THE SEDIMENTOLOGY OF THE CHARNIAN SUPERGROUP

by

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Summary

The sedimentary part of the Charnian Supergroup consists of a predominantly volcaniclastic sequence, indicating sporadic and then waning vulcanicity, that is interbedded with and succeeded by greywackes and pelites. Deposition of tuffs and greywackes largely of volcanigenic composition, in some instances after reworking, is largely by turbidity current and debris flow mechanisms. Slump breccias are the product of debris flows. Pelites and fine-grained tuffs accumulated largely by settling out from suspension in water.

Charnian sediments are mostly silicified and some show evidence of albitization. Current directions, mainly derived from cross-bedding and folded clasts in slump breccias suggest that the Charnian sediments accumulated in a trough with a present day trend of 054°. The Charnian Supergroup is interpreted as a fragment of a late Proterozoic island arc/basin system.

Introduction

The Charnian Supergroup (B.G.S. Sheet 155, Coalville, 1983; Moseley, 1979; Moseley and Ford, 1985; Worssam and Old, 1988) is divided stratigraphically into the Blackbrook, Maplewell and Brand Groups (Table 1) and the calc-alkaline volcanic complexes of Whitwick and Bardon Hill (Fig. 1). The dacite to basaltic andesite porphyries and volcanic breccias of Whitwick and Bardon represent the remnants of a volcanic centre and appear to be contemporaneous with part of the Maplewell Group. The Charnian sedimentary rocks are cut by dioritic intrusions of probable very late Precambrian age. In the south of Charnwood, the Southern Diorites display a discordant contact with the junction of the Brand and Maplewell Groups, and in the north-east the Northern Diorites intrude the Beacon Tuffs with resultant contact metamorphism as seen in Longcliffe and Newhurst Quarries. Revised isotopic ages (Pankhurst, 1982) of 540 ± 57 Ma for Southern Diorites, and (doubtfully) 304 ± 90 Ma for Northern Diorities, which Boulter and Yates (1987) show to be pre-cleavage, have been re-set and date either albitization or Hercynian mineralization (King, 1968). Probably the Northern and Southern Diorites are roughly contemporary and of late Precambrian age.

The Charnian Supergroup has been folded into an open asymmetric anticline plunging 15°/091°, pervaded by a later, intense slaty cleavage. Though mainly sub-parallel, the trends of the cleavage and main anticlinal axis locally diverge by up to 60°. The Charnian rocks have suffered minor re-folding, faulting, low grade regional metamorphism and mineralization and are overlain unconformably by Carboniferous, Triassic and Pleistocene sediments.

Despite recent additions to our knowledge of the age (Cribb, 1975; Pankhurst, 1982); structure (Evans, 1963; Boulter and Yates, 1987); palaeontology (Ford, 1958, 1968, 1980; Boynton, 1978; and Boynton and Ford, 1979); geochemistry (Thorpe, 1972, 1979, 1982; Le Bas, 1981, 1982) and stratigraphy (Moseley and Ford, 1985; Worssam and Old, 1988), little has been contributed on the sedimentology of these rocks. The Charnian Supergroup is composed largely of volcaniclastic, pyroclastic and epiclastic rocks. These are here defined thus: *volcaniclastic* sands and sandstones are those rich in volcanic debris which may have been derived as pyroclastic detritus or from the erosion of volcanic terrains. The *pyroclastics* were derived directly by explosive vulcanicity from the volcanic vent(s) and underwent minimal reworking. *Epiclastic material* was produced from the erosion of older rock terrains. Mature epiclastic material may have undergone more than one sedimentary cycle. The locally distinctive and spectacular rock types such as slump breccias, volcanic breccias, pull-apart breccias, conglomerates and quartz-arenites are discussed below.

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Earlier works relating to sedimentology are confined to a series of papers by Hill and Bonney (1877–1891) describing the petrography of the Charnian rocks, and Watts (1947) who described and accounted for some of their sedimentological features. A geological map of Charnwood by Bennett (1928) suggested that he might have recognised, but not appreciated, the sedimentological and stratigraphic significance of the discontinuous and recurrent nature of slump breccias, volcanic breccias and conglomerates.

Stratigraphic Note

The stratigraphy of the ancient rocks of Charnwood, originally established by Watts (1947) has recently been updated and summarised (B.G.S. Coalville Sheet 155, 1983) and reviewed in detail (Fig. 2 and Table 1) (Moseley and Ford, 1985; Worssam and Old, 1988).

Watts (1947) interpreted distinctive slump breccias, sedimentary and volcanic breccias and conglomerates as unique stratigraphic marker horizons. The variable thickness and repetitive and discontinuous nature of these lithological units has since been recognised and they are no longer regarded as reliable long-distance stratigraphic markers. However, such horizons remain valuable as the only practical means of establishing a stratigraphy and are used, in the absence of reliable regional ones, as local stratigraphic markers, (Moseley and Ford, 1985). The Charnian sequence totals over 3500 m in thickness (Table 1) and is known to extend a further 835 m downwards as a result of the Morley Lane borehole (Pharaoh & Evans, 1987).

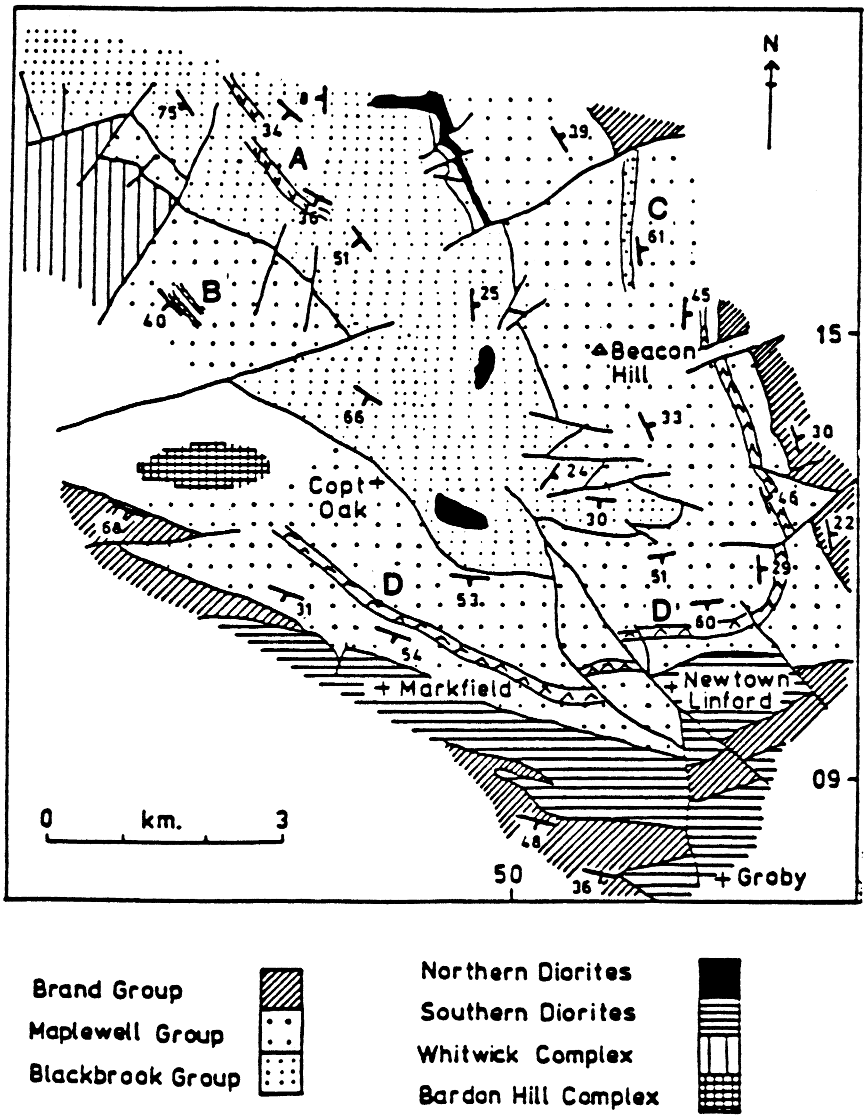

Fig. 1. Geological map of Charnwood Forest to show the distribution of the main stratigraphic divisions of the Charnian Supergroup. The outcrops of the main slump breccia horizons are indicated and A–D refer to their horizons as shown on Fig. 2.

Table 1. Stratigraphic Divisions of the Charnian Supergroup
(slightly modified from Moseley & Ford, 1985)

BRAND GROUP	Swithland Formation 260 m	No division is made into Members and Beds	Purple pelites and fine to very fine-grained greywackes. Thin discontinuous shale-pebble conglomerates are developed at and near the base of the Formation.
	Brand Hills Formation 0–95 m	Stable Pit Quartz-arenite Member	Quartz-arenites with interbedded pelites, greywackes and a breccia (9.2–94.7 m)
		Hanging Rocks Conglomerate Member	Interbedded greywackes and crystal lithic tuffs (40 m). Tuffaceous conglomerates and conglomeratic greywackes (7 m).
MAPLEWELL GROUP	Bradgate Formation 649 m	Hallgate Member 640 m	Tuffaceous pelites, pelites and dust tuffs are the dominant lithologies. Thin horizons of coarse-grained tuffs and medium-grained greywackes are developed
		Sliding Stone Slump Breccia Member 9 m	5 m of coarse-grained andesitic tuffs that grade into medium-grained tuffaceous lithic greywackes.
			4 m of slump breccias composed of clasts, sometimes distorted, of dust tuffs and tuffaceous pelites in a matrix of coarse-grained tuffs and medium-grained greywackes
	Beacon Hill Formation 1119 m	Old John Member 430 m	Tuffaceous pelites are the dominant lithology with dust tuffs and subordinate coarse-grained tuffs and greywackes, slump breccias and pull-apart breccias.
		Sandhills Lodge Member 27 m	6.4 m of coarse-grained tuffs with some lapilli tuff
			12.8 m of coarse-grained tuffs
		Beacon Tuffs Member 740 m	Coarse-grained tuffs dominant. Some dust tuffs, tuffaceous pelites and pelites
		Benscliffe Member 22 m	Main development is of lapilli tuffs, coarse-grained tuffs with some volcanic breccias. There is a finer grained development of the Member at Rocky Plantation with dust tuffs containing rotten, limonitic lapilli.
BLACKBROOK GROUP	Blackbrook Reservoir c. 610 m	None	c. 370 m of tuffaceous pelites, dust tuffs and subordinate coarse-grained tuffs
			c. 30 m of very weathered coarse-grained tuffs with subordinate tuffaceous pelites
			c. 210 m of tuffaceous pelites, dust tuffs, pelites and subordinate coarse-grained tuffs
	Ives Head Formation at least 820 m	South Quarry Slump Breccia Member c. 32 m	Slump breccia, coarse-grained tuffs and dust tuffs
		Lubcloud Greywackes Member c. 550 m	Medium- to very fine-grained greywackes are dominant. Some greywackes are tuffaceous. Subordinate coarse-grained greywackes and tuffaceous pelites
		Morley Lane Tuffs Member at least 238 m	Coarse-grained tuffs with subordinate dust tuffs and tuffaceous pelites
		Morley Lane borehole	Tuffs, pelites and sandstones, 541 m (vertical thickness). Dacitic lavas 294 m (vertical thickness)

The Charnian Sedimentary Rocks

(i) *Summary of rock-types and mineralogy*

The Blackbrook Group consists of pelites, dust tuffs and greywackes with thinner, discontinuous horizons of coarse-grained tuffs and a slump breccia. A recent borehole (Pharaoh and Evans, 1987) showed this sequence to be underlain by 530 m of tuffs, lithic sandstones and thin dacitic lavas, with a further 300 m of dacitic lavas below. The Maplewell Group is predominantly volcaniclastic, with distinctive horizons of slump breccias, pull-apart breccias, with sedimentary and volcanic breccias both of which are absent or of limited development in the underlying Blackbrook Group. The Brand Group is composed largely of epiclastic material and has only a very small pyroclastic fraction confined to the Hanging Rocks Conglomerate Member.

The proportion of volcaniclastic rocks exceeds epiclastics in volume. Many greywackes, tuffs and coarser-grained sedimentary rocks do, however, contain a mature epiclastic fraction of rounded quartz, quartzite, and less commonly quartz-feldspar and foliated quartz-chlorite grains intimately mixed with an immature fraction of feldspar, quartz and rhyolitic, andesitic and pumiceous grains. This indicates a mixing of local essential and accessory pyroclastic ejectamenta with a varied exotic lithic fraction.

The essential pyroclastic fraction consists of broken and euhedral quartz, plagioclase and orthoclase phenocrysts. Quartz phenocrysts sometimes display corrosion embayments. Trachytic, rhyolitic, pumiceous and porphyritic grains may be of both essential and accessory origin. The likely provenance of a possible metamorphic and plutonic fraction is discussed below.

The composition of the sandstones varies from highly immature greywackes, in some cases contaminated with pyroclastic ejectamenta to mature quartz-arenites (Table 2). With the exception of the Lubcloud Greywackes Member, which includes greywackes where $Q/F + R_x > 1$, the Blackbrook and Maplewell Groups are characterised by sandstones where $Q/F + R_x < 1$. Greywackes from the Lower Bradgate Formation contain no, or extremely little quartz. Except for those from Hanging Rocks Conglomerate Member, sandstones from the Brand Group consist of relatively mature greywackes ($Q/F + R_x > 1$) and thin quartz-arenites, $F/R_x - 1$, except for those sandstones in the Lubcloud Greywacke and Hanging Rocks Conglomerate Members where F/R_x varies from < 0.5 to > 3.5, and in the Stable Pit Quartz-arenite Member and Swithland Formation where $F/R_x < 1$. (Q = quartz; F = feldspar; R_x = rock fragments: the formulae using these are based on Pettijohn (1975) and are a measure of the proportions of components. $Q/F + R_x$ is an approximate measure of compositional maturity, and F/R_x reflects provenance where feldspar grains are characteristic of a deep-seated or plutonic provenance while supracrustal rocks are fine-grained and yield sand-sized rock fragments). The composition of the tuffs ranges from rhyolitic to andesitic. Those from the Blackbrook Group are rhyolitic or rhyodacitic, whereas Maplewell tuffs vary from rhyolitic to andesitic (Table 3). The total mineralogy and geochemistry of these pyroclasts suggests that predominantly acidic volcanism during Blackbrook times gave way to more intermediate activity, with a possible bimodal rhyolite/rhyodacite—andesite association during Maplewell times.

(ii) *Diagenesis and metamorphism*

Many of the Charnian sedimentary rocks appear to lie on the threshold of high grade diagenesis and very low grade regional metamorphism for they retain diagenetic features but are cut by a penetrative slaty cleavage in which muscovite is sparsely developed.

Original clay minerals and those which were the products of decomposition of unstable volcanic material have been entirely reconstituted to chlorite and lesser amounts of muscovite and biotite. These phyllosilicates are either non-orientated or developed in the plane of the cleavage. Rarely some muscovite, which may be detrital, is aligned with the bedding.

The earliest and most intense silicification is strongly developed in the very fine-grained sedimentary rocks of the Blackbrook Group and Beacon Hill Formation. This has formed fine, micro-crystalline quartz aggregates that smother both primary detrital grains and the secondary chlorite and muscovite. Throughout the Charnian the more acid rocks show the greater degree of silicification.

Some of the secondary silica may have been derived from the devitrification and recrystallisation of rhyolite grains and glass. Possible evidence for this occurs in much coarser-grained tuffs where some rhyolitic lapilli, now recrystallised to form interlocking quartz-albite mosaics, blend into their silicified matrices.

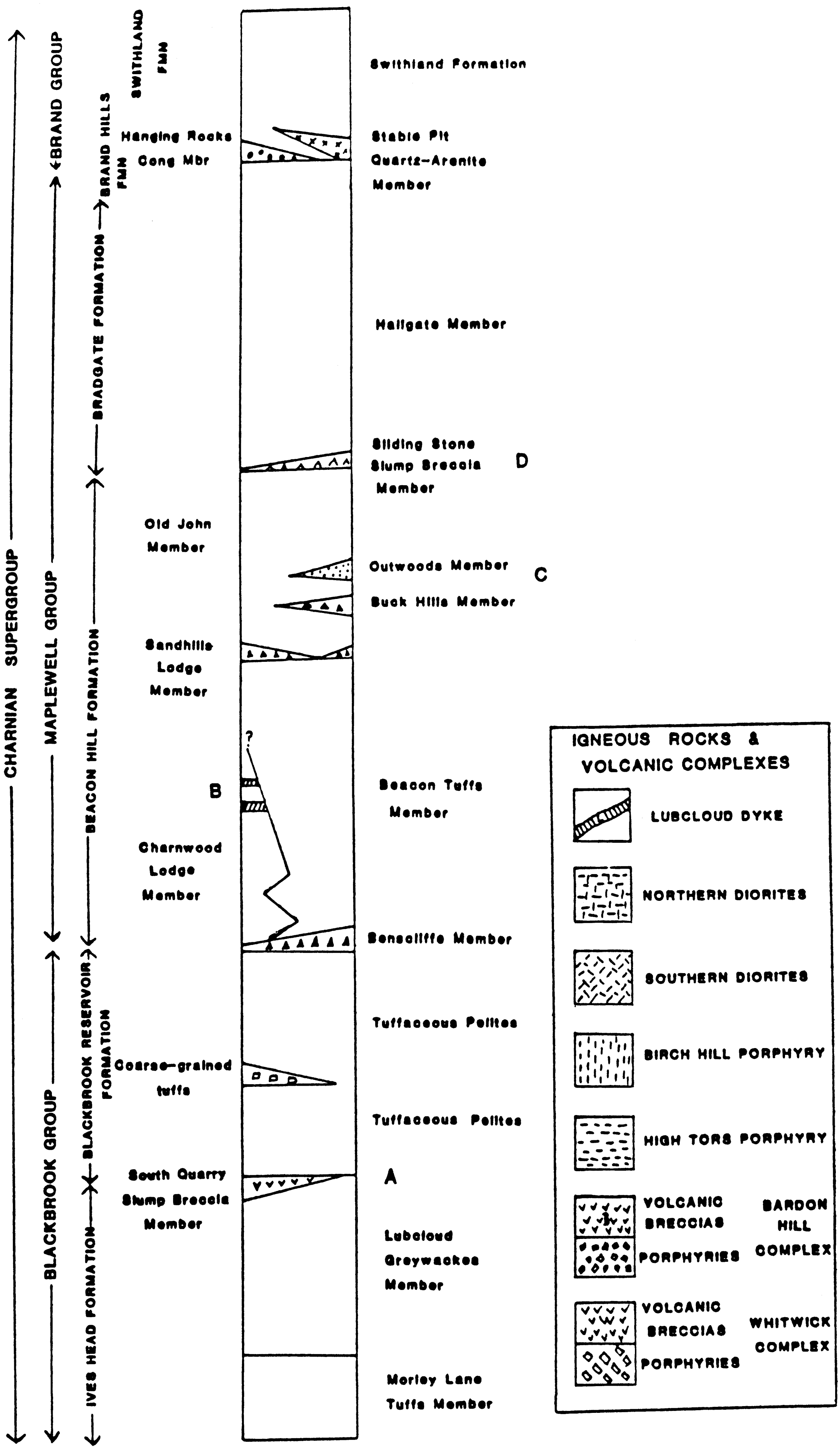

Fig. 2. Stratigraphic column and classification of the Charnian Supergroup with the main slump breccia horizons marked A–D.

Table 2. Modal analyses of sandstones from the Charnian Supergroup

	1	2	3	4	5	6	7	8	9
Quartz	19.28	22.02	16.67	21.43	13.05	12.38	16.89		11.04
Orthoclase	9.86	8.54	4.63	15.47	18.98	9.52	17.70	4.84	6.23
Albite						0.95	0.81	0.96	
Oligoclase	2.14	1.80	0.62	3.57	7.12	1.92	6.44	4.81	1.39
Andesine	0.71	4.50	0.93	1.00	1.18	1.91	3.19	3.87	0.57
Igneous				3.99	12.95	0.95	15.29	4.87	2.55
Metamorphic	0.65				4.75	3.47	5.54	2.90	1.48
Sedimentary									0.85
Others	27.36	3.14	2.15	4.54	11.32	8.90	4.14	7.75	5.89
Matrix	40	60	75	50	30	60	30	70	70
$Q/F+R_x$	0.47	1.22	2.00	0.75	0.23	0.45	0.32		0.58
F/R_x	0.36	4.72	2.84	2.35	0.92	1.07	1.13	0.93	0.76

1–3 Lubcloud Greywackes Member

1 T.S.* 75002 Coarse-grained lithic greywacke
Ives Head Hill (SK 4772.1702)

2 T.S. 75001 Fine- to very fine-grained greywacke
Ives Head Hill (SK 4771.1701)

3 T.S. 75005 Very fine-grained greywacke
Fenny Bank Farm (SK 4644.1810)

4 Beacon Tuffs Member
T.S. 75046 Very fine-grained tuffaceous greywacke
Benscliffe Wood (SK 5144.1245)

5–6 Sandhills Lodge Member

5 T.S. 75056 Medium- to fine-grained tuffaceous lithic greywacke
Hunts Hill (SK 5347.1164)

6 T.S. 75050 Very fine-grained greywacke
Sandhills Lodge (SK 5020.1101)

7 Old John Member
T.S. 75085 Medium- to very fine-grained tuffaceous lithic greywacke
Warren Hill (SK 5277.1179)

8 Sliding Stone Slump Breccia Member
T.S. 75093 Medium-grained tuffaceous lithic greywacke
Hallgates (SK 5340.1156)

9–13 Hanging Rocks Conglomeratic Member

9 T.S. 75110 Very coarse- to very fine-grained lithic greywacke
Charnwood Forest Golf Course (SK 5244.1506)

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*T.S. 75000–75200 University of Leicester Geology Department thin section accession number.

Table 2 continued

	10	11	12	13	14	15	16	17	18
Quartz	9.65	18.18	25.89	18.98	86.01	67.06	48.79	29.52	31.18
Orthoclase	9.41	14.28	7.90	16.67			0.56	7.83	0.92
Albite		1.31							
Oligoclase	2.72	4.54	2.72	3.52					
Andesine			0.63	2.36				0.60	
Igneous	0.51	3.89	9.80	9.23				5.73	7.65
Metamorphic	0.74	1.94	2.84	3.46	3.99	11.94	3.37	1.81	10.59
Sedimentary			3.25						0.59
Others	1.93	5.86	6.97	5.78		1.00	7.28	4.51	9.07
Matrix	75	50	40	10	20	40	50	40	
$Q/F+R_x$	0.63	0.57	0.65	0.46	21.52	5.18	4.35	1.44	1.08
F/R_x	3.77	1.72	0.49	1.22			0.05	0.70	0.03

9–13 Hanging Rocks Conglomerate Member (continued)

10 T.S. 75109 Very fine-grained felspathic greywacke
Charnwood Forest Golf Course (SK 5245.1507)

11 T.S. 75117 Matrix of a conglomerate. Very coarse- to very fine-grained tuffaceous greywacke
Bradgate Park (SK 5418.1098) (not in situ)

12 T.S. 75111 Matrix of a conglomerate. Very coarse- to very fine-grained lithic greywacke
Charnwood Forest Golf Course (SK 5245.1498)

13 T.S. 75115 Very coarse- to very fine-grained tuffaceous lithic greywacke
Bradgate Park (SK 5421.1097)

14–16 Stable Pit Quartz-arenite Member

14 T.S. 75124 Medium-grained quartz-arenite
Deer Park Spinney (SK 5374.1051)

15 T.S. 75131 Coarse- to medium-grained greywacke
Stable Pit (SK 5341.0996)

16 T.S. 75129 Medium-grained greywacke
The Brand (SK 5348.1331)

17–18 Swithland Formation

17 T.S. 75140 Very fine-grained lithic greywacke
Swithland Wood (SK 5381.1290)

18 T.S. 75136 Medium- to very fine-grained lithic greywacke
Woodhouse Eaves (SK 5315.1411)

Table 3. Modal analyses of tuffs from the Charnian Supergroup

	1	2	3	4	5	6	7	8	9
Quartz	25.61	0.78	12.14	9.60	0.48	2.62	8.05	3.74	2.61
Orthoclase	48.24	15.96	13.13	3.40	20.00	20.09	14.94	21.76	10.08
Albite	2.44	0.74	2.25	1.20	1.17	0.68	5.17		0.75
Oligoclase	18.30	7.60	4.44	2.00	8.24	11.68	9.77	2.50	8.21
Andesine	1.24	6.84	1.73	1.00	7.64	4.56	5.75	8.27	1.86
Labradorite						0.41		1.23	
Igneous		0.80	2.63	1.80	0.49	9.77	2.30	11.02	1.14
Metamorphic		0.76	2.10	0.40			1.72	4.28	
Other lithic	4.17	1.52	1.58	0.60	11.98	5.19	2.30	7.20	0.35
Matrix		65	60	80	50	45	50	40	75

1–3 Morley Lane Tuffs Member

1 T.S.* 75000 Coarse-grained rhyolitic tuff
Morley Lane Quarry (SK 4764.1787)

2–5 Benscliffe Member

2 T.S. 75027 Coarse- to fine-grained trachyandesitic tuff
Strawberry Hill Plantation (SK 4560.1710)

3 T.S. 75034 Medium- to very fine-grained rhyolitic tuff
Collier Hill (SK 4684.1583)

4 T.S. 75040 Fine- to very fine-grained rhyodacitic tuff
Rocky Plantation (SK 4938.1183)

5 T.S. 75150 Coarse- to very fine-grained trachyandesitic tuff
Whittle Hill (SK 4984.1580)

6–7 Beacon Tuffs Member

6 T.S. 75074 Fine-grained trachyandesitic tuff
Beacon Hill (SK 5091.1487)

7 T.S. 75043 Coarse- to medium-grained rhyodacitic tuff
Abell's Wood (SK 5190.1285)

8 Buck Hills Member
T.S. 75058 Medium- to very fine-grained trachytic tuff
Buck Hills (SK 5102.1624)

9 Outwoods Member
T.S. 75061 Very fine-grained trachyandesitic tuff
Outwoods (SK 5102.1624)

Table 3 continued

	10	11	12	13	14	15	16	17
Quartz	14.21			7.23	10.88			0.01
Orthoclase	20.00	8.60	15.29	15.90	21.80	6.25	5.26	14.32
Albite	1.04	2.72	4.29	3.12	5.19	1.10	1.32	1.14
Oligoclase	11.06	9.74	12.00	9.63	5.20	4.41	5.92	13.18
Andesine	2.11	5.38	5.28	2.41	2.60	2.55	3.29	1.72
Labradorite					0.52			
Igneous	5.79	12.07	13.71	11.57	6.74	4.05	5.26	14.96
Metamorphic	1.58	1.72	3.43	5.06		0.74	0.66	0.06
Other lithic	4.21	9.77	6.00	5.08	2.07	5.90	3.19	9.61
Matrix	40	50	40	40	45	75	75	45

10–14 Old John Member

10 T.S. 75081 Coarse- to very fine-grained rhyodacitic tuff
Broombriggs (SK 5250.1438)

11 T.S. 75083 Fine- to very fine-grained andesitic crystal lithic tuff
Windmill Hill (SK 5262.1431)

12 T.S. 75082 Medium-grained trachyandesitic crystal lithic tuff
Windmill Hill (SK 5261.1431)

13 T.S. 75069 Medium- to very fine-grained rhyodacitic crystal
Ulverscroft Mill (SK 5144.1078)

14 T.S. 75065 Fine-grained rhyolitic tuff
Greystones (SK 4833.1178)

15–16 Sliding Stone Slump Breccia Member

15 T.S. 75089 Medium-grained trachyandesitic tuff
Raunscliffe (SK 4845.1093)

16 T.S. 75091 Fine-grained andesitic tuff
Warren Hill (SK 5318.1188)

17 Hanging Rocks Conglomerate Member
T.S. 75108 Coarse- to fine-grained trachyandesitic crystal lithic tuff
Charnwood Forest Golf Course (SK 5243.1505)

The devitrification of shards from a horizon in the Beacon Tuffs Member (SK 5089 1484) post-dates the main silicification. Evidence for this is empty, Y-shaped cavities, that represent the earliest existence of glass shards; a few of these cavities are partially silicified suggesting a second, far less intense silicification. Thin quartz veins commonly cut rocks such as these pointing to a third, minor phase of silicification. Where the silicification is very intense the fine-grained rocks adopt a tough, splintery, hornfels-like character.

Secondary hematisation and silicification of cleavage planes is common, especially where fine, incipient fractures are developed parallel to the alignment of phyllosilicates and detrital grains. Secondary epidote, possibly of hydrothermal origin, occurs in all Charnian rocks but tends to be more abundant in the coarser-grained lithologies. Limonite is a common weathering product.

(iii) *Geochemical identification of fine-grained sedimentary rocks*

Sedimentary rocks of clay to coarse silt grade occur throughout the Charnian Supergroup, often comprising significant thicknesses in some stratigraphic units (B.G.S. Sheet 155, 1983; Moseley and Ford, 1985, table 1). In the past such rocks from the Blackbrook and Maplewell Groups have attracted much casual interest and have been variously described as honestones, hornstones, procellaneous ash and deposits of fine volcanic dust (Watts, 1947). Whereas most are now readily identified by optical methods as dust tuffs, pelites or tuffaceous pelites, this procedure cannot be applied when the products of diagenesis, cleavage formation and weathering have considerably changed and obscured primary mineralogical and textural features. In these cases chemical analysis has proved useful in distinguishing between pyroclastic and epiclastic sediments (see also Pharaoh et al. 1987). X-ray fluorescence and electron microprobe analyses for major elements were carried out on representative rocks selected from various stratigraphic horizons, and compared with analyses of known pelites and dust tuffs (Table 4). In interpreting these analyses the effects of the post-depositional change described above were carefully considered.

The percentage FeO^T in Charnian rocks may be enhanced by the secondary hematite that impregnates cleavage planes. (FeO^T = total for iron oxides expressed as FeO, as analyses did not distinguish between FeO and Fe_2O_3). Specimens from the Blackbrook Group (q, r^1 and r^2) may be compared with two similar rocks (g and h). Charnian rocks (l and m) provided lower values for Al_2O_3/FeO^T + MgO than those obtained from averages of pelitic rocks (a-d). This is attributed to rock l being of basaltic andesite composition, the FeO^T + MgO value being inflated by secondary limonite and epidote. In rock m, unexpectedly high MgO and low CaO values may indicate an original silicic pelite contaminated by andesitic tuff.

Plotted on a total alkali—silica diagram, the chemical data for the Charnian volcanic rocks, given in Table 4, suggest that the majority correspond to normal andesites, dacites and rhyolites such as occur in calc-alkaline volcanic island-arcs (Fig. 3) (Thorpe, 1982; Le Bas et al. 1986). The particular style of island-arc volcanics

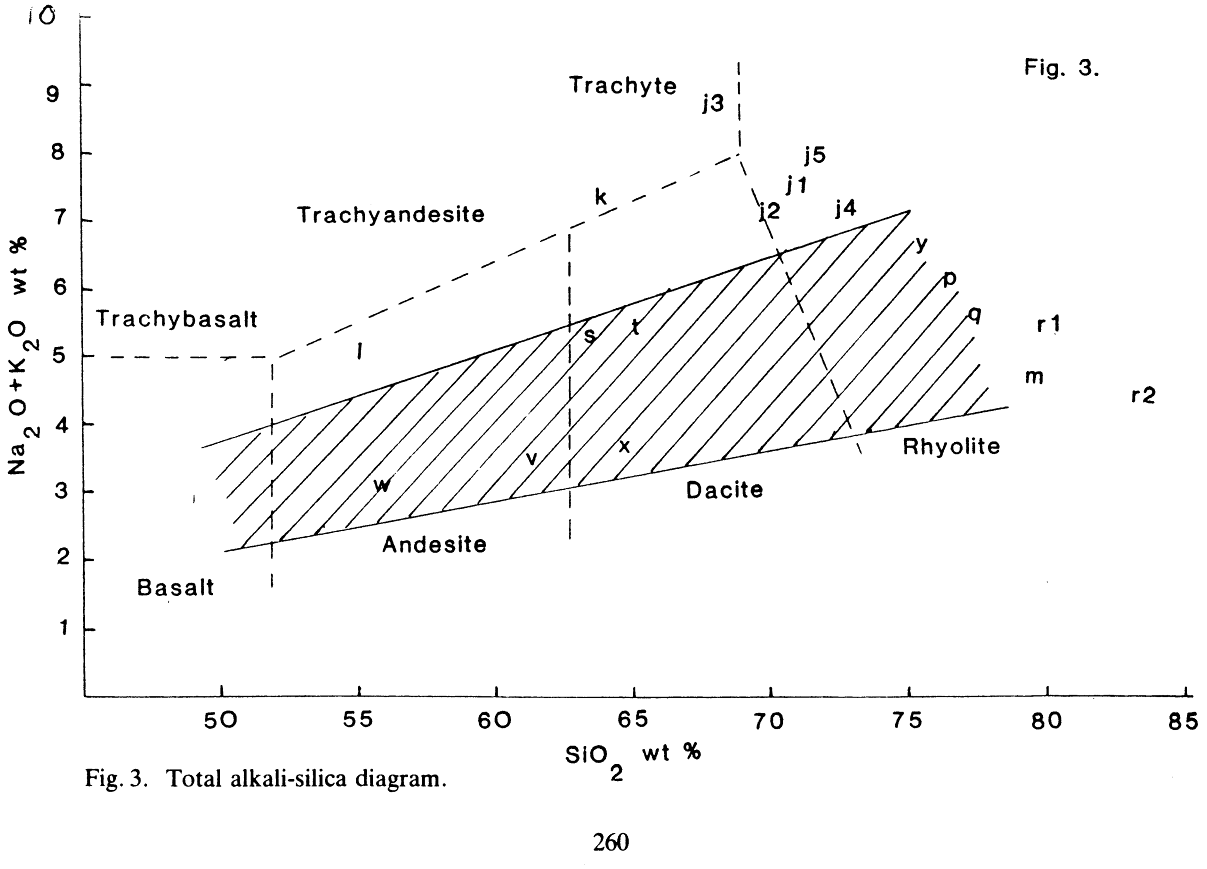

Fig. 3. Total alkali-silica diagram.

becomes apparent when the data are plotted on a K_2O– SiO_2 diagram (Fig. 4). Most plot in the low-K field typical of the outer arc volcanic products of island-arc calc-alkaline magmatism. However, if the Na_2O/K_2O ratio is considered, then it is seen (Fig. 5) that some of the Charnian rocks do not follow the normal calc-alkaline trend which is indicated by the shaded area; instead several have unusually high Na_2O contents and a few have high K_2O.

Considering each analysed Charnian sample listed in Table 4, the following interpretations can be made. The five analyses j^1 to j^5 are rhyolitic except for the alkalis. They have high Na_2O and low K_2O, and evidently have been albitized as can be deduced from the petrography. Sample *k* has also been albitized but its bulk chemistry suggests it was a dacite prior to albitization.

Sample *l* is a basaltic andesitic tuff surprisingly rich in K_2O. The K_2O content is inappropriate to the geochemistry of the remainder of the Charnian volcanic rocks, and the potassic character is considered most likely to be because it occurs not far from the intrusive contact of the markfieldite (a potassic diorite) and was probably affected by fluids from it. Sample *n* on the other hand appears to be a rhyolitic tuff, and its high K_2O content may be attributed to pelitic material of composition *m* mixed into this epiclastic rock. Sample *p* is another albitized rhyolite, but rhyolite *q* is unaltered. Sample r^1 is both albitized and silicified whereas r^2 is silicified only; both were dacites or rhyolites prior to the alteration. There is some evidence of propylitisation at Bardon Hill Quarry where some porphyries contain feldspars partly altered to an epidote + chlorite + quartz ± calcite mineral assemblage.

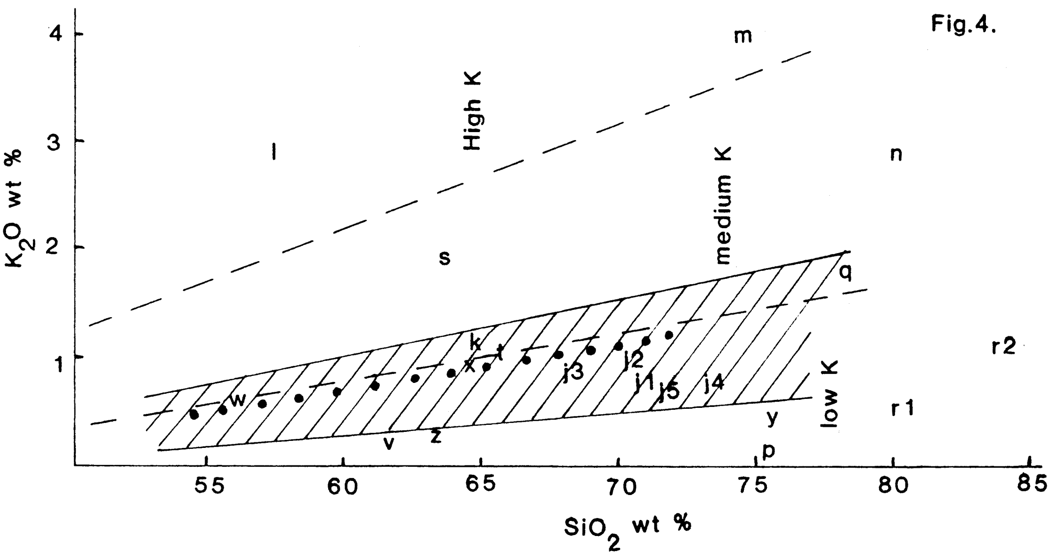

Fig. 4. Potassium oxide-silica diagram.

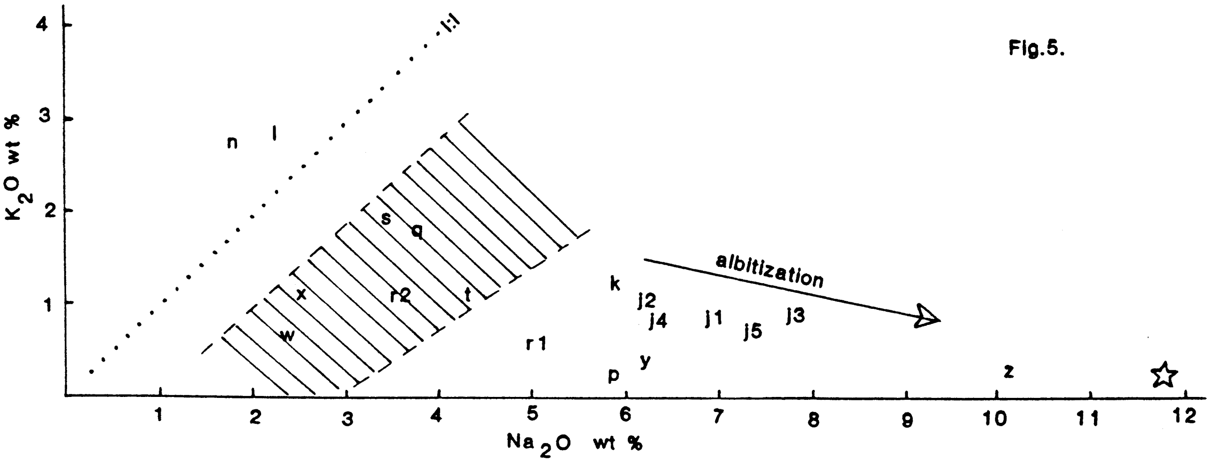

Fig. 5. Potassium oxide-sodium oxide diagram.

Since sample *s* comes from the porphyroids of Whitwick, the enrichment in K_2O could be the result of potassic fluids circulating beneath high level propylitic alteration above the Whitwick intrusive centre. Such propylitic alteration, usually associated with copper mineralization, is well known above dacite porphyry centres. Samples *t*, *v*, *w* and *x* are relatively unaltered andesites and dacites, but *y* and *z* are strongly albitized like the *j* samples.

These limited data indicate that three processes of K and Na addition are apparent in Charnwood:

1. K-metasomatism around the markfieldite intrusion.
2. Mild K-enrichment at the Whitwick intrusive centre possibly from beneath a former covering zone of propylitic alteration now removed by erosion.
3. Variable degrees of albitization which have affected much of the Charnian.

Albitization is particularly apparent in the Hallgate area, in some of the beds of the Blackbrook Formation and in some of the blocks in the 'Bomb Rocks' of Charnwood Lodge, which perhaps are derived from the underlying Blackbrook Formation. Since alibitization is a common phenomenon in island-arc volcanic rocks, the original source of the Na for the albitization is most likely to be marine water trapped in the pores of the sediments formed at the time of the Charnian pyroclastic and epiclastic action, which would also have been a period of rapid deposition.

Key to table 4

*	Total Fe expressed as FeO.
+	Total Fe expressed as Fe_2O_3.
a	Average shale (Clarke, 1924, p. 24; Pettijohn, 1975, Table 61, p. 334. As quoted by Pettijohn 0.64% SO_3 and 0.80% C are included giving a total of 99.95%).
b	Composite sample of 51 Palaeozoic shales (Clarke, 1924, p. 552; Pettijohn, 1975, Table 61, p. 334, also includes 0.58% SO_3, 0.88% C and 0.04% BaO giving a total of 100.46%).
c	Average of 33 analyses of Precambrian shales (Nanz, 1953; Pettijohn, 1975, Table 61, p. 334 also includes 0.28% SO_3, 1.18% C and 1.98% FeS_2 giving a total of 100.00).
d	Average of two Longmyndian shales, Greig et al. (1968).
e	Rhyolite Tuff (Peru), Jenks and Goldich (1956).
f	Andesitic Pumice (Japan), Yagi (1962).
g	Rhyolite tuff from John Day Formation, Pettijohn, p. 305 (1975).
h	Buxton Rock, Rhyolite Dust Tuff at base of Burway Group, Eastern Longmyndian, Greig et al. (1968).
j–r	*Charnian sedimentary rocks*
j^a	Average of 5 samples of $j(j^1 - j^5)$
j	Rhyolitic dust tuff, Hallgate Formation, Hallgate Reservoir site (SK 5356.1155).
k	Dacitic dust tuff, Old John Member, Charnwood Forest Golf Course (SK 5222.1554).
l	Basaltic andesitic dust tuff, Old John Member, A50 Markfield bypass (SK 4863.1094).
m	Pelite, Sandhills Lodge Member, Sandhills Lodge, (SK 5026.1099).
n	Tuffaceous pelite. Beacon Tuffs Member. Beacon Hill, (SK 5090.1488).
p	Acid dust tuff, Blackbrook Reservoir Formation, Newhurst Quarry (SK 4844.1806).
q	Acid dust tuff, Blackbrook Reservoir Formation, Ringing Hill (SK 4508.1844).
r^1, r^2	Acid dust tuffs, Blackbrook Reservoir Formation, Blackbrook Reservoir (SK 4562.1799).
s–z	*Charnian porphyries and volcanic breccias*
s	Average of four quartz-felspar porphyries. Whitick.
t	Dacitic quartz-porphyry. Bardon Hill Quarry.
v	Average of three blocks of andesitic porphyry from volcanic breccia. Bardon Hill Quarry.
w	Andesitic matrix of volcanic breccia, Charnwood Lodge.
x	Dacitic matrix of volcanic breccia, Charnwood Lodge.
y	Average of three porphyry blocks from a volcanic breccia.
z	Porphyry block from Charnwood Lodge.
j (1–5)	Electron microprobe, Leicester.
k–z	XRF, Birmingham.

Table 4. Comparative geochemical analyses of selected fine-grained rocks, volcanic breccias and porphyries in the Charnian Supergroup

Wt%	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	j^1	j^2
SiO_2	58.10	60.15	56.30	61.95	70.81	63.53	70.40	72.47	71.11	70.60
TiO_2	0.65	0.76	0.77	0.66	0.19	0.75	0.21	0.18	0.49	0.33
Al_2O_3	15.40	16.45	17.24	18.57	13.12	16.01	13.65	14.88	13.76	13.32
Fe_2O_3	4.02	4.04	3.83	4.41	1.11	2.50	1.18	0.81		
FeO	2.45	2.90	5.09	2.96	0.06	2.81	1.81	2.27	2.49*	3.05*
MgO	2.44	2.32	2.54	2.13	0.35	1.44	0.07	0.83	0.77	0.96
CaO	3.11	1.41	1.00	0.62	1.05	4.84	1.58	0.62	1.63	1.98
Na_2O	1.30	1.01	1.23	1.90	4.92	4.29	3.76	4.08	6.98	6.11
K_2O	3.24	3.60	3.79	3.19	4.20	0.84	3.90	1.95	0.70	0.92
P_2O_5	0.17	0.15	0.14	tr	-	-	0.06	-		
H_2O	5.00	4.71	3.69	3.47	2.44	3.24	4.03	1.79		
CO_2	2.63	1.46	0.84	-	0.02	-	-	-		
MnO	-	tr	0.10	0.13	-	-	0.04	-		
Total	98.51	98.96	96.56	99.86	98.27	100.25	100.69	99.88	97.93	97.27

Wt%	j^3	j^4	j^5	j^6	*k*	*l*	*m*	*n*	*p*	*q*
SiO_2	68.19	72.96	71.29	70.83	64.35	54.93	72.63	79.81	76.79	77.52
TiO_2	0.20	0.55	0.52	0.42	0.94	0.98	0.63	0.29	0.20	0.27
Al_2O_3	15.34	13.05	13.58	13.81	15.15	15.18	10.49	10.45	11.85	12.23
Fe_2O_3					7.42^{+}	10.68^{+}	6.25^{+}	2.07^{+}	4.71^{+}	2.45^{+}
FeO	2.69*	2.61*	3.01*	2.77*						
MgO	0.80	0.78	0.92	0.85	2.66	4.97	2.54	0.68	1.79	0.75
CaO	1.73	1.83	1.64	1.76	1.69	4.01	0.36	1.29	0.34	0.15
Na_2O	7.73	6.12	7.22	6.84	5.93	2.15	0.42	1.84	5.90	3.85
K_2O	0.82	0.70	0.66	0.76	1.18	2.88	3.86	2.88	0.18	1.74
P_2O_5					0.23	0.17	0.10	0.04	0.02	0.02
H_2O										
CO_2										
MnO					0.16	0.23	0.16	0.07	0.15	0.02
Total	97.50	98.60	98.84	98.04	99.71	96.18	97.44	99.42	101.93	99.00

Wt%	r^1	r^2	*s*	*t*	*v*	*w*	*x*	*y*	*z*
SiO_2	80.16	83.36	63.46	65.22	61.40	55.95	64.72	75.46	63.13
TiO_2	0.21	0.21	0.40	0.38	0.39	0.52	0.46	0.42	0.6
Al_2O_3	9.01	7.94	15.67	15.95	13.01	12.91	13.71	10.83	18.08
Fe_2O_3	2.29^{+}	1.61^{+}	6.09^{+}	4.53^{+}	8.74^{+}	11.11^{+}	7.10^{+}	3.67^{+}	4.41^{+}
FeO									
MgO	0.49	0.64	5.06	1.88	5.07	8.18	3.99	0.87	1.97
CaO	0.14	0.51	3.49	5.23	8.63	4.01	4.02	1.30	0.76
Na_2O	5.06	3.52	3.47	4.32	3.12	2.33	2.51	6.13	10.60
K_2O	0.52	1.03	1.91	1.10	0.21	0.63	1.07	0.33	0.25
P_2O_5	0.02	0.02	0.06	0.10	0.05	0.02	0.07	0.08	0.15
H_2O									
CO_2									
MnO	0.03	0.04	0.11	0.09	0.11	0.18	0.13	0.03	0.03
Total	97.93	98.88	99.72	98.80	100.73	95.84	97.78	99.12	99.99

Charnian Breccias

(i) *Introduction*

The Charnian Supergroup contains three types of breccia, volcanic, slump and pull-apart, which have originated in different ways from a combination of volcanic and/or sedimentological processes. Volcanic breccias are a direct result of explosive vulcanicity. They consist of blocks of porphyry in a matrix of mainly essential ejectamenta.

Slump breccias are the result of the mass movement on both large and small scale of unstable water-saturated sediment in response to gravity, instability and/or seismicity. This gave rise to a largely chaotic deposit composed of pelitic clasts, sometimes contorted, in a sand-sized matrix.

Pull-apart breccias bear some resemblance to slump breccias. Formation of pull-aparts is by the sliding or dragging of sand and pelite layers with the latter breaking up to give rise to discrete pelite clasts in a structureless sand-sized matrix. The pelite clasts are not contorted, unlike those in the slump breccias, and remain parallel to stratification.

(ii) *Slump Breccias*

Slump breccias and debris flow deposits occur at several stratigraphic horizons within the Blackbrook and Maplewell Groups (Fig. 2) and have some value as short range stratigraphic markers (Moseley and Ford, 1985, p. 15). They range from 30 cm to 5 m in thickness. The Sliding Stone Slump Breccia was at least 44 km^2 in extent, prior to folding.

Charnian slump breccias contain clasts of laminated dust tuff or pelite, up to one metre long, in a matrix of unsorted greywacke or tuff. Associated with most slump breccias there is an overlying tuff unit without clasts that fines upwards. Prior to slumping the sedimentary sequence consisted of water-saturated pelites or pyroclastic dust interbedded with sand-sized pyroclastic and epiclastic material. The severe contortion of some clasts indicates soft-sediment deformation and flowage prior to consolidation. When subjected to flowage the layers of pelite and dust tuff would have displayed a greater degree of cohesiveness than the sand-sized matrix. This is apparent from the break up of pelitic acid dust tuff layers into a finite number of discrete rafts or clasts that retain primary laminations. The greywacke or tuff matrix is unsorted and this sand-sized material is thought to have behaved in a thixotropic manner when slumping was instigated.

Slumping may have been triggered seismically causing liquefaction and movement of the water-saturated sediment, which, aided by gravity, flowed downslope as a debris flow. The occurrence of very coarse- to very fine-grained tuffs as the matrix of the slump breccia and the succeeding beds suggests that local explosive pyroclastic activity was approximately contemporaneous with slumping. An association may thus exist between seismicity, vulcanicity and slumping. The pattern of high concentration debris-flows succeeded by massive tuff units has been compared to part of the Bouma sequence of a typical turbidite (Sutherland et al. 1987).

The structure of the Sliding Stone Slump Breccia Member (Fig. 6), which is the thickest and most extensive slumped unit, is not simply a chaotic jumble of clasts in matrix. In Bradgate Park and on Hallgate Hill there is some evidence of a weak orientation of clasts and slump folds parallel to the local stratification, in a narrow zone towards the base of the unit, which may constitute part of the mobile sole, or decollement, of the slumped mass. Above, clasts display no discernible orientation and at the top of the slumped unit discrete clasts are approximately parallel to the stratification in the overlying sediment (Fig. 6). This tripartite structure is not observed in other slump breccias, which are less extensive, thinner and generally not as well exposed. Thus for the Sliding Stone Slump Breccia at least a post-depositional origin is proposed, rather than a syn-depositional and erosional one; the slumping sediment tore up clasts of underlying dust tuff or pelitic sediment.

In an attempt to find the direction of slumping and to begin defining the strike of palaeoslope and geometry of the basin in which the Charnian sediments accumulated, the model proposed by Woodcock (1979) was utilised which assumes that the axial surfaces of recumbent folds within a slump breccia dip upslope relative to the slumped sheet. Unfortunately contortion of clasts in Charnian slump breccias rarely forms such discrete folds so measurements are few.

Axial surfaces were measured from the Sliding Stone Slump Breccia Member at three localities and the effects of the plunge of the main Charnian anticline, local folding and faulting were removed. Strain analyses indicate that the Charnian rocks have suffered a very weak component of flattening in the plane of the cleavage. Values for octahedral unit shear are, however, so low as to be considered negligible when analysing slump folds. The limited data provided a wide spread of results (Table 5) but by ignoring extreme variations from the mean the direction of slumping was estimated to be in the range 012°–217° with an average direction of 144°. This provides a tentative estimate for strike of the palaeoslope of 054°.

The wide range of results obtained from limited raw data may indicate a fanning of the slump sheet in a general south-easterly direction away from the volcanic centres in the north-western part of Charnwood. The presence of former other centres, no longer exposed, cannot be discounted.

Table 5. Orientation of folded clasts from the Sliding Stone Slump Breccia Member

Orientation of axial surface measured from outcrop		Structural Corrections			Direction of slumping
		Plunge	Faulting	Dip	
1	49°/071°	15°/091°	-	55°/178°	217°
2	Horizontal (x4)	"	-	37°/172°	161° (x4)
3	77°/300°	"	-	"	300°
4	Vertical strikes 013°	"	-	"	256°
5	10°/180° (x2)	"	-	"	166 (x2)
6	45°/202°	"	-	"	072°
7	20°/099° (x2)	"	) Rotate 045°	"	012° (x2)
8	Horizontal (x2)	"	) Rotate 045°	"	089° (x2)

1. Bradgate Park. SK 5274 1117
2–6. Sliding Stone Spinney, Bradgate Park. SK 5305 1133
7,8. Hallgate. SK 5340 1157

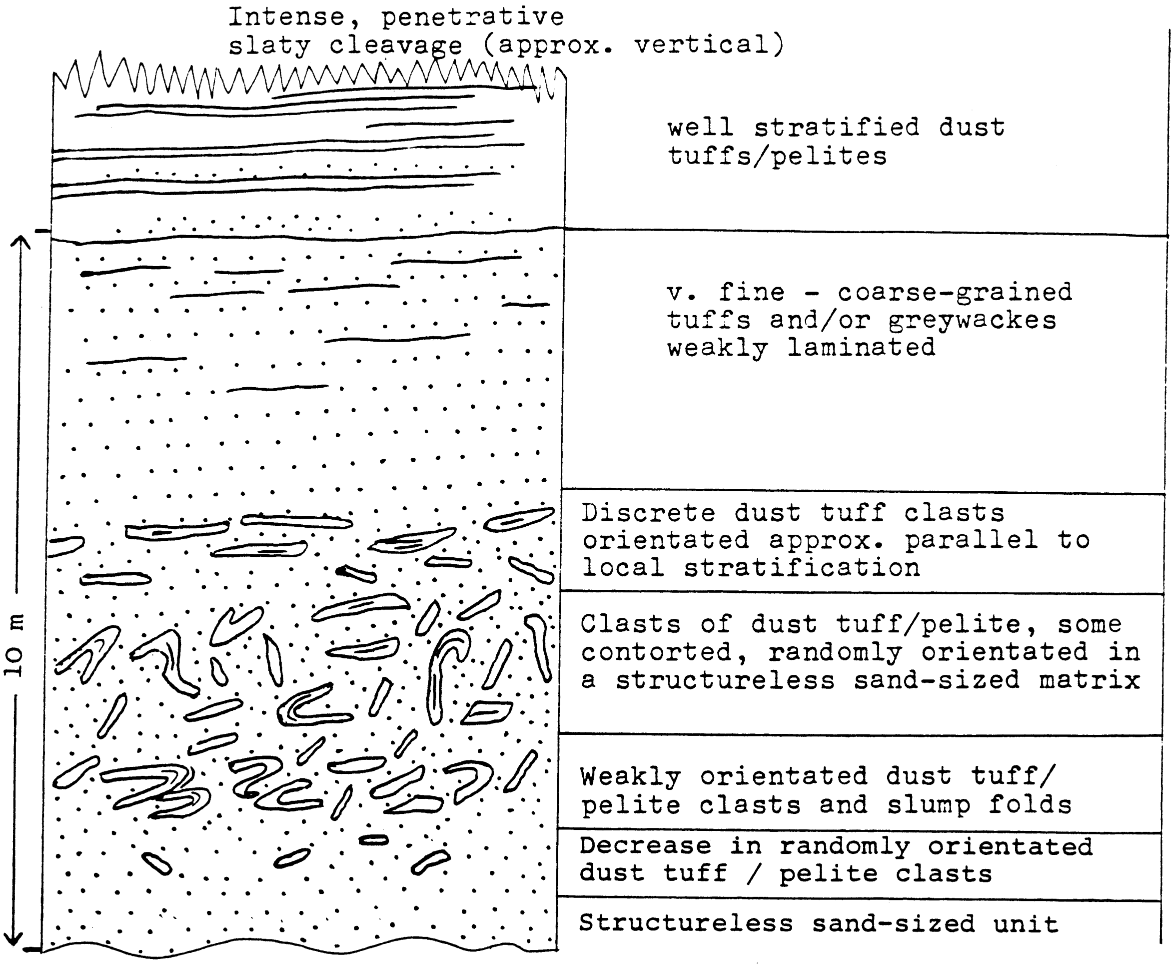

Fig. 6. Structure of Sliding Stone Slump Breccia

(iii) *Pull-apart Breccias*

Pull-apart breccias consist of discrete clasts of pelite in an unsorted matrix of tuffs or greywackes. The clasts are up to 84 cm long, although usually in the range 5 cm to 30 cm. They are sometimes slightly distorted and lie parallel to bedding. Clasts make up only 5%–10% of these breccias suggesting that the original sediment was mainly unsorted tuffs or greywackes with thin pelitic layers or partings.

Pull-apart breccias within the Old John Member crop out in Bradgate Park (SK 5309 1148) and on the A50 Markfield bypass (SK 4861 1095), 67 m and 98 m respectively below the base of the Sliding Stone Slump Breccia Member. The sliding of sands and interbedded thin pelitic layers on a gentle slope under the influence of gravity, or the drag exerted by a turbidity current have been suggested (Natland and Keunen 1951) to explain the formation of such breccias. The structureless matrix makes it impossible to determine whether pull-apart or soft-sediment boudinage has occurred (Fig. 7). Although the origin of these breccias is uncertain the name 'pull-apart' is given so as to emphasise the development of discrete clasts from an originally continuous pelitic unit.

Possible pull-apart breccias occur immediately above the debris-flow within the Sliding Stone Slump Breccia Member. The formation of these is attributed to an internal slump movement exerting a dragging effect on the overlying interbedded pelites and medium-grained tuffs. The pull-apart breccia described from the Old John Member is not underlain by a debris-flow. In the formation of all these pull-aparts the original pelitic layers behaved in a more cohesive manner than the unlithified tuffs or greywackes.

(iv) *Volcanic Breccias*

Thick deposits of volcanic breccias built up in and around the volcanic centre in the north-west, in association with the acid to intermediate porphyries, to form the Whitwick Complex. Volcanic breccias of the Charnwood Lodge Member, and perhaps the Bardon Hill Complex, occupy a marginal position on the slopes between this volcanic centre and body of water in which the Charnian sediments accumulated. The 1286 m of volcanic breccias, lapilli tuffs and coarse-grained tuffs of the Charnwood Lodge Member are contemporaneous at least with the lower part of the much finer-grained Beacon Tuffs Member.

All these volcanic breccias contain blocks of quartz-feldspar porphyry, up to 60 cm (major axis) long, typically in a matrix of coarse-grained tuff. Only a very few blocks, from breccias in Cademan Wood (SK 4390 1714), have the ellipsoidal shape that is characteristic of bombs. The blocks are aligned with their longest axes in the cleavage and have suffered a very weak component of flattening so that present shapes may not be entirely original. Some blocks demonstrate a degree of rounding and this is attributed to either fluidization prior to expulsion or downslope movement perhaps in the manner of "cannonball bombs" (Francis 1973), or a combination of both of these mechanisms. 66.33% of blocks from the Charnwood Lodge Member show some degree of rounding (9.15% rounded, 57.18% subrounded, 22.24% subangular, 11.43% angular). Blocks from volcanic breccias of the Whitwick Complex are slightly less rounded.

Sedimentology of the Blackbrook Group

This Group consists predominantly of finely laminated pelites, dust tuffs and tuffaceous pelites with intercalated unstratified discontinuous coarse-grained tuffs; a slump breccia and thicker, coarse- to very fine-grained greywackes exhibit graded bedding and load-structures. Cross-stratification is uncommon and the limited data suggests current directions towards 300°–030°. There is some lateral thinning and thickening of beds visible in single outcrops as well as minor channelling and small sedimentary faults.

Throughout the Blackbrook and Maplewell Groups the ungraded nature of some coarse- to fine-grained tuff units suggests rapid deposition from short-lived submarine pyroclastic flows (Fisher, 1984; Fisher and Schmincke, 1984). Ungraded and sand-sized, volcaniclastic deposits containing less essential pyroclastic material, and not directly related to an eruption, are the result of rapid deposition from short-lived, high density, turbidity currents (Pickering *et al.*, 1986). Graded silt and sand-sized units represent deposition by a low-density, low velocity normal turbidity current mechanism or simply by settling through air and water.

Within the area of Blackbrook Reservoir and Ives Head Hill there is an overall upward increase in the proportion of dust tuffs and pelites. The horizons of coarse- and fine-grained tuffs indicate local, probably short-lived, explosive pyroclastic activity that interrupted the slow accumulation under low energy conditions of laminated tuffs and pelites. Greywackes in the Ives Head Formation, which grade into and are interbedded with pelites, represent the introduction of some non-volcanic detritus to the sedimentary basin.

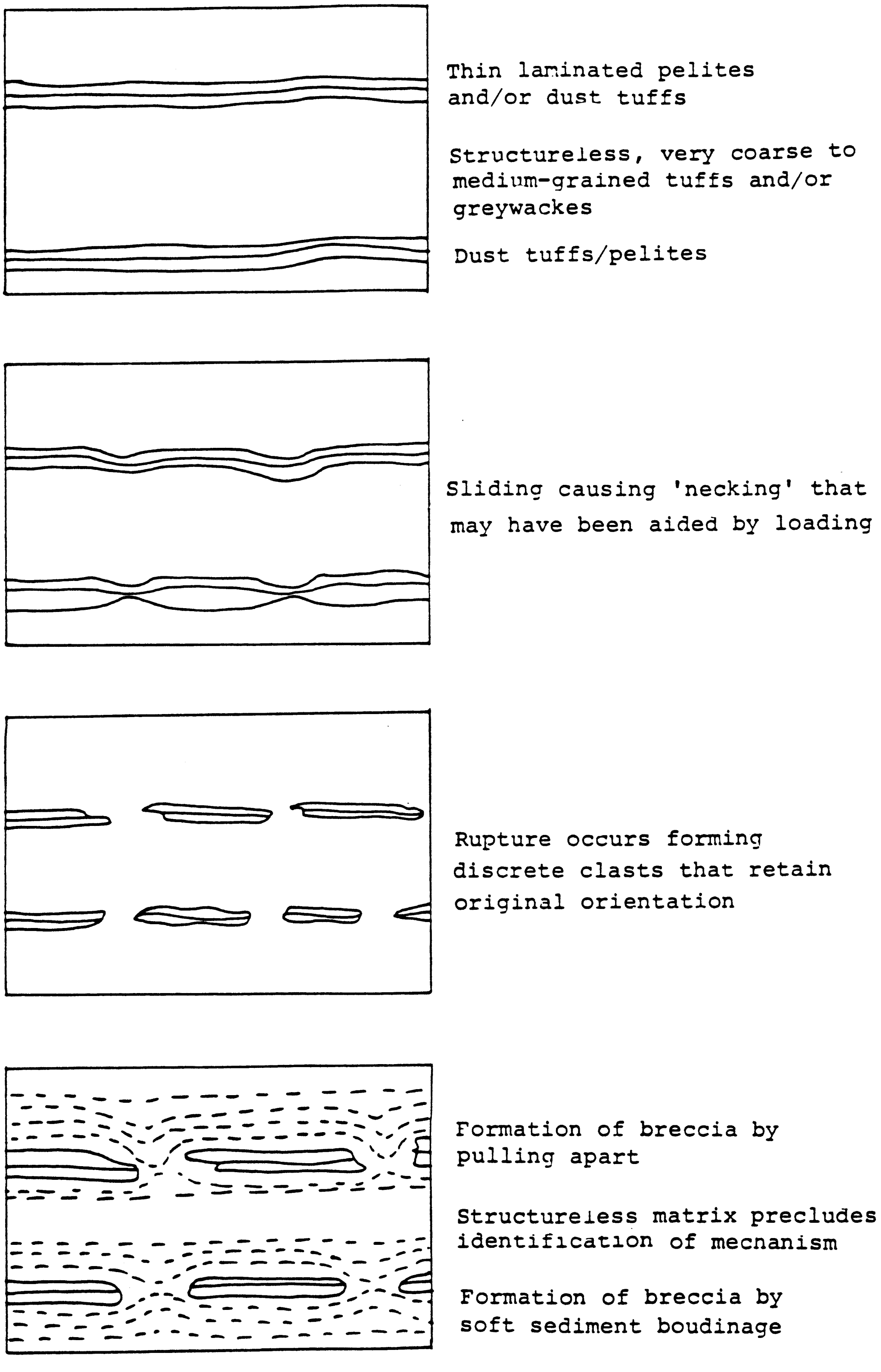

Fig. 7. The development of pull-apart breccias.

The Members of the Blackbrook Group cannot be traced to the north-east limb of the anticline where there are fewer exposures and structural complications which are not clearly resolved. The available information suggests a thinning and coarsening of the Group on the north-east limb of the anticline. This consists of a decrease in dust tuffs and pelites and an increase in greywackes of the type found in the Lubcloud Greywackes Member. The pattern of coarsening and thinning cannot be verified in the centre of Charnwood where there are very few exposures, but in the area of Benscliffe Wood there is some coarsening of the Blackbrook Reservoir Formation.

Sedimentology of the Maplewell Group

The intermittent vulcanicity of the Blackbrook Group was succeeded by more persistent activity so that the lower half of the Maplewell Group is characterised by a thick accumulation of volcanic breccias, lapilli tuffs and very coarse- to fine-grained tuffs (the Charnwood Lodge, Benscliffe and Beacon Tuffs Members). This activity then waned so these volcanic breccias and tuffs are overlain by dust tuffs and pelites (Old John and Hallgate Members), with only thin horizons of coarse-grained pyroclastics. The 887 m of volcanic breccias and lapilli tuffs that form the Charnwood Lodge Member (Fig. 2) are thought to be contemporaneous with at least the lower part of the Beacon Tuffs Member. The spatial distribution of the Charnwood Lodge Member is uncertain. This unit is now partly fault-bounded (see below), and its lateral extent is unknown. This thick accumulation of very coarse pyroclastics is likely to have occurred in immediate proximity to the volcanic centre, perhaps in a marginal position between this and the basin in which the Charnian sediments accumulated. Evidence for an eastwardly fining of the Charnwood Lodge Member, away from the volcanic centre, is seen in Cat Hill Wood (SK 4862 1492) and on the north-east slopes of Timberwood Hill (SK 4823 1481) where there is a passage into some fine-grained tuffs. The location of the Charnwood Lodge Member with respect to the Whitwick and Bardon Hill Complexes and Beacon Tuffs Member has been modified by faulting. This is apparent from the displacement of stratigraphic marker horizons by faults which trend north-south and northeast-southwest, and are all downthrown to the west. The throw of one of these, the Abbots Oak Fault, may be as much as 1800 metres.

In the north-east the coarse-grained tuffs, lapilli tuffs, breccias and greywackes of the Outwoods and Buck Hills Members represent a local coarsening within the Old John Member. The Outwoods and Buck Hills Members become finer-grained and thin southwards, eventually forming feather edges slightly north of northing 15. This may be compared to the eastwards coarsening of the Blackbrook Group. The thinning to the north-east of the Beacon Tuffs and Hallgate Members is another parallel with the Blackbrook Group. Within the Outwoods Member a conglomerate slump breccia suggests a phase of local instability including coarse detritus entering the sedimentary basin. As a result channelling is developed on a much larger scale (SK 5140 1666) than elsewhere in the Maplewell Group. Pebbles and lithic grains from the conglomeratic horizon of the Outwoods member are mainly of quartz and quartzite; a few are of an unfoliated quartz-felspar rock, and some are of igneous origin displaying a trachytic texture. Only a small number of current directions, on which no confidence can be placed, are available from the Outwoods area, and the provenance of the conglomeratic fraction remains uncertain.

Table 6. The division of the Beacon Hill Formation into members

W. Charnwood	S.W., S and S.E. Charnwood	N.E. Charnwood
Charnwood Lodge	Chitterman Hills— Benscliffe Wood— Bradgate Park— Beacon Hill	Buck Hills—Outwoods
Base of Bradgate Formation→		
Charnwood Lodge Member 1300 m	Old John Member 330 m	Old John Member 860 m Outwoods Member 71 m Buck Hills Member 176 m
	←Sandhills Lodge Member→ 9 m	11 m
	←Beacon Tuffs Member→ 560 m	350 m
←Benscliffe Member→ 47 m	22 m	28 m
←Blackbrook Group→		

Slump breccias are developed just below, within and 57 m above the Sliding Stone Slump Breccia Member, whereas pull-apart breccias are confined to a horizon between 67 m (SK 5309 1148) and 98 m (SK 4861 1095) below the top of the Old John Member. The occurrence of these breccias all within 125 m of section indicates a period in which intermittent slumping and sliding mainly towards the south, south-east and east took place.

Recent studies (Sutherland *et al.*, 1987) have identified several fining-upwards cycles in the upper Old John, Sliding Stone Slump Breccia and lower Hallgate Members in Bradgate Park. Each of these units consists of a medium- or coarse-grained tuff which gives way to a well-laminated, fine-grained tuff and then a dust tuff capped by pelite. Sutherland *et al.* suggest that this sequence is comparable to, and perhaps transitional between a sedimentary turbidite sequence (the Bouma cycle) and a subaqueous pyroclastic flow (Yamada, 1984).

Small-scale cross-stratification is common in this Group and data obtained at the intersection of joint, cleavage and bedding planes, after corrections for plunge, dip and faulting indicate that currents flowed towards 007°–141°. This range is close to that for the movement of the main slump sheet of the Sliding Stone Slump Breccia Member (012°–217°, see above). However, the average direction from cross-stratified units is 047°, with a peak at 007°–021°, compared with the average direction of slumping of 144°. The value of these analyses in interpreting the geometry of the basin in which the Charnian sediments accumulated is discussed later.

There is only one horizon of vitric tuff, and that is within the Beacon Tuffs Member, where Y-shaped, partially silicified cavities show that glass shards fell end-on into soft, fine-grained sediment. Although evidence of vitric constituents in Charnian tuffs may have been lost through devitrification, the apparent absence of a significant vitric fraction suggests that the Charnian pyroclastics may have accumulated some distance from the volcanic source or are partly epiclastic. Alternatively, explosive vulcanicity affecting cooling igneous rocks would be unlikely to produce a vitric pyroclastic fraction.

Sedimentology of the Brand Group

The lower Brand Group marks a change from the pelites and dust tuffs of the Hallgate Member to higher energy and shallower conditions with the development of discrete conglomerates and very coarse- to very fine-grained quartz-arenites and greywackes. The Hanging Rocks Conglomerate Member, which contains a small pyroclastic fraction, is succeeded by the entirely epiclastic sedimentary rocks of the Stable Pit Quartz-arenite Member and Swithland Formation.

The tuffaceous conglomerates and conglomeratic greywackes consist of rounded pebbles and grains of quartz and non-sedimentary lithic material, and an immature fraction of pelite clasts. The influx of coarse detritus that formed the Hanging Rocks Conglomerate Member caused erosion and channelling within this unit and of the underlying Hallgate Member. This became evident with the aid of a temporary excavation of the exposure of conglomerate in Bradgate park (SK 5421 1097). Similarly in the type section for the Hanging Rocks Conglomerate Member (SK 5246 1497) there is an irregular contact with the underlying Hallgate Member, and the conglomerate here contains clasts of pelite. Analysis of 127 pebbles showed angular clasts of pelite (23.63%) derived locally by the erosion of the Hallgate Member; the remainder were of rhyolite (8.66%), trachytic rocks (18.11%), quartzite (18.11%), quartz (25.20%), a foliated quartz-chlorite rock (1.58%) and a non-foliated quartz-felspar rock (2.36%). 2.36% were unidentified. The provenance of these is discussed below.

The quartz-arenites are interbedded with fairly mature greywackes in the south, but to the north-east both grade into less mature greywackes. The mainly subrounded to subangular framework grains of the quartz-arenites make up 85%–90% of the rock and are composed entirely of quartz and quartzite (Table 2). The quartz-arenites are moderately well sorted and the product of a high energy environment. These quartz-arenites may be of cratogenic derivation but their association with greywackes and thin pelites is atypical and they may in part be multicyclic having been derived from the erosion of an earlier sedimentary sequence. Associations of sediments similar to these have been attributed by Folk (1959) to reworking in littoral and inner neritic zones. The thin pelites may represent fluctuations in the energy conditions that allowed silt to accumulate in the absence of sand-sized sediment.

The Stable Pit Quartz-arenite Member in Bradgate Park (SK 5341 0998) includes a sedimentary breccia and several clastic dykes. The breccia consists of angular pelite clasts in a matrix of coarse-grained quartz-arenites and greywackes. The pelite clasts are derived locally from pelites that are interbedded with quartz-arenites and greywackes. The breccia was formed due to the erosion of a pelite layer by a sudden influx of sand-sized detritus, or as a turbidity flow in a manner similar to the slump breccias described above.

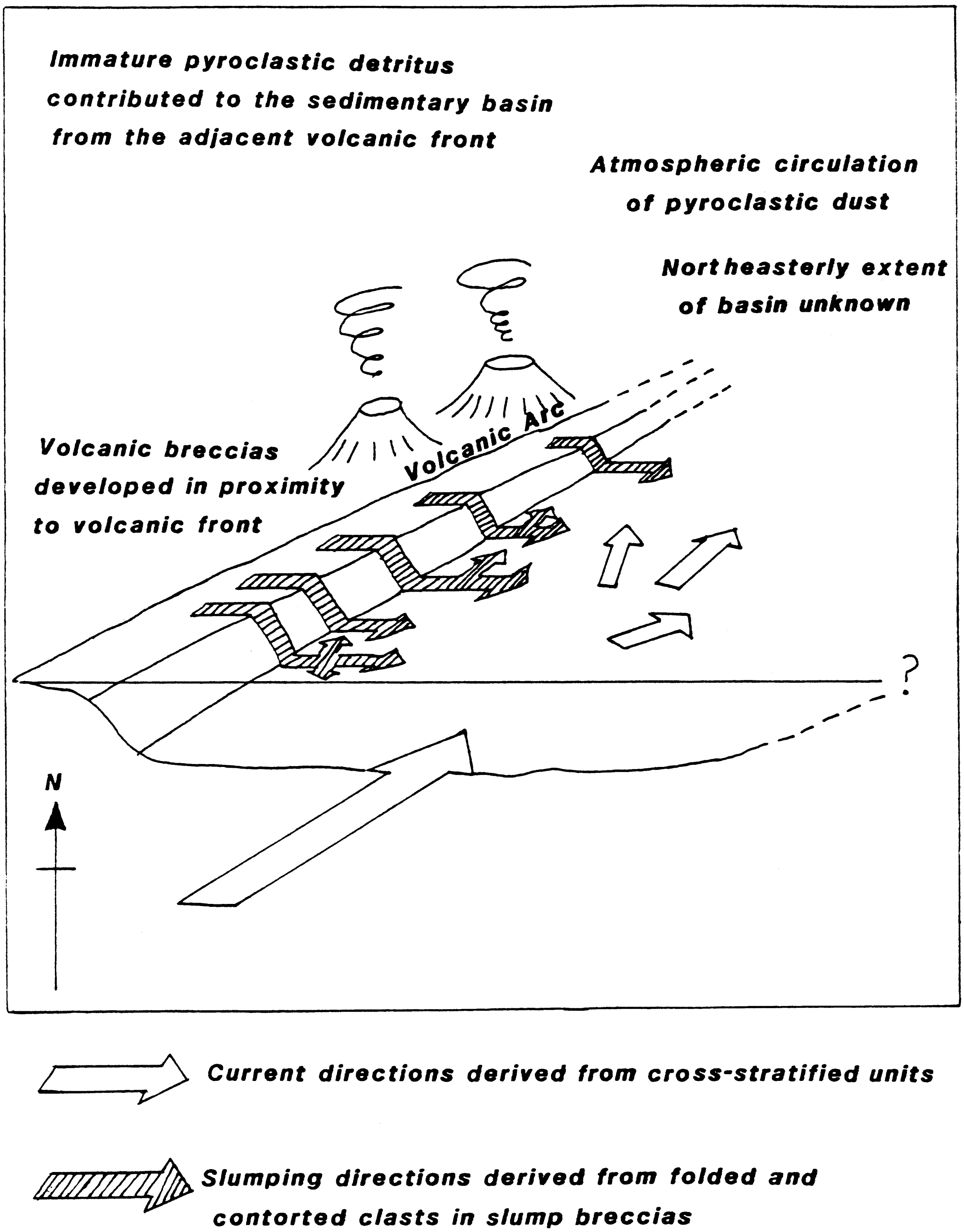

Fig. 8. Diagram illustrating the volcanic arc depositional setting of the Charnian Supergroup.

The clastic dykes are vertically emplaced, parallel to slaty cleavage in the cleaved pelites. This is thought to be coincidental as structural and stratigraphic evidence suggests that the intense Charnian cleavage post-dates the Southern Diorites (Boulter and Yates, 1987) which intrude the Maplewell and Brand Groups. The dykes show no internal structure and consist of coarse quartz grains that are feebly cemented. The feeder bed is not exposed. After structural corrections, indistinct cross-stratification in the quart-arenites suggests a current direction towards the east.

Thin, discontinuous shale-pebble conglomerates at the base of the Swithland Formation indicate local erosion of pelites by currents that carried some sand-sized epiclastic detritus. The predominantly high energy environment of early Brand times gave way to lower energy conditions and the accumulation of the pelites and fine- to very fine-grained greywackes of the Swithland Formation.

Summary of Depositional Processes

The volcaniclastic sediments of the Charnian Supergroup are comparable to those normally associated with island arc vulcanism. A volcanic centre, probably part of an island arc, the remnants of which are seen in the Whitwick and Bardon Hill Complexes, is thought to have contributed essential and accessory pyroclastic ejectamenta to the marine basin in which the Charnian sediments accumulated (Fig. 8).

The sedimentary rocks of the Charnian Supergroup indicate a variety of depositional processes ranging from the rapid accumulation of volcanic breccias to the atmospheric and submarine suspension and circulation of some pyroclastic dust before this settled out slowly as a well-laminated waterlain deposit. Instability was related to vulcanicity, seismicity and gravity-instigated debris flows and various turbidity flows which rapidly deposited slump breccias, tuffs and some greywackes. Other greywackes and tuffs were deposited after marine reworking. Some dust tuffs and tuffaceous pelites may have originated as dust suspensions above submarine debris and turbidity flows.

The coarse-grained tuffs—dust tuffs—tuffaceous greywackes—pelites assemblage of the Blackbrook Group suggests sporadic vulcanicity. In the lower half of the Maplewell Group volcanic breccias, lapilli and coarse-grained tuffs indicate explosive vulcanicity which then waned and was succeeded by the slow deposition of mainly submarine pyroclastic dust from suspension. With the exception of a small essential pyroclastic fraction of broken and euhedral quartz and feldspar phenocrysts in the Hanging Rocks Conglomerate Member, the tuffs which form part of the matrix of a slump breccia 57 m above the base of the Hallgate Member represent a late phase of volcanic activity within the exposed Charnian sequence.

Pyroclastic dust, mainly of submarine origin, settled slowly giving rise to the dust tuffs of the Hallgate Member.

The cessation in volcanic activity marks a change to more uniform sedimentation with the accumulation of pelites (upper Hallgate Member), and pelites and fine-grained greywackes (Brand Group). The lowest 0–95 m of the Brand Group indicate a phase of short-lived, intermittent higher energy conditions with the deposition of a tuffaceous conglomerate (Hanging Rocks Conglomerate Member), and a quartz-arenite, greywacke and breccia (Stable Pit Quartz-arenite Member).

Varying amounts of mature, epiclastic detritus contaminate Charnian tuffs and greywackes and form a very significant fraction in conglomerate and quartz-arenite horizons. This material may be of proximal cratogenic derivation, although the source, perhaps to the south and east on the basis of current directions established from cross-bedding, is impossible to establish. Erosion of a Malvernian-type suite of plutonic acid igneous rocks and cataclasised and schistose metamorphic rocks may be suggested.

Discussion of depositional setting

The sedimentary rocks of the Charnian Supergroup are typical of those that are known to accumulate at a destructive plate margin in an island arc environment. Geophysical evidence (Maguire, Whitcombe and Francis, 1981, 1985) suggested an oceanic setting for the Charnian rocks with sediments accumulating in one of a series of fore-arc or back-arc basins (Le Bas, 1981, 1982). A diagram illustrating the volcanic arc depositional setting is presented in Fig. 8.

There are interesting parallels with the mainly volcaniclastic sequence of the Arfon Group of North Wales (Reedman, Leveridge and Evans, 1984) which accumulated in a volcano-tectonic depression. Here a sedimentary sequence similar to the Charnian, and including rhyolite and andesite flows in the lowest Padarn Tuff Formation, overlies the Mona Complex in a block-faulted basin. In comparison the recent BGS borehole for geothermal investigations near Morley Lane (SK 4765 1787) which initially drilled the lowest exposed Charnian (Morley Lane Tuffs Member), encountered dacitic lavas at 541 to 835 m having first penetrated typical Blackbrook tuffs and greywackes (Pharaoh and Evans, 1987). These dacites are locally highly sheared, and in conjunction with evidence for intense brecciation of the Morley Lane Tuffs Member at the surface the possibility of structural complications should not be disregarded.

Further geophysical evidence has revealed NW-SE faulting affecting the basement below the Charnian. This is approximately parallel to the much publicised but grossly simplified "Charnoid" structural trend and to a possible East Midlands aulacogen (Evans, 1979). There is, however, no direct evidence to indicate that the Charnian sedimentary basin was fault-bounded or fault-controlled. The strike of palaeoslope of 054° for the basin was obtained from limited data and is interpreted with some caution.

Palaeocurrent directions derived from slump breccias and cross-bedded units provide a wide spread of results. The wider spread demonstrated by slump breccias is in keeping with the "fanning" effect typically demonstrated by such flows moving down-slope and out onto a basin floor. The average (047°) and peak (007°–021°) directions from cross-bedding imply currents moving in a basin with a north to north-east trend. This limited data points tentatively to a basin, perhaps arcuate, with an average strike of 054°. The contrast of this with the NW-SE structural trend may not be significant.

The arcuate nature of island arcs and adjacent basins means that some parts of any particular subduction zone will not have the same strike as other parts of the system. This may account for the contrast between the strike of the Charnian basin and that of the proposed north-east dipping subduction zone (Maguire et al. 1981, Le Bas 1982).

Borehole and geophysical evidence from the East Midlands and Norfolk suggests that the exposed Charnian Supergroup may be a fragment of an extensive late Proterozoic volcaniclastic province. It is proposed that the Charnian Supergroup represents part of the mainly volcaniclastic fill of a continental margin or island arc system.

Conclusions

1. The Charnian sedimentary assemblage consists of volcaniclastics interbedded with and succeeded by epiclastic greywackes and pelites. This sequence represents sporadic, then waning vulcanicity followed by the more uniform accumulation of predominantly argillaceous sediments.

2. Major diagenetic changes are hematisation, epidotisation, albitization and polyphase silicification, some of the latter being pene-contemporary.

3. Both volcaniclastic and epiclastic deposition was from debris-flows and turbidity currents and by slower settling after submarine reworking. Some pyroclastic dust may have initially undergone atmospheric circulation.

4. Limited palaeocurrent analyses suggest that deposition occurred in a basin or trough at present trending northeast-southwest.

5. The Charnian Supergroup represents a fragment of a Late Proterozoic island arc basin system.

Acknowledgements

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References

Bennett, F.W., 1928. The Geology of Charnwood Forest, *Proc. Geol. Assoc.*, 39, 241–298.

Boulter, C.A., and M.G. Yates, 1987. Confirmation of the pre-cleavage emplacement of both the northern and southern diorites into the Charnian Supergroup. *Mercian Geol.*, 10, 4, 281–286.

Boynton, H.E., 1978. Fossils from the Pre-Cambrian of Charnwood Forest, Leicestershire. *Mercian Geol.*, 6, 291–296.

Boynton, H.E. & Ford, T.D., 1979. *Pseudovendia charnwoodensis*—a new Precambrian arthropod from Charnwood Forest, Leicestershire. *Mercian Geol.*, 7, 175–177.

Clarke, F.W., 1924. Data of geochemistry. U.S. *Geol. Survey Bull.*, 770, 841pp.

Cribb, S.J., 1975. Rubidium-strontium ages and strontium isotope ratios from the igneous rocks of Leicestershire. *J. Geol. Soc. London*, 131, 203–213.

Evans, A.M., 1963. Conical folding and oblique structures in Charnwood Forest. *Proc. Yorks. Geol. Soc.*, 34, 674, 67–79.

Evans, A.M., 1979. The East Midlands Aulacogen of Caledonian Age. *Mercian Geol.*, 7, 31–42.

Fisher, R.V., 1984. *Submarine volcanoclastic rocks.* In: B.P. Kokelaar and M.F. Howells (Editors), *Marginal Basin Geology*. Geol. Soc. Lond. Spec. Pub. No. 16, 5–27.

Fisher, R.V. and Schmincke, H.-U., 1984. *Pyroclastic Rocks.* Springer-Verlag, Heidelberg.

Folk, R.L., 1959. Practical petrographic classification of limestones. *Bull. Amer. Assoc. Petrol. Geologists.*, 1–38.

Ford, T.D., 1958. Precambrian fossils from Charnwood Forest. *Proc. Yorks. Geol. Soc.*, 31, 211–217.

Ford, T.D., 1968. Precambrian Palaeontology of Charnwood Forest; pp. 12–14, *Geology of the East Midlands.* P.C. Sylvester-Bradley & T.D. Ford (eds.), Univ. Leicester Press. 400pp.

Ford, T.D., 1980. The Ediacaran fossils of Charnwood Forest, Leicestershire. *Proc. Geol. Assoc.*, 91, 81–84.

Francis, P., 1973. Cannonball Bombs, a new kind of volcanic bomb from the Pacaya volcano, Guatemala. *Bull. Geol. Soc. America*, 84, 2791–2794.

Greig, D.C., J.E. Wright, B.A. Hains, & G.H. Mitchell, 1968. *Geology of the country around Church Stretton, Craven Arms, Wenlock Edge and Brown Clee*, Mem. Geol. Surv. G.B. 379pp.

Hill, E. & Bonney, T.G., 1877–1880. The pre-Carboniferous Rocks of Charnwood Forest. *Q. J. Geol. Soc. London*, 33, 754–789; 34, 199–239; and 36, 337–350.

Hill, E. & Bonney, T.G., 1891. On the northwest region of Charnwood Forest, with other notes. *Q. J. Geol. Soc. London*, 42, 78–100.

Jenks, W.F. & Goldich, S.S., 1950. Rhyolitic tuff flows in southern Peru. *J. Geology*, 64, 156–172.

King, R.J., 1968. Mineralization. Chapter 7 in *Geology of the East Midlands*. P.C. Sylvester-Bradley & T.D. Ford (eds), Univ. Leicester Press, 400pp.

Le Bas, M.J., 1981. The igneous basement of Southern Britain. *Trans. Leicester Lit. & Phil. Soc.*, 75, 41–57.

Le Bas, M.J., 1984. Geological evidence from Leicestershire on the Crust of Southern Britain. *Trans. Leic. Lit. & Phil. Soc.*, 76, 54–67.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A. and Zanettin, B., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. *J. Petrology*, 27, 745–750.

Maguire, P.K.H., Whitcombe, D.N. and Francis, D.J., 1981. Seismic studies in the Central Midlands of England 1975–1980. *Trans. Leic. Lit. & Phil. Soc.*, 75, 58–66.

Maguire, P.K.H., Whitcombe, D.N. and Francis, D.J., 1985. Determination of the three-dimensional seismic structure of the crust and upper mantle in the Central Midlands of England. *Geophys. J. Roy. Astr. Soc.*, 83:2, 347–362.

Moseley, J.B., 1979. *The Geology of the Late Precambrian Rocks of Charnwood Forest, Leicestershire.* Unpub. Ph.D. thesis, Univ. of Leicester.

Moseley, J.B. and T.D. Ford, 1985. A Stratigraphic Revision of the Late Precambrian Rocks of Charnwood Forest, Leics. *Mercian Geol.*, 10, 1–18.

Natland, M.L. & Keunen, P.H., 1951. *Sedimentary history of the Ventura Basin, California, and the action of turbidity currents.* S.E.P.M. Spec. Publn., 2, 76–107.

Nanz, R.H., 1953. Chemical composition of Precambrian slates with notes on the chemical evolution of lutites. *J. Geology*, 61, 51–64.

Pankhurst, R.J., 1982. *Geochronological tables for British Igneous Rocks.* Appendix C, pp. 575–582, in *Igneous Rocks of the British Isles*, D.S. Sutherland (ed.) Wiley, Chichester, 645pp.

Pettijohn, E.J., 1975. *Sedimentary Rocks.* Harper & Row, New York, 3rd edn. 628pp.

Pharaoh, T.C., Webb, P.C., Thorpe, R.S. and Beckinsale, R.D., 1987. *Geochemical evidence for the tectonic setting of late Proterozoic volcanic suites in central England.* In *Geochemistry and Mineralization of Proterozoic Volcanic Suites*, Geol. Soc. Spec. Pub. No. 33, pp. 541–552.

Pharaoh, T.C. and Evans, C.J., 1987. Morley Quarry No. 1 Borehole: Geological Well Completion Report. *Invest. Geotherm. Potent. UK, Br. Geol. Surv.*

Pickering, K.T., Stow, D.A.V., Watson, M.P. and Hiscott, R.N., 1986. Deep-water Facies, Processes and Models: A Review and Classification Scheme for Modern and Ancient Sediments. *Earth-Science Reviews*, 23, 75–174.

Reedman, A.J., Leveridge, B.E. and Evans, R.B., 1984. The Arfon Group ('Arvonian') of North Wales. *Proc. Geol. Assoc.* 95, 313–321.

Sutherland, D.S., Boynton, H.E., Ford, T.D., Le Bas, M.J., Moseley, J., Pontin, K. and Whateley, M.K., 1987. A guide to the Geology of the Precambrian Rocks of Bradgate Park, Leicestershire. *Trans. Leic. Lit. & Phil. Soc.*, 81, 47–83.

Thorpe, R.S., 1972. The geochemistry and correlation of the Warren House, Uriconian and Charnian volcanic rocks from the English Precambrian. *Proc. Geol. Assoc.*, 83, 269–286.

Thorpe, R.S., 1979. Late Precambrian igneous activity in southern Britain; pp. 579–584 in *The Caledonides of the British Isles—reviewed.* A.L. Harris, C.H. Holland & B.E. Leake (eds.) Geol. Soc. London Spec. Publn. 8.

Thorpe, R.S., 1982. *Andesites: orogenic andesites and related rocks.* John Wiley & Sons, Chichester, 724pp.

Watts, W.W., 1947. *The Geology of the Ancient Rocks of Charnwood Forest, Leicestershire.* Leic. Lit. & Phil. Soc. publn. 160pp.

Woodcock, N.H., 1979. The use of slump structures as palaeoslope orientation estimators. *Sedimentology*, 26, 83–99.

Worssam, B.C. & Old, R.A., 1988. *Geology of the country around Coalville.* Mem. Brit. Geol. Survey, Sheet 155, H.M.S.O., 162pp.

Yagi, K., 1962. Welded tuffs and related pyroclastics deposits in northeastern Japan. *Bull. Volcanologique.* Series 2, 24, 109–128.

Yamada, E., 1984. *Subaqueous pyroclastic flows: their development and their deposits*, pp. 29–35 in: *Marginal Basin Geology*, B.P. Kokelaar and M.F. Howells (eds.) Geol. Soc. London, Spec. Publn. No. 16.

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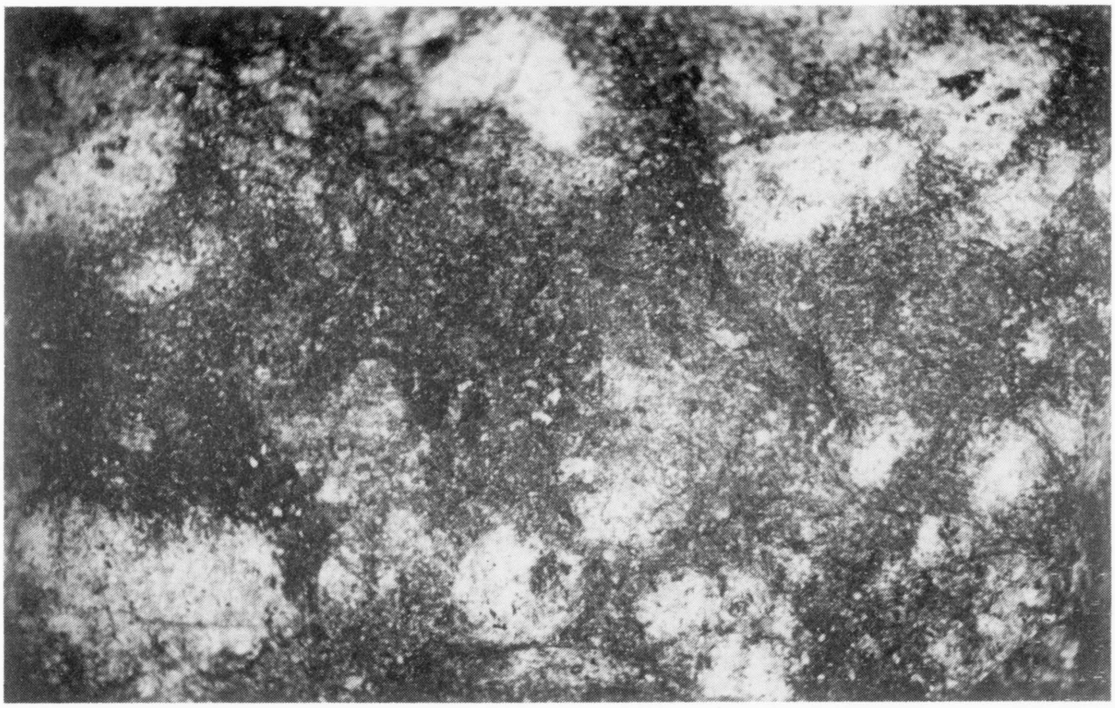

Plate 1. Coarse-grained tuff with up to 4 cm wide lapilli of pale pink devitrified rhyolite with silicified margins bending into chloritic tuff matrix. Width of view c 10 cm. Benscliffe Member (SK 51451247). Formerly known as Felsitic Agglomerate.

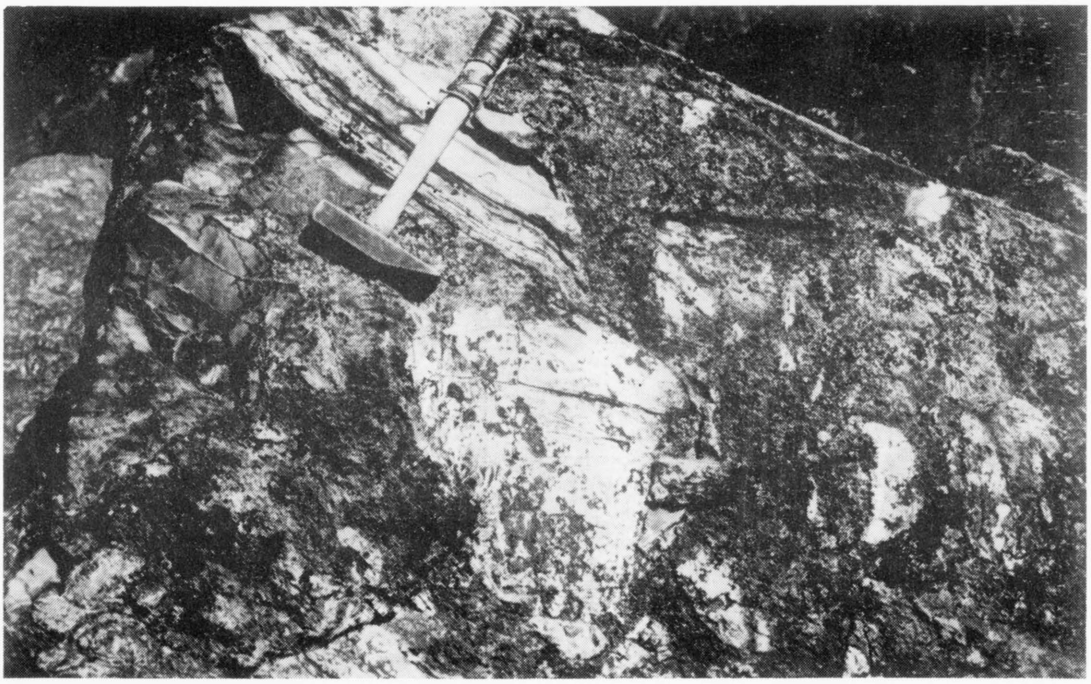

Plate 2. Slump breccia with large clasts of pelite in a corase tuff matrix. Sliding Stone Slump Breccia Member, (SK 53061130). Formerly known as Slate Agglomerate.

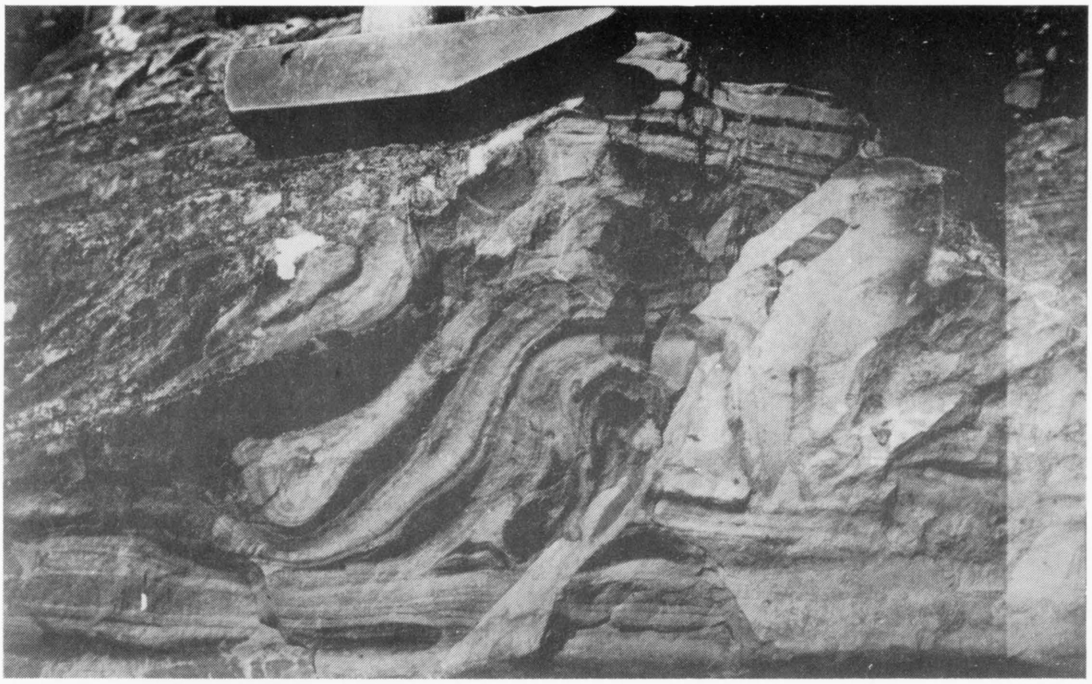

Plate 3. Slump structure in tuffaceous pelites of Old John Member, near Old John Tower in Bradgate Park (SK 52561125).

Plate 4. Conglomerate in Hanging Rocks Conglomerate Member from Charnwood Golf course (SK 52461497) with pebbles of porphyritic dacite, rhyolite, fine-grained quartz arenite and pelite. Width of view c 10 cm.

Plate 5. Soft-sediment deformation in laminated tuffs of the Old John Member, north of Old John Tower. Sliding on planar surfaces has disturbed the bedding left of the lens cap but the beds above and below are undisturbed. (SK 524113).

Plate 6. Infilled depressions in Old John Member south of the Memorial, Bradgate Park. The depressions are due to collapse by de-watering of medium-grained tuff, and are infilled by fine-grained tuff (SK 524110).

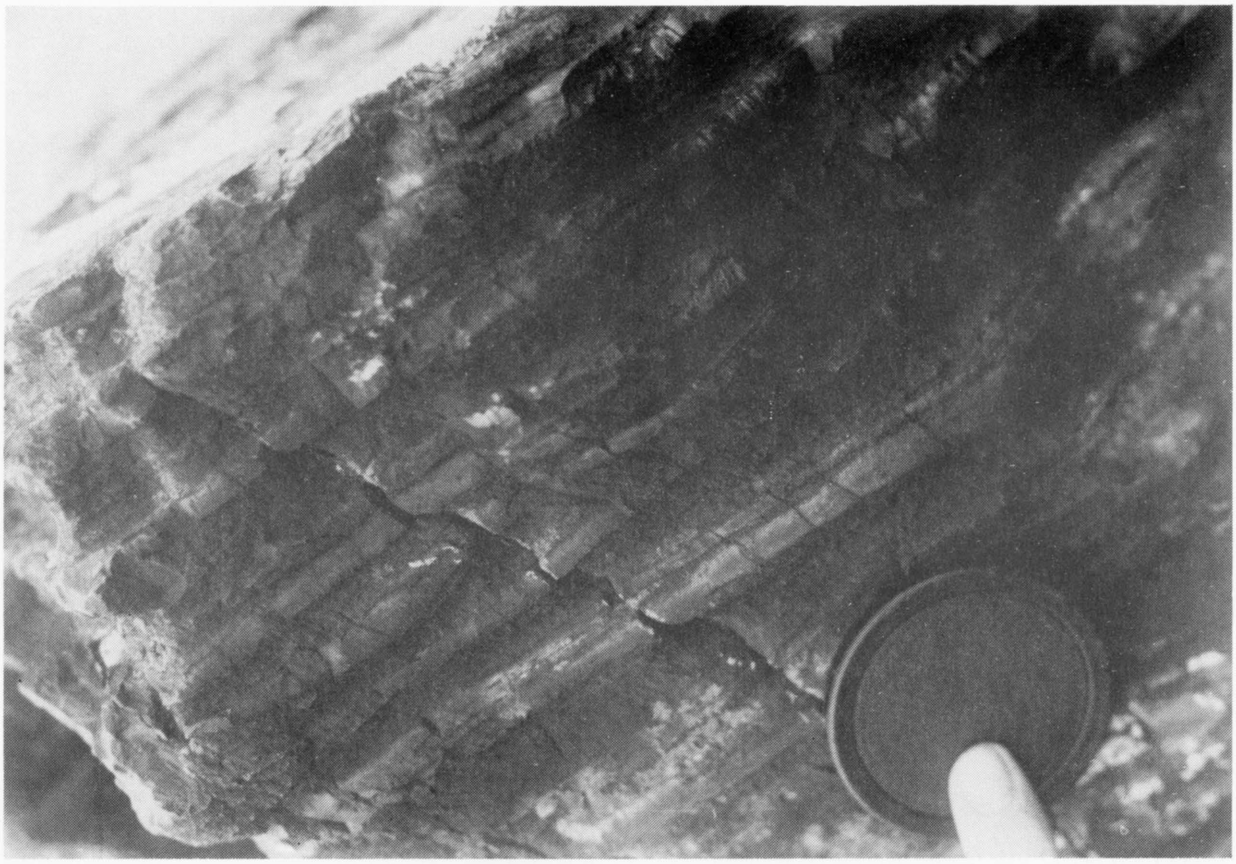

Plate 7. Laminated turbidites in Hallgate Member of Brand Hills Formation, near The Coppice, Bradgate Park (SK 539109).

Plate 8. Pull-apart structures in tuffs of the Old John Member, near Old John Spinney, Bradgate Park (SK 524111).