli and abundant shards set in a calcitised matrix with analcite.

Plate14, Fig.B.

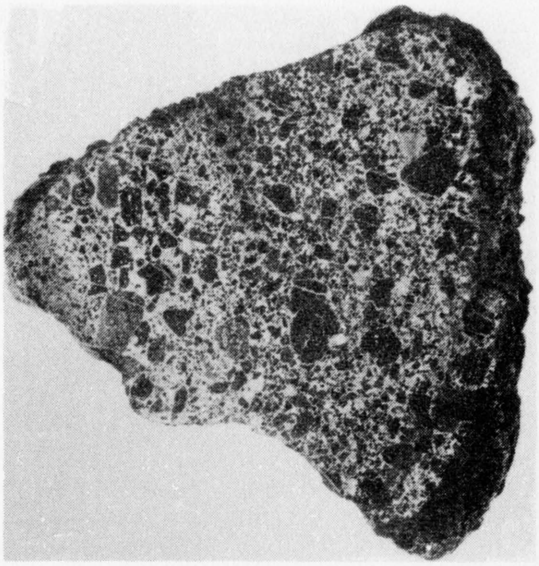
Photomicrograph of highly fragmented and devitrified tuff. Devitrified shards now replaced by chlorite set in a matrix of recrystallised calcite and analcite. Locality: as Plate13; Fig.C.

Plate 13



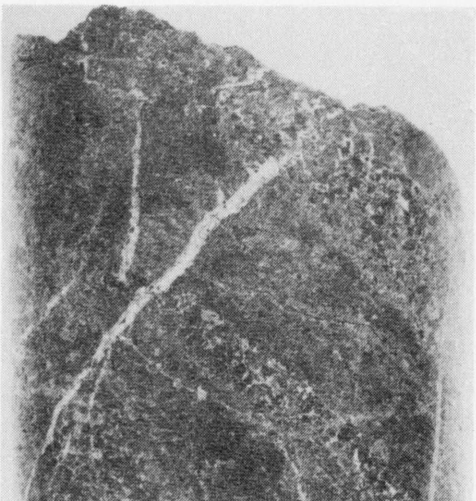
A

35 mm



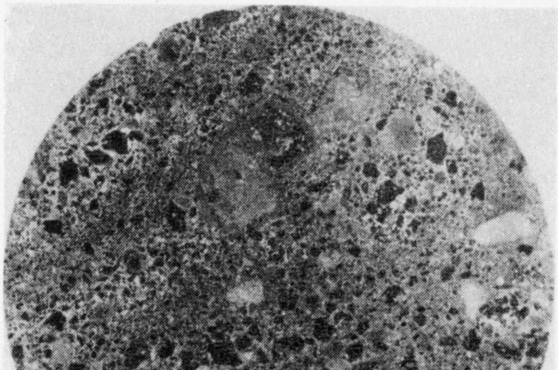
B

30 mm



C

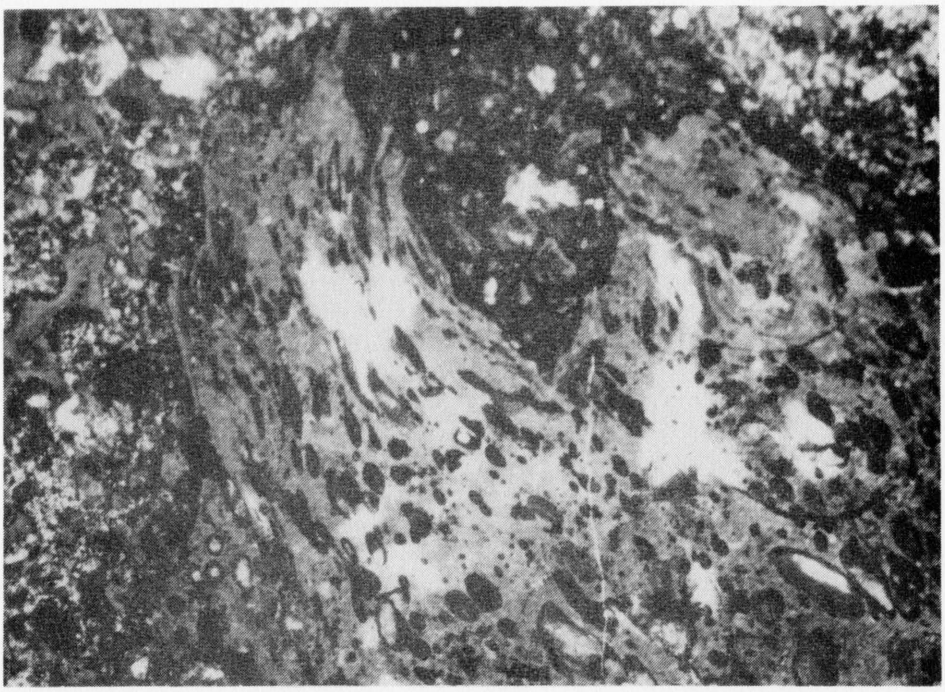
30 mm



D

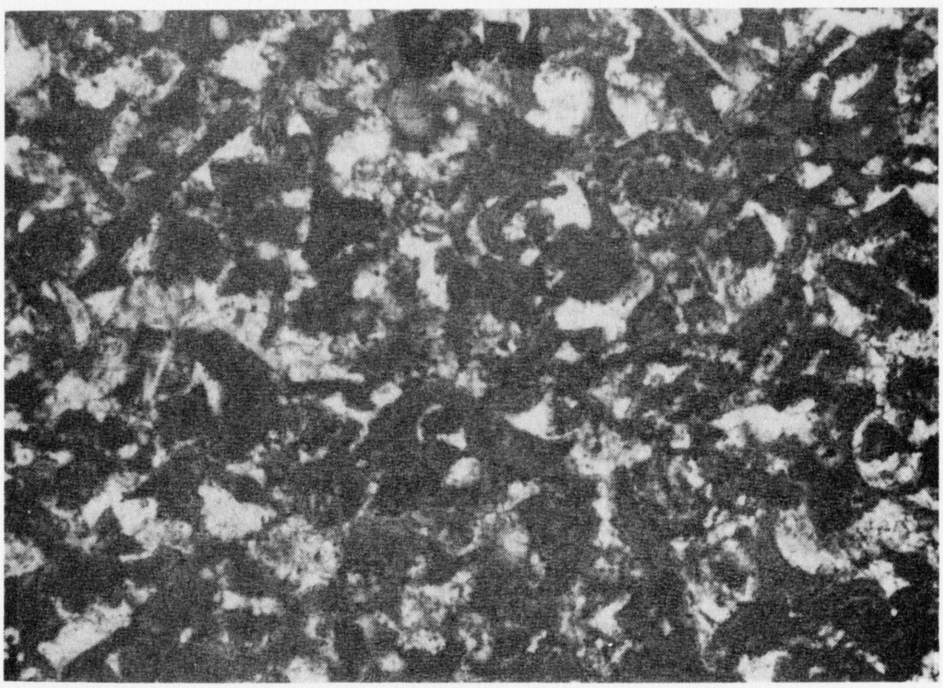
30 mm

Plate 14



A

1·0 mm



B

1·0 mm