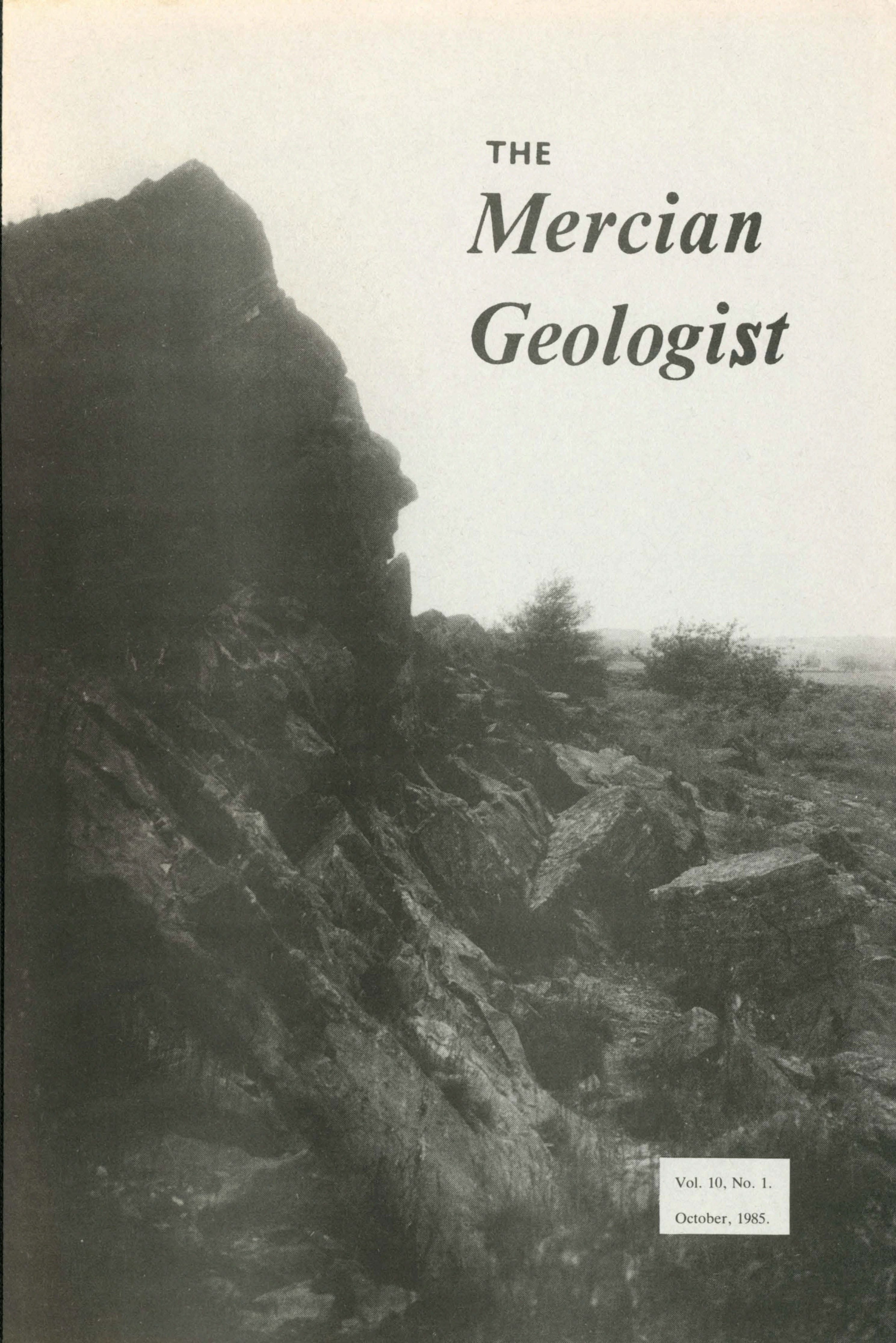
THE
Mercian Geologist



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Front Cover: Outcrops of the Beacon Hill Beds at Beacon Hill, Leicestershire. Photographer Mrs. P. E. Firman.

A STRATIGRAPHIC REVISION OF THE LATE PRECAMBRIAN ROCKS OF CHARNWOOD FOREST, LEICESTERSHIRE

by

J. Moseley & T.D. Ford

Summary

It is proposed in keeping with modern stratigraphical procedure that the Late Precambrian rocks of Charnwood Forest should be redefined as the Charnian Supergroup and a division into the Blackbrook, Maplewell and Brand Groups and two volcanic complexes is recommended.

The slump breccias, conglomerates and volcanic breccias previously used as long range stratigraphic marker horizons are shown to be inadequate for this purpose and only of limited local value for correlation. The remnants of a volcanic centre, composed largely of volcanic breccias and quartz-feldspar porphyries, are represented by the Whitwick and Bardon Hill complexes and these may be contemporaneous with part of the completely clastic Maplewell Group.

Introduction

Precambrian rocks crop out in Charnwood Forest, Leicestershire, a triangular area of 110 km^2 rising above the general level of the Midland Plain to 280 m above ordnance datum at Bardon Hill. The Charnian Supergroup is not well exposed, being overlain unconformably by Triassic and Pleistocene sediments.

Modern stratigraphic practice and international rules of nomenclature require that a tightening and some re-definition of Watts' (1947) rock units is necessary. Where the degree of exposure permits, formations must now have strictly defined type sections with the bases of units clearly indicated so that other sections may be compared and correlated. This new nomenclature is introduced herein: it supercedes and revises the simplified version already published in the key to the revised edition of the Coalville Sheet (No. 155) of the Geological Survey (Old & Worssam, 1982).

Although Cribb (1975), Evans (1963), Ford (1958, 1968, 1979, 1980, 1981 & 1983), Thorpe (1972, 1979, 1982), Le Bas (1981, 1982), Boynton (1978) and Boynton & Ford (1979) have recently added to our knowledge of the age, structure, palaeontology and geochemistry respectively of the ancient rocks of Charnwood Forest, little has been written on the stratigraphy since the work of W. W. Watts. He published many papers from 1895 onwards and the culmination of these studies was the posthumous publication of "Geology of the Ancient Rocks of Charnwood Forest" (1947). The bulk of Watts' work was compiled for the Geological Survey beginning in 1896 and there has long been a need for his stratigraphic classification to be revised (table 1), modern terms for the rocks and rock units to be introduced and, particularly, a reinterpretation of certain distinctive lithologies and their reliability as stratigraphic marker horizons. To define these predominantly volcaniclastic rocks accurately, an integration of the classifications for pyroclastic (Fisher, 1960, 1961 and 1966; Le Bas & Sabine, 1980) and epiclastic rocks (Pettijohn, Potter & Siever, 1972, p. 71) became necessary (table 2).

Of other earlier works, Howell and Hull, working for the Geological Survey, mapped the Charnwood area (c. 1857-1860) without erecting a stratigraphic succession; Hill and Bonney published papers (1877-1891) describing the petrography of the Charnian. Bennett (1928) published a geological map of Charnwood that suggests he may have recognised, without appreciating the full significance, the discontinuous nature of certain slump breccias, conglomerates and volcanic breccias. The history of research into the Charnian was comprehensively summarized by Ford (1979).

Mercian Geologist, vol. 10, no. 1,
1985, pp. 1-18, 3 figs., 1 folded
map (Plate 1)

Table 1 The main stratigraphic divisions of the Charnian supergroup

Earlier stratigraphic divisions by W.W. Watts (1947) in parentheses

Groups	Formations	Members
The Brand Group (The Brand Series)	*Swithland Formation* (Swithland Slates) Purple pelites and very fine-grained greywackes.	None
	Brand Hills Formation Quartz-arenites, greywackes, conglomerates. A tuff at or near the base of the Brand Group.	Stable Pit Quartz-arenite Member. (Trachose Grit and Quartzite) Hanging Rocks Conglomerate (Hanging Rocks Conglomerate)
The Maplewell Group (The Maplewell Series)	*Bradgate Formation* Pelites, dust tuffs, greywackes. Slump breccias at base of the Formation.	Hallgate Member (Woodhouse and Bradgate Beds) Sliding Stone Slump Breccia Member (Slate Agglomerate)
	Beacon Hill Formation Pelites and coarse-grained tuffs, with some lapilli tuffs and volcanic breccias. Subordinate slump breccias, pull-apart breccias, conglomerates and breccias.	Old John Member (Beacon Hill Beds) Sandhills Lodge Member Beacon Tuff Member (Beacon Hill Beds) Benscliffe Member (Felsitic Agglomerate)
The Blackbrook Group (The Blackbrook Series)	*Blackbrook Reservoir Formation* (Blackbrook Beds) Tuffaceous pelites, dust tuffs and subordinate coarse-grained tuffs.	None
	Ives Head Formation (Blackbrook Beds) Greywackes, tuffs, pelites and a slump breccia.	South Quarry Slump Breccia Member Lubcloud Greywackes Member Morley Lane Tuffs Member

Table 2 The classification of the main types of epiclastic and pyroclastic rocks

(after Pettijohn, Potter and Siever, 1972, p. 71; Fisher, 1960, 1961 and 1966; Le Bas and Sabine 1980).

	Epiclastic		Pyroclastic	
	Rock	*Fragment*	*Rock*	*Fragment*
			Coarse volcanic breccia	blocks
	Conglomerate	boulder		
			Coarse agglomerate	bombs
256 mm				
	Conglomerate	Cobble	Fine volcanic breccia Fine agglomerate	blocks bombs
64 mm				
	Conglomerate	pebble	Lapilli tuff	lapilli
4 mm				
	Conglomerate	granule		
2 mm				
	Very coarse-grained arenite/greywacke	grains	Coarse-grained tuff	lithic grains crystals shards
1 mm				
	Coarse-grained arenite/greywacke	grains		
1/2 mm				
	Medium-grained arenite/greywacke	grains		
1/4 mm				
	Fine-grained arenite/greywacke	grains		
1/8 mm				
	Very fine-grained arenite/greywacke	grains		
1/16 mm				
	Pelite	grains	Dust tuff or fine-grained tuff	

In the north-east and south, pre-Triassic dioritic rocks, referred to here as the Northern and Southern Diorites, intrude and are faulted against the sedimentary rocks of the Charnian Supergroup. The main mass of the Southern Diorites obliquely cuts the contact of the Brand and Maplewell Groups and may not form a laccolith as previously suggested (Watts, 1947, p. 72). The Northern Diorites form intrusive bodies, some with faulted contacts, at Longcliffe and Newhurst Quarries, Bawdon Hill, on the Buck Hills and the Ulverscroft Nature Reserve (fig. 1).

In 1975, Cribb determined the Rb and Sr isotopic compositions of these diorites, but the ages calculated from these data are geologically difficult to accept as the date of emplacement given by Cribb (1975) but revised for new decay contents by Pankhurst (1982) for the Northern Diorite is 304 ± 90 Ma, and is probably a re-set age dating the Hercynian mineralization (King 1968) of that area. The Southern Diorite yielded an isochron corresponding to an age of 540 ± 57 Ma (Cribb 1975 revised by Pankhurst, 1982) which, if one sets aside the error margins, is rather young for a Precambrian intrusion, the Precambrian-Cambrian boundary being placed usually at about 570 Ma (Sepkoski 1983) but ranging from 550-570 Ma (Glaessner 1984) to 610 ± 10 Ma (Xiaofeng 1984).

The Charnian Supergroup

The assemblage of ancient, Precambrian sedimentary and igneous rocks outcropping in Charnwood Forest, Leicestershire, is here designated the Charnian Supergroup. The assemblage indicates an active zone with intermittent vulcanicity and earthquake activity. Calc-alkaline porphyry masses, thick local accumulations of volcanic breccias and waterlaid tuffs indicate an explosive, volcanic focus that became dormant or extinct after the deposition of the conglomerates at the base of the Brand Group. Earthquakes, possibly triggered by vulcanicity, are thought to have been responsible for the development of slump breccias that are confined to the Blackbrook and Maplewell Groups. The interbedding of coarse-grained tuffs, volcanic breccias and slump breccias with sparsely fossiliferous, finely laminated dust tuffs and pelites suggests sporadic volcanic and seismic activity with longer periods of quiescence. Directional sedimentary structures show that the Charnian sediments accumulated in a N.N.E.-S.S.W. trending basin sited to the immediate south-east of the volcanic centre.

The Charnian Supergroup has been folded into an open asymmetric anticline that plunges gently to the south-east. Minor folds are superimposed and there has been considerable faulting. Very low grade metamorphism has been imposed and cleavage affects fine-grained rocks along a trend nearly parallel to but not identical with the main fold axis (Evans, 1963).

The Division of the Charnian Supergroup into Groups

The division of the Charnian Supergroup into the Blackbrook, Maplewell and Brand Groups is based on major lithological differences (see table 1). The Brand Group, being almost entirely devoid of pyroclastic detritus, is distinct from the Blackbrook and Maplewell Groups that are comparatively rich in this material. The Blackbrook and Maplewell Groups both contain thick sequences of dust tuffs, pelites and tuffaceous pelites. The main differences are that the Maplewell Group contains well-developed horizons of volcanic and sedimentary breccias, slump breccias and lapilli tuffs which are absent or only poorly represented in the Blackbrook Group.

The Blackbrook Group

The division of Blackbrook Group into the Ives Head and Blackbrook Reservoir Formations (table 3) was determined on the south-west limb of the anticline (fig. 1). On the north-east limb there are lithological variations, structural complications and an eastward thinning of the Group. This pattern of coarsening and thinning is not easily resolved, but the general increase in greywackes over dust tuffs eastwards may be related to increasing distance from a volcanic centre lying to the north-west. Type sections are located around Blackbrook Reservoir and on Ives Head Hill (kilometre squares SK 45.17, 46.17 and 47.17) and together show an overall upward increase in the proportion of dust tuffs and pelites as the spasmodic explosive vulcanicity responsible for the development of local coarse-grained tuffs waned. The base of this Group is not seen but the lowest section exposes dust tuffs and coarse-grained tuffs in the disused quarries at Morley Lane, Shepshed (SK 47531796 and 47651790). The highest strata of the Blackbrook Group are the tuffaceous pelites and coarse-grained tuffs in Benscliffe Wood (51481250) and on the M1 Motorway section (49041705) and underlie the lowest volcanic breccia, the base of which is taken as the bottom of the Maplewell Group.

Table 3 The stratigraphic divisions of the Blackbrook Group

	Members	Lithologies
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

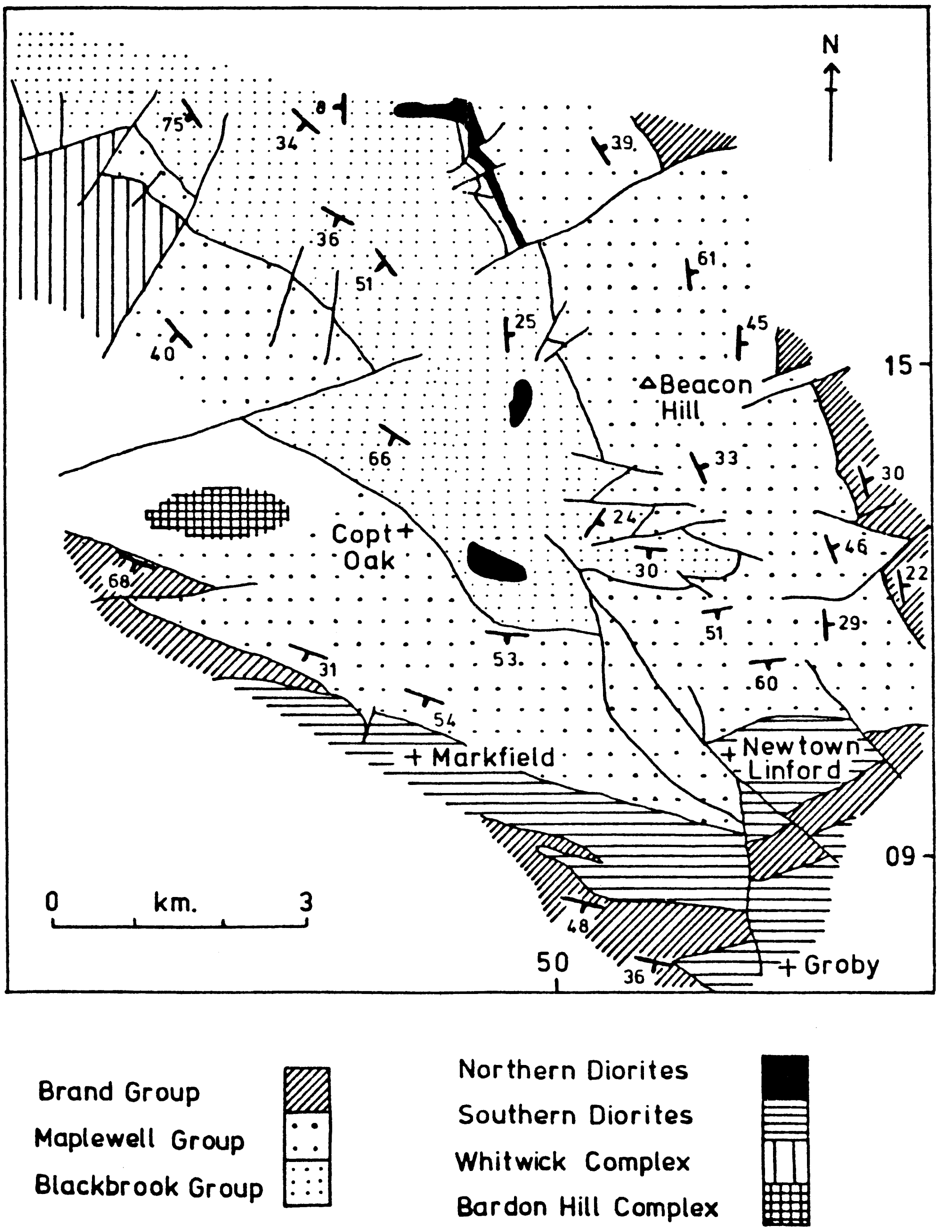

Fig. 1. The outcrop pattern of the Blackbrook, Maplewell and Brand Groups.

(*a*) *Ives Head Formation*

This formation is divided into the following Members:-

(i) *Morley Lane Tuffs Member*

The only localities for this Member, the lowest of the Blackbrook Group, are the disused quarries at Morley Lane, Shepshed (47531796 and 47651790). The base of the Member and the contact with the overlying Lubcloud Greywackes Member is not exposed. Coarse-grained rhyolitic crystal tuffs and dust tuffs are predominant (table 3) in the 14.7 m of strata in the type section (47651790).

(ii) *Lubcloud Greywackes Member*

The base of this Member is not exposed but the contact with the overlying South Quarry Slump Breccia Member is at the eastern end of Blackbrook Reservoir (46431712) and Lubcloud Farm (47871627). The type section is represented by the following 39 m of strata that crop out on Ives Head Hill (47731701):

Fine-grained greywackes and tuffaceous pelites	11.0 m
Medium-grained lithic greywackes	5.5 m
Very fine-grained tuffaceous greywackes	5.5 m
Medium-grained lithic greywackes	11.0 m
Very fine-grained tuffaceous greywackes and pelites	6.0 m

Lithic grains in the greywackes from the type section are of acid igneous origin, and in the coarser-grained greywackes exceed the pyroclastic (fraction of broken, euhedral quartz and feldspars).

The Lubcloud Greywackes Member can be tentatively traced around the nose of the anticline to Short Cliff (48621715) where medium- to coarse-grained tuffaceous greywackes are the dominant lithology and may represent an eastwards thickening of the coarser beds exposed on Ives Head Hill.

(iii) *South Quarry Slump Breccia Member*

Both top and base of this Member are exposed at the south-east end of Blackbrook Reservoir (46401712) in the following type section:-

Interbedded coarse-grained rhyodacitic tuffs and rhyolitic dust-tuffs	29.0 m
Coarse-grained rhyodacitic tuff	0.5 m
Slump breccia	2.0 m

This breccia consists of randomly orientated, contorted and undeformed clasts of rhyolitic dust-tuffs in a structureless matrix of weathered coarse-grained rhyodacitic tuffs. The bed of slump breccia which is a useful, but limited stratigraphic marker horizon is underlain by the Lubcloud Greywackes Member and the interbedded tuffs are succeeded by the lowest tuffs and tuffaceous pelites of the Blackbrook Reservoir Formation. The Member can be traced to Moult Hill (46501701) and Lubcloud Farm (17871627) beyond which it is not exposed and may die out laterally.

(*b*) *The Blackbrook Reservoir Formation*

Tuffaceous pelites and rhyolitic dust-tuffs are the main lithologies of the Blackbrook Reservoir Formation but thin horizons of coarse-grained rhyolitic and rhyodacitic tuffs occur 210 m above the base, and in Benscliffe Wood (51271277, 51371281 and 5138126) near the top of the Formation. Basal dust-tuffs and tuffaceous pelites are exposed at 46401708 (see above) and the dust tuffs at 45681774 are succeeded by 30 m of very weathered, coarse-grained tuffs. These tuffs and pelites comprise the type section which is intermittently exposed in the north-east corner of kilometre square 45.17. The coarse-grained tuffs are tentatively correlated with those near Rock Farm (48051543 and 48321526) Hall Farm (47861428) and the band of coarse grit (Watts, 1947, p. 27) at Ringing Hill (45211838) which is no longer exposed. The top of this Formation is exposed on the M1 Motorway section (49041705) where 12.5 m of tuffaceous pelites and dust tuffs are overlain by the lapilli tuff of the Benscliffe Member (Plate 1).

The Maplewell Group

The rocks of the Maplewell Group are exposed in a horseshoe-shaped area reflecting the gently plunging structure of the Charnian anticline (fig. 1). Type sections occur in kilometre squares 51.12 (Benscliffe Wood), 52.11 and 53.11 (Bradgate Park), and 50.14 (Beacon Hill). The base of the Group is defined in the preceding section while the top is represented by the highest pelites of the Hallgate Member. The Group is divided into the Beacon Hill and Bradgate Formations (tables 1, 4 & 5). In the north-east the coarse tuffs and slump breccias of the Outwoods and Buck Hills Members, which cannot be traced south of northing 15, represent a coarsening within the Old John Member (page 9), presumably due to a localized phase of explosive vulcanicity with

Table 4 The stratigraphic divisions of the Maplewell Group

	Members	*Lithologies*
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. 4.7 m of pelites with some very fine-grained greywackes. 0–0.1 m of deeply weathered breccia. 2.4 m of pelites.
	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.

Table 5 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 →		

associated seismicity and instability (table 5). In parallel with the thinning of the Blackbrook Group is the decrease in thickness to the north-east of the Beacon Tuffs and Hallgate Members although the Old John Member thickens in this direction. Volcanic breccias and lapilli tuffs developed in the west from the Charnwood Lodge Member.

(*a*) *The Beacon Hill Formation*

In the type area this Formation is divided into four Members (table 4) and their description precedes that of the Buck Hills, Outwoods and Charnwood Lodge Members (table 5).

(i) *The Benscliffe Member*

Previously called the Felsitic Agglomerate (Watts, 1947) this Member consists of volcanic breccias, lapilli tuffs, rhyolitic to andesitic tuffs and subordinate dust tuffs. The distinctive coarser lithologies contain pale pink blocks, lapilli and grains usually composed of devitrified rhyolite that due to a patchy secondary silicification often appear to blend into a dark chlorite matrix. The type section in Benscliffe Wood (51451247) is overlain by the lowest beds of the Beacon Tuffs Member:-

Coarse-grained tuffs	5.4 m
Volcanic breccias, rhyolitic lapilli tuffs and coarse-grained tuffs	16.2 m

The base of the Member is not exposed here although Blackbrook beds (51481250) lie 5.4 m below the crags of volcanic breccia and lapilli tuff. In the vicinity of Benscliffe Wood the Member can be traced to Brockers Cliff (50491239) and, tentatively, due to structural complications, to Green Hill (51021306) and Black Hill (50521351).

On the north-east limb of the anticline the Benscliffe Member is exposed at Whittle Hill (49841580), in Roe's Plantation (49811623), on the M1 (Longcliffe) cutting (49051708 and 49021700) and Ingleberry Rock (48971731). On the south-west limb the Member is exposed at Stoneywell Cottage (49771172), in Rocky Plantation (49831183), on the M1 (Birch Hill) cutting (48181339 and 48231387), at Abbot's Oak (46411424), in Cat Hill Wood (47531521) and on Collier Hill (46841583), at Charnwood Towers (46291625) and in Strawberry Hill Plantation (45601710) (Plate 1).

The lithology and thickness of the Benscliffe Member varies as it is traced westwards from the type section, particularly in Rocky Plantation where the massive coarse-grained lithology is not exposed and in Strawberry Hill Plantation where the coarse-grained rhyodacitic to andesitic tuffs and lapilli tuffs are only tentatively correlated with the Benscliffe Member. The Benscliffe Member represents a zone of varying stratigraphic thickness of interdigitating coarse-grained tuffs, lapilli tuffs and volcanic breccia that can be used as a stratigraphic marker horizon only over small areas. The variations in the lithology and thickness prevent its use as an accurate marker horizon throughout Charnwood Forest.

(ii) *The Beacon Tuffs Member*

Previously referred to as the Beacon Hill Beds (Watts, 1947), the base of the Beacon Tuffs Member is exposed in Benscliffe Wood (51441244), at Ingleberry Rock (49001730) and on the M1 (Birch Hill) cutting (48211345). The top of the Member is not exposed. The type section is at Beacon Hill (50941481) where there is the following succession:

Interbedded coarse-grained tuffs with subordinate tuffaceous pelites and dust tuffs	55.1 m
c. 14m of strata not exposed. Thickly bedded coarse-grained tuffs with some thin tuffaceous pelites and dust tuffs	27 m
Dust-tuffs	0.8 m
Coarse-grained tuffs	2.8 m
Dust-tuffs	0.8 m
Dust-tuffs with subordinate coarse-grained tuffs	2.8 m
Very thickly bedded coarse-grained epidotic tuffs	2.8 m

The Beacon tuffs Member consists of coarse-grained tuffs, pelites with subordinate grewackes. It is exposed on the north-east limb of the main anticline in Longcliffe Quarry (49331700), on Nanpantan Hill (49951686 and 50021694), at Whittle Hill (49911577), on Beacon Hill, Broombriggs Hill (51471422 and 51821428) and Ling Hill (52151257 and 51291229). West of Benscliffe Wood and the Member is very poorly exposed and estimates of the stratigraphic thickness vary because of this and structural complications, particularly folding in the Beacon Hill — Broombriggs area.

Of the wide range of rock types in this Member the coarse-grained tuffs range from rhyodacitic to trachyandesitic; the dust tuffs are rhyolitic. Subordinates vitric tuffs, which are restricted to the type section, contain acicular and Y-shaped moulds of shards orthogonal to bedding in a dust-tuff matrix. The shard moulds indicate the former presence of glass shards that fell 'end-on' into unconsolidated dust.

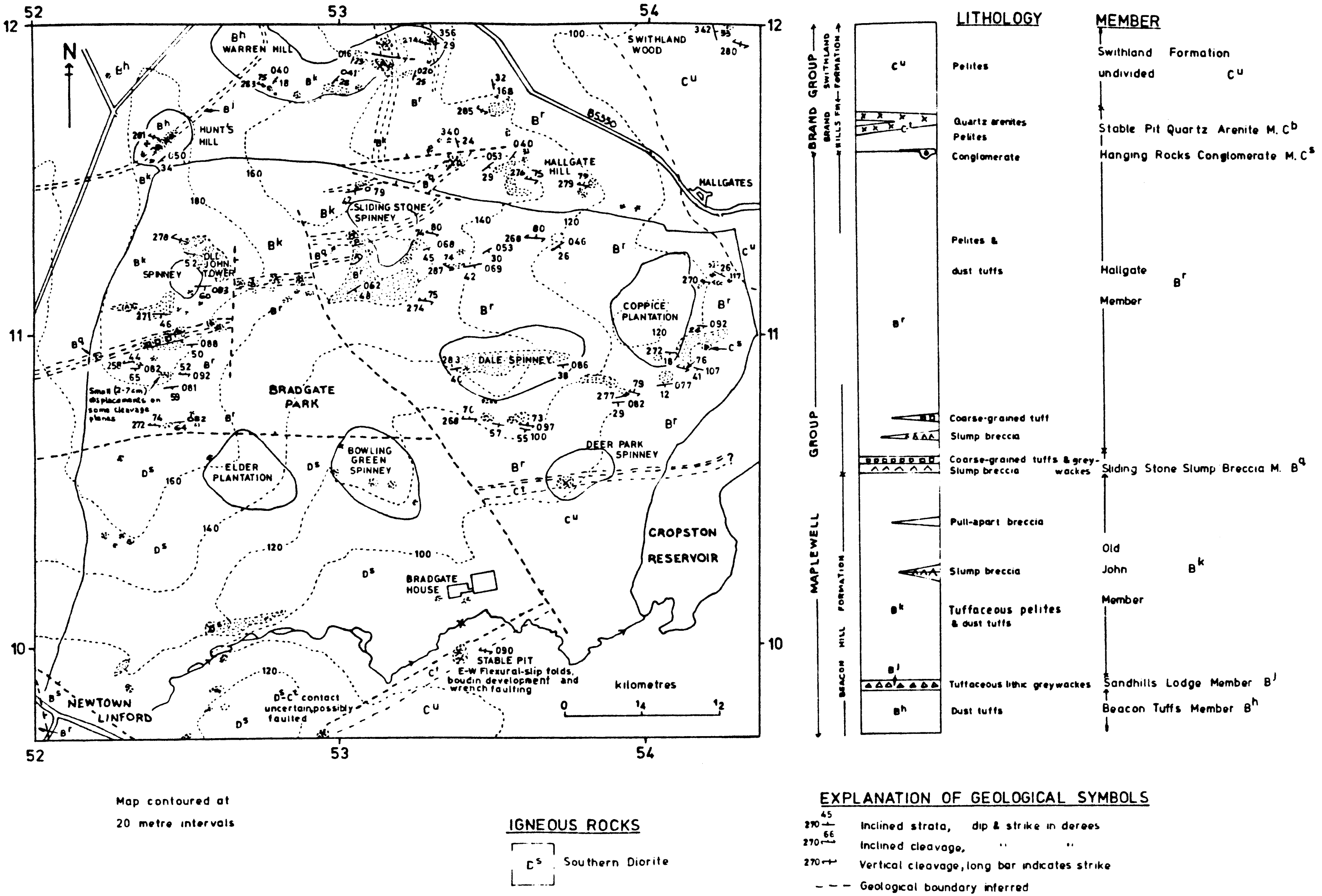

Fig. 2. Detailed geological map of the Bradgate Park area.

(iii) *The Sandhills Lodge Member*

The top and base of this Member are not seen and although exposed at only eight localities it has some value as a stratigraphic marker consisting mainly of coarse-grained lithologies that separate the dominantly fine-grained overlying and underlying Members. The type section for the Member is near Sandhills Lodge (50251100, table 4) and it can be traced to Stinking Wood and new Plantation (49921089) where breccias are interbedded with coarse-grained tuffs. Tracing the Member eastwards 9.4 m of coarse-to fine-grained tuffaceous lithic greywackes are exposed on Hunt's Hill (52441161) and weathered breccias at Maplewell School (52201323). The breccias contain pelitic clasts and, like the greywackes, grains of trachyte and devitrified rhyolite. To the north, near the Buck Hills, 10.7 m of coarse-grained tuffs (50291639 and 50471569) and lapilli tuffs (50361621 and 50411603) are petrographically similar to and tentatively correlated with those seen in the type section (table 4).

(iv) *Old John Member*

The base of this Member is not seen but the top is exposed on the Charnwood Forest Golf Course (52201550), Warren Hill (55131188) and the M1 (Hollies) cutting (47871172). At each of these localities tuffaceous pelites, dust tuffs and subordinate coarser-grained tuffs are overlain by the Sliding Stone Slump Breccia Member. The type section is in the north-west part of Bradgate Park where there is the following semi-continuous exposure around the War Memorial (52441109) and Old John Tower (52561125): (fig. 2)

Sliding Stone Slump Breccia Member	9.1 m
Interbedded tuffaceous pelites, dust tuffs, and coarse-grained tuffs c. 57 m of strata not exposed	72.5 m
Tuffaceous pelites, dust tuffs and subordinate coarse-grained tuffs	12.6 m
Coarse-grained tuffs with thin dust tuffs c. 18 m of strata not exposed	5.7 m
Dust tuffs and tuffaceous pelites	18.5 m
Sandhills Lodge Member	9.4 m

A pull-apart breccia 67.6 m below the top of the Member (53091148) is not exposed again in the southeast of Charnwood Forest, but one does crop out 98.3 m below the top of the Member in the A50 cutting (48611095):

Coarse-grained tuffs	2.8 m
Tuffaceous pelites, dust tuffs and subordinate coarse-grained tuffs	0.2 m
Coarse-grained tuffs	0.2 m
Coarse-grained tuffaceous lithic greywacke grading upwards into tuffaceous pelite	0.1 m
Coarse-grained tuffaceous lithic greywacke with pull-apart breccia at base	1.4 m
Coarse-grained tuffaceous lithic greywacke with large and small clasts of pelite and tuffaceous pelite	0.8 m
Coarse-grained tuffs	0.1 m
Coarse-grained lithic greywackes with pull-apart breccias	2.0 m

The Member can be traced north-eastwards from the type area to Warren Hill (53001180), Spring Hill Wood (52801270), Windmill Hill (52621430), Longhill Plantation (51521535) and the Charnwood Forest Golf Course (52201550). North of grid northing 15 it interdigitates with the Outwoods and Buck Hills Members (table 5) and shows a slight coarsening. Westwards the Member can be traced to Ulverscroft Mill (51441080), where there are pelites and coarse-grained tuffs, and to the A50 and M1 cuttings. Tuffaceous pelites predominant in this Member over rhyolitic to andesitic tuffs, greywackes and pull-apart breccias. The latter contain elongate pelite clasts lying approximately parallel to bedding in coarse-grained andesitic tuffs.

(v) *The Buck Hills Member*

The development of this Member is confined to the north-east of the Forest (Table 5), where it cannot be traced south of Blackbird's Nest Farm (51351557) or to the north of the Home Farm (50481672). Exposures are in the Buck Hills where the following type section occurs between 50901624 and 50971633:

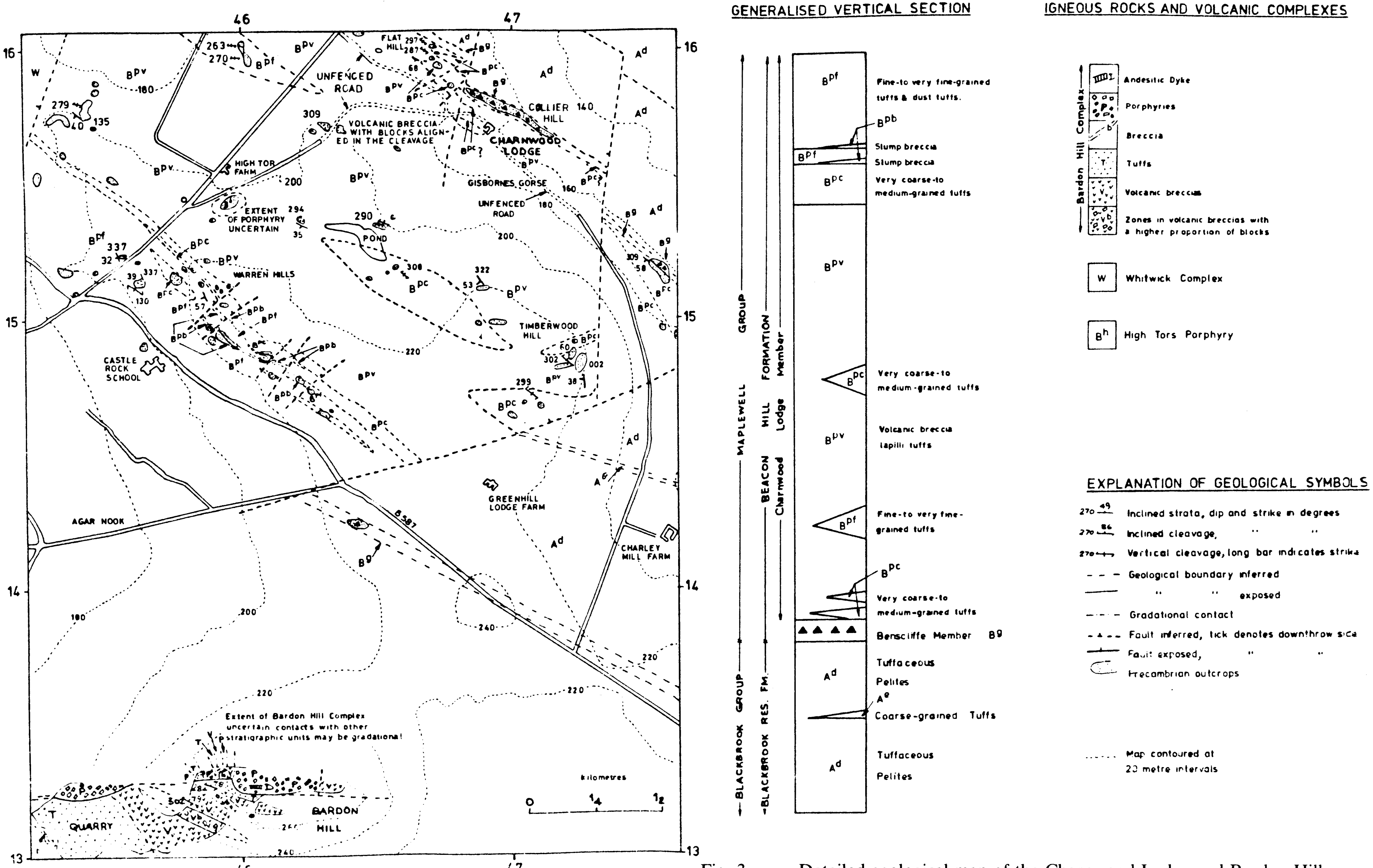

Fig. 3. Detailed geological map of the Charnwood Lodge and Bardon Hill area.

Coarse-grained tuff	10. m
Coarse-grained rhyodacitic to andesitic tuffs with some rhyolitic dust tuffs	149.2 m
Coarse-grained tuffaceous greywackes	12.2 m
Breccias	3.5 m

The breccias and 10.8 m of coarse-grained tuffs which mark the base and top of the Member respectively wedge out to the north and south away from the type section. When traced southwards all the coarser-grained lithologies thin and become finer-grained, until the very thin coarse-grained tuffs at 51291576 are thought to represent the most southerly development and feather-edge of the Member.

(vi) *The Outwoods Member*

The following type section is in the Outwoods (51371662):

Coarse-grained tuffs with channelling and an associated breccia	38.0 m
Coarse-grained tuffs	16.9 m
Lapilli tuff	6.3 m
Slump breccia	9.5 m

South of this also in the Outwoods (51451638) is a partially exposed, thinner succession

Conglomerate, conglomeratic coarse-grained tuff with a subordinate slump breccia	6.2 m
Coarse-grained tuffs	9.2 m
Dust tuffs and coarse-grained tuffs	0.5 m
Lapilli tuff	6.2 m

The Old John Member, which interdigitates with the Outwoods Member (table 5), can be seen to underlie the slump breccia at 51371662 and to overlap the conglomerate at 5141638; otherwise the base and top of the Member are not exposed. On the Charnwood Forest Golf Course a very thin band of conglomeratic tuff (52091539) may represent the feather-edge of the Outwoods Member which thins southwards from the type section.

Tuffs are of rhyodacitic to andesitic composition; pebbles and lithic grains from the conglomerate include of quartz, quartzite, trachyte and a quartz-feldspar rock.

This Member also occurs in the north-east but is not developed south of northing 15 nor exposed north of northing 17.

(vii) *The Charnwood Lodge Member*

The development of the Charnwood Lodge Member is confined to the area around Charnwood Lodge and Mount St. Bernard Abbey and, as it overlies the Benscliffe Member, it is thought to be contemporaneous at least with the lower part of the Beacon Tuffs Member and may be correlated with the Bardon Hill Complex (section 8b). The following type section is in the Nature Reserve between Flat Hill (4651606) and Warren Hills (46051481): (fig 3)

Coarse-grained andesitic tuffs with thin dust tuffs and tuffaceous pelites	214.0 m
Slump breccia	0-1 m
Coarse-grained andesitic tuffs	92.0 m
Volanic breccias, lapilli tuffs and subordinate coarse-grained tuffs	980.0 m
Benscliffe Member	

The top and the base of the Charnwood Lodge Member are not exposed. West and east of the type section there is a thinning and fining respectively of the volcanic breccias, lapilli tuffs and coarse-grained tuffs with the resultant development of finer grained tuffs. The thick accumulation of nearly 1000 m of volcanic breccias and lapilli tuffs suggests the existence of an adjacent volcanic centre (section 8). From the stratigraphical and petrographical evidence it is impossible to tell if the slump breccias exposed on Warren Hills should be correlated with those of the Sliding Stone Slump Breccia Member (section 5b(i)) as originally suggested by Watts (1947). The Charnwood Lodge Member is not exposed east of Little Hill (47621493) or west of Mount St. Bernard Abbey (45781621) where it is faulted against the Blackbrook Group and Whitwick Complex respectively.

(*b*) *The Bradgate Formation*

The Bradgate Formation is divided into the Hallgate and Sliding Stone Slump Breccia Members: the type section for both Members is in the Bradgate Park-Warren Hill-Hallgate Hill area.

(i) *The Sliding Stone Slump Breccia Member*

This Member was previously known as the Slate Agglomerate (Watts, 1947). It can be used as a stratigraphic marker horizon with some confidence around the southern half of Charnwood Forest (fig. 3). Thinner, discontinuous slumped horizons within the Old John and Hallgate Members suggest an intermittent zone of slumping in which the Sliding Stone Slump Breccia Member is the main component. The base of the Slump Breccia Member and of the Bradgate Formation is exposed on Warren Hill (53131188), at the Altar Stones (48431094) and on the M1 (Hollies) cutting (47861169). On Hangingstone Hills (52221559) the Member has thinned to a minimum and here the top and base are exposed. The top of the Sliding Stone Slump Breccia Member is seen in Bradgate Park (52401097 and 53061130) and on Warren Hill (53231187).

The Sliding Stone Slump Breccia Member is traced easily across Bradgate Park into Hallgate Filter Station grounds (53391156) and on to Warren Hill. North of this area, at Roeclife (53231276) a slump breccia is intercalated with coarse-grained tuffs (18.4 m). At Windmill Hill a very small outcrop (52631440) of slump breccia is tentatively correlated with the Sliding Stone Slump Breccia Member. On the Hangingstone Hills the Member thins northward to its minimum development beyond which it is not exposed and presumably has wedged out. West and north-west of Bradgate Park the Member is recognised at Field Head (47951026), the Altar Stones (4843-092), an M1 cutting (47861169) and possibly near Hobby Hall (47191213). The stratigraphic horizon of the zone of thin, discontinuous slump breccias found on the Warren Hills (46051481) is uncertain (section 5a (vii)).

(ii) *The Hallgate Member*

The base of the Hallgate Member, formerly the Woodhouse and Bradgate Beds (Watts, 1947), is exposed in Bradgate Park (52401097 and 53061130) and on Warren Hill (53231187) where dust tuffs and tuffaceous pelites are underlain by the Sliding Stone Slump Breccia Member, and on the Hangingstone Hills (52221559) where the Breccia has almost completely wedged-out (see above). The top of the Member is exposed at Billa Barra Hill (46581142) and on the Hangingstone Hills (52451496) where tuffaceous pelites are overlain conformably by coarse-grained crystal lithic tuffs of the Brand Hills Group and conglomerates of the Hanging Rocks Conglomerate Member respectively. In the north-east of Bradgate Park, an area complicated by minor folding, no contact is exposed but pelites of the Hallgate Member (54081087, 54141094 and 54221120) appear to be succeeded by coarse-grained sedimentary rocks of the Brand Hills Group. The predominantly fine-grained strata of the Hallgate Member (dust tuffs, tuffaceous pelites, pelites and medium-grained greywackes) are best exposed in Bradgate Park (53851085, 53491074 and 53151115), on Hallgate Hill (53531174 and 53541151), at Broombriggs (52701450) and on the Hangingstone Hills (52221554). In the north-east the Member is terminated by faulting. The most westerly exposure of the Hallgate Member is at Bardon Lodge (45771188).

In the type area the Member is 640 m thick and thins towards the north-east where there is the complication of faulting in the Brand-Roecliffe area. To the west poorly exposed folding and a faulted contact with the Southern Diorites precludes an accurate estimate of the thickness.

The Hallgate Member contains the fossiliferous beds noted by Ford (1958, 1963, 1968, 1980), Boynton (1978), and Boynton & Ford (1979). The impressions of *Charnia masoni, Charniodiscus concentricus, Pseudovendia charnwoodensis* and various medusoids have all been found a few metres above the base of the Member.

The Brand Group

This Group is intermittently exposed around the eastern, southern and south-western margins of the Forest (fig. 1) and is divided into the Brand Hills and Swithland Formations (table 6). Type sections for the Group are in Bradgate Park (53400999), on the Charnwood Forest Golf Course (52461497) and the Brand Estate, including part of Swithland Wood.

Table 6 The stratigraphic divisions of the 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	*Hanging Rocks Conglomerate Members* Interbedded very coarse to very fine-grained tuffaceous greywacke with subordinate trachyandesitic crystal lithic tuffs — 40 m Tuffaceous conglomerates with conglomeratic greywackes — 7 m Similar lithologies at about the same horizon are developed at small outcrops in Bradgate Park and at Bardon. Coarse-grained trachyandesitic crystal lithic tuffs on Billa Barra Hill are at the same horizon as in the type section	*Stable Pit Quartz Arenite Members* Pelites — 2.2 m (cut by clastic dykes of quartz arenite) Quartz arenites and greywackes — 0.9 m Breccia — 1.8 m (pelite clasts in a quartz-arenite matrix; equivalent greywackes also have pelite clasts) Quartz arenites and greywackes — 4.3 m (greywackes from The Brand may represent facies equivalents of the quartz arenite lithology — 94.7 m)

(*a*) *The Brand Hills Formation*

This Formation is divided into the Hanging Rocks Conglomerate and Stable Pit Quartz-arenite Members which are discontinuous and show lithological variations and consequently are of little value as stratigraphic markers.

(i) *Hanging Rocks Conglomerate Member*

The type section, in which the base and top of the Hanging Rocks Conglomerate Member are exposed, is at the Charnwood Forest Golf Course on the Hangingstone Hills (52461497, table 6) and at this locality the base of the Member represents the base of the Brand Group. The tuffaceous conglomerate in the type section consists of a mature fraction of pebbles and lithic and quartz grains, an immature fraction of elongate pelite clasts and euhedral and broken feldspar and quartz phenocrysts. The 40 m of fine-grained greywackes overlying the conglomerate are petrologically comparable to the coarser-grained rocks in the Hanging Rocks Conglomerate Member, and not to the succeeding greywackes of the Swithland Formation (table 6). Pebbles and lithic grains found in this Member consist mainly of quartz, quartzite, trachyte or rhyolite; less common are grains of granite and schist. To the north of the type section the Member is not exposed and to the south its outcrop is terminated by a small fault. In Bradgate Park (54211097) the Hanging Rock Conglomerate Member crops out at a lower topographic level than the adjacent crags of pelite of the underlying Hallgate Member. An excavation around this outcrop revealed an irregular base to the conglomerate which was underlain by very fine- to very coarse-grained tuffaceous lithic greywackes.

The conglomerate contains a block of pelite (43 × 21cm × 30cm) and is thought to represent deposition in a channel that locally scoured and eroded the top beds of the Hallgate Member.

Tuffaceous lithic greywackes at Bardon (44711267) and crystal lithic tuffs on Billa Barra Hill (46601134) are tentatively correlated with the Hanging Rocks Conglomerate Member. As the Member is exposed at only four localities it is a poor stratigraphic marker. It is thought to consist of discrete lenses developed at approximately the same stratigraphic level.

(ii) *Stable Pit Quartz-arenite Member*

The type section for the Stable Pit Quartz-arenite Member, previously called Trachose Grit and Quartzite (Watts, 1947), is the Stable Pit in Bradgate Park (53400999, table 6). From here the Member can be traced to Deer Park Spinney (53761052), Lady Hay Wood (51700832) and New Plantation (50230900). On the Brand Hills where the top of the Stable Pit Quartz Arenite Member is exposed (53481322 and 53641315) there is the following facies equivalent to the typical quartz-arenite lithology:

Swithland Formation	
Very coarse-grained greywackes with clasts of pelite and interbedded thin pelites	15.2 m
Pelites, with some fine- to coarse-grained lithic greywackes	79.5 m
Base of Member not exposed	

This correlation is based on the petrological comparison between and the gradation from quartz-arenites and quartzwackes at the Stable Pit and Deer Park Spinney to comparatively mature greywackes on the Brand Hills. This Member is of limited value as a stratigraphic marker as it can only be traced around the south of Charnwood Forest.

Secondary enlargement of the rounded quartz grains by quartz overgrowths is common in the quartz-arenites: the contact between overgrowth and detrital grain is sometimes marked by a thin film of chlorite. Lithic grains in the greywackes are mainly of quartzite, and there is also a minor feldspar fraction.

(*b*) *The Swithland Formation*

The type section for the Swithland Formation, which is not subdivided into Members, is on the Brand Estate and in the northern part of Swithland Wood:

Pelites with very fine- to fine-grained lithic greywackes	250.0 m
Interbedded shale-pebble conglomerates, pelites and greywackes	7.0 m
Stable Pit Quartz-arenite Member	

The occurrence of shale-pebble conglomerates near the base of the Formation in the type section is not recognised as a reliable indicator of stratigraphic position. Although similar conglomerates near Nanpantan (51051737) and Swithland Camp (53731200) are close to the base of the Swithland Formation they are absent from this stratigraphic level on the Charnwood Forest Golf Course (52531508) and in the Groby Parks area (50170877). The base of the Swithland Formation is also exposed on the Charnwood Forest Golf Course (52481509) where 54 m of pelites and very fine-grained greywackes succeed the Hanging Rocks Conglomerate Member. The highest strata of the Swithland Formation and of the Charnian Supergroup are pelites and very fine-grained lithic greywackes on the margin of Swithland Wood (54131285 and 54221220). There are excellent sections in the old flooded quarries in the Brand and Swithland Woods from which Swithland Slate was once obtained (53841336, 53851312, 53761310, 53721322, 53901314, 53871300 and 53901218). In the south-west of Charnwood Forest there are c. 160 m of folded pelites and greywackes in the area of Little John (50120830), Bradgate Home Farm (51050830 and 50810824), Groby Upper Park (49680915), Burchnall Spinney (49730900) and Groby Lodge (50390782).

Sedimentary rocks of uncertain stratigraphic position

In the Grace Dieu area in the extreme north-west of the Forest there are tuffs and shale-pebble conglomerates whose stratigraphic position is unresolved (fig. 1). The most northerly outcrop (43951878) of the Charnian Supergroup consists of weathered, hematite-stained dust tuffs and coarse-grained tuffs that are tentatively placed in the Blackbrook Group. At three localities near Grace Dieu Warren, which are all close to the fault zone that delimits the Whitwick Complex, there are tuffaceous shale-pebble conglomerates (44361768 and 44191780) and coarse-grained tuffs (44051759). From the same area Watts (1947, p. 59) described a 'fine-grained slate breccia' (presumably a shale-pebble conglomerate) exposed in a small quarry 366 m south-west of Spring Barrow Lodge (44901792), now filled in.

Igneous Complexes

In the north-west of Charnwood there are the remnants of one or more volcanic centres here called the Whitwick and Bardon Hill Complexes (fig. 4). On stratigraphic and petrographic evidence the latter may be correlated with the Charnwood Lodge Member. It is thought that these calc-alkaline complexes originated as an explosive volcanic arc on the north-west margin of a basin in which the Charnian sediments accumulated. Vulcanicity became dormant or extinct during Brand times.

(*a*) *The Whitwick Complex*

This is composed mainly of fine- to coarse-grained volcanic breccias and extrusive acid to intermediate dacitic quartz-feldspar-porphyries, with subordinate breccias, lapilli tuffs, very coarse- to medium-grained tuffs and dust tuffs (fig. 4). The type section occupies kilometre squares SK 44.16 and 44.17 and consists of the porphyries at High Sharpley (44771705) and High Cademan (44181690), and volcanic breccias (44031680 and 44501724). Contacts with the tuffaceous shale-pebble conglomerates at Grace Dieu Warren (section 7) and the Bardon Hill Complex are faulted. Bedding or layering is rarely preserved so it is difficult to estimate the thickness of the porphyries and volcanic breccias. The distinctive colouration of the purple groundmass and red, corroded, embayed quartz phenocrysts in the porphyries are due to secondary hematite impregnation. Broken, euhedral and twinned feldspar phenocrysts are of orthoclase, albite, oligoclase and andesine. The plagioclases are sometimes zoned with reverse zoning suggesting mixing. Contacts between volcanic breccias and porphyries are gradational, unless faulted, partly because the matrix and groundmass of breccias and porphyries are recrystallized and partly due to the development of friction breccias by autobrecciation at porphyry margins. Some rounding of the blocks in the volcanic breccias has occurred and may be due to fluidization prior to expulsion and/or downslope movement after explosive ejection in the manner of 'Cannonball bombs' (Francis, 1973).

(*b*) *Bardon Hill Complex*

The quarried area of Bardon Hill represents the type section where the Bardon Hill Complex is composed of acid to intermediate dacitic quartz-feldspar porphyries (petrologically similar to those of the Whitwick Complex), and of the lithologies previously referred to as Bardon Rock (Watts, 1947) which are volcanic breccias, tuffs and brecciated porphyries. Distinguishing between igneous and clastic rocks in the Bardon Hill Complex is often difficult because groundmasses and matrices have been recrystallized obliterating any diagnostic fine textures, and the framework constituents (euhedral and broken quartz and feldspar phenocrysts) of tuffs and porphyries are similar. Evidence for clastic origin is found in some grains which consist of an embayed, cracked quartz phenocryst partly surrounded by original igneous groundmass and abraded feldspar and trachytic grains. These volcanic breccias and tuffs may be correlated with the Charnwood Lodge Member of the Maplewell Group (see Table 5), for both are underlain by the Benscliffe Member at Abbots Oak (46411425) and Collier Hill (4901580) respectively. Also thin slump breccias occur near the top of both stratigraphic units. In Bardon Hill Quarry recent quarrying activities (1983) show the porphyry is intrusive as a small dome some 50 m across into dominantly clastic rocks, some of the clasts being identical with the dacite of the dome, suggesting the dome and its clastic envelope probably belong to a single volcanic episode. Later, sheared dykes, striking 088°, cut the porphyries and may be the same age as a similar dyke in Whitwick Quarry.

Discussion and Conclusions

The Charnian Supergroup is composed of some 3500 metres of thickly-bedded tuffs, pelites and greywackes with comparatively thinly-bedded slump breccias, volcanic breccias, conglomerates and quartz-arenites that have been used previously as long range stratigraphic markers. These special lithologies used by Watts characterize submarine volcanic piles and cannot be regarded as once-only unique events. For example, the discovery of a slump breccia within the Blackbrook Group approximately 1400 m below the Sliding Stone Slump Breccia Member,. and lapilli tuffs within the Sandhills Lodge Member 350 m above the Benscliffe Member indicate that long range correlation of the same lithology is not feasible. Stratigraphic markers such as the Sliding Stone Slump Breccia, Outwoods and Buck Hills Members thin to a feather-edge and these are only of local use for correlation purposes, although still extremely valuable as the only practical means of establishing a stratigraphy. Stratigraphic marker units are rarely composed of one continuous bed, but usually consist of discrete lenses, as in the Hanging Rocks Conglomerate Member, or more than one bed of the same rock type that may or may not be interbedded with finer-grained rocks as in the Sliding Stone Slump Breccia Member. Slump breccias, volcanic breccias, conglomerates and quartz-arenite are inconsistent in thickness and extent and the compilation of the stratigraphy of the predominantly volcaniclastic Charnian succession has been based on dovetailing these short range stratigraphic markers within a pelitic sequence in the absence of reliable regional ones.

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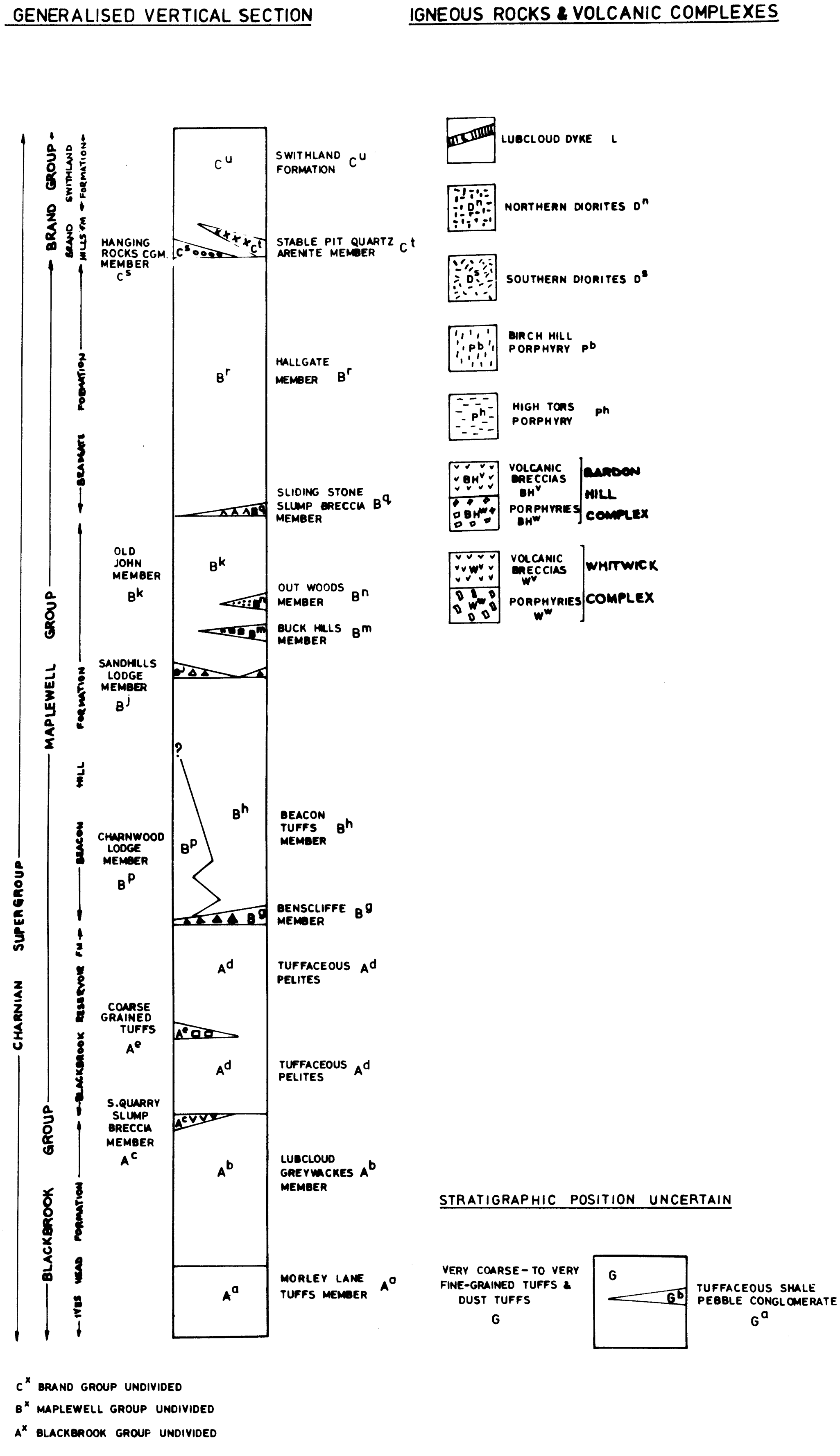
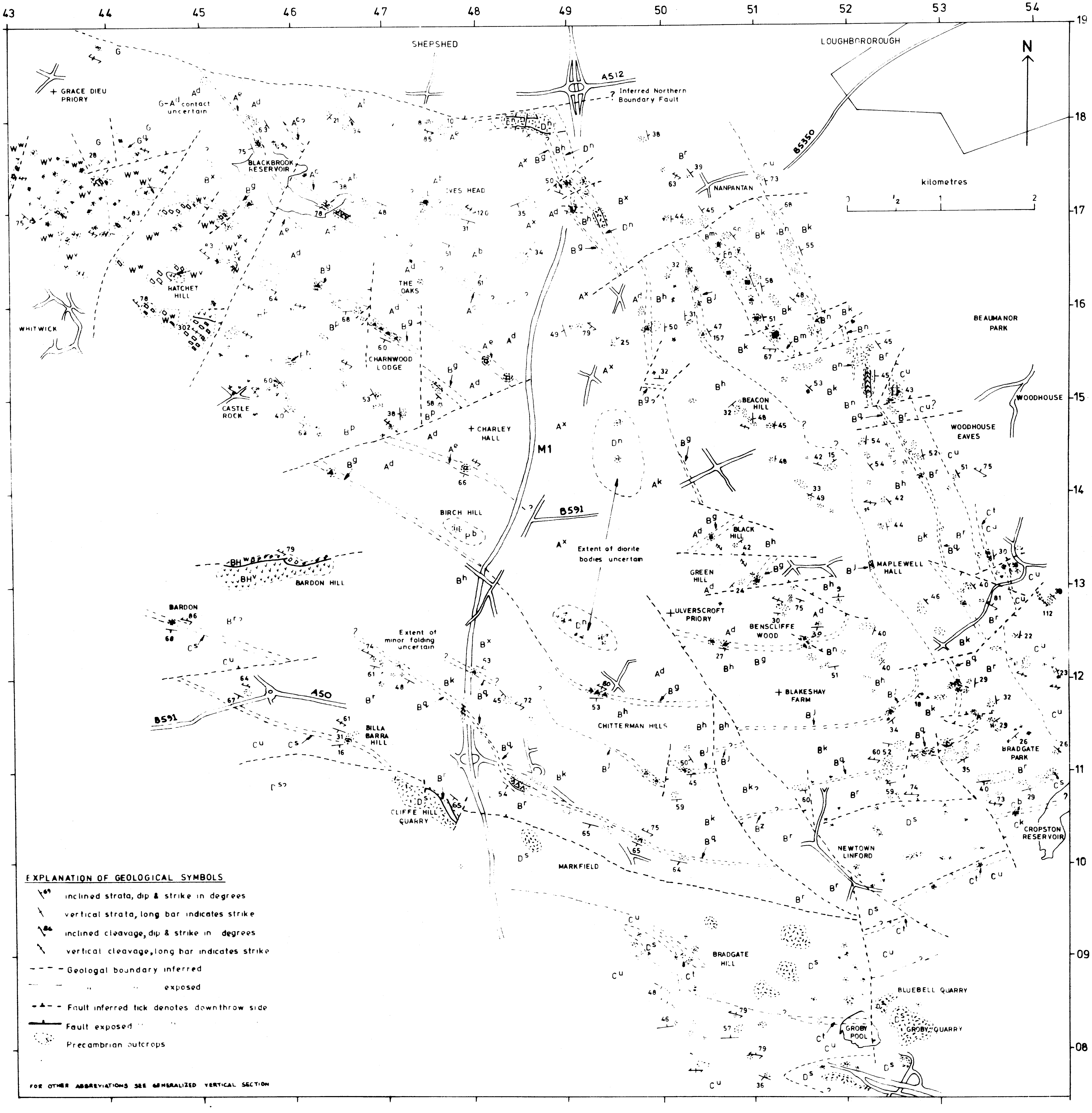


Plate 1 Detailed geological map of the Late Precambrian rocks of Charnwood Forest. (Key above and folded map on facing page)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? Inferred Northern Boundary Fault
B5350
+ GRACE DIEU PRIORY
G-A^d contact uncertain
BLACKBROOK RESERVOIR
IVES HEAD
NANPANTAN
HATCHET HILL
WHITWICK
THE OAKS
CHARNWOOD LODGE
BEAUMANOR PARK
CASTLE ROCK
+ CHARLEY HALL
BEACON HILL
WOODHOUSE
WOODHOUSE EAVES
M1
B591
BIRCH HILL
Extent of diorite bodies uncertain
BLACK HILL
GREEN HILL
MAPLEWELL HALL
BARDON HILL
BARDON
+ ULVERSCROFT PRIORY
BENSCLIFFE WOOD
Extent of minor folding uncertain
A50
B591
BILLA BARRA HILL
+ BLAKESHAY FARM
CHITTERMAN HILLS
BRADGATE PARK
CLIFFE HILL QUARRY
MARKFIELD
NEWTOWN LINFORD
CROPSTON RESERVOIR
BRADGATE HILL
BLUEBELL QUARRY
GROBY POOL
GROBY QUARRY
EXPLANATION OF GEOLOGICAL SYMBOLS
inclined strata, dip & strike in degrees
vertical strata, long bar indicates strike
inclined cleavage, dip & strike in degrees
vertical cleavage, long bar indicates strike
Geologal boundary inferred
" " exposed
Fault inferred tick denotes downthrow side
Fault exposed " "
Precambrian outcrops
FOR OTHER ABBREVIATIONS SEE GENERALIZED VERTICAL SECTION

RELATIVE SEA-LEVEL MOVEMENTS, PALAEO-HORIZONTALS AND THE DEPOSITIONAL RELATIONSHIPS OF UPPER ORDOVICIAN SEDIMENTS BETWEEN CORRIS AND BALA, MID WALES.

by

D.M.D. James

Summary

Consideration of palaeo-horizontals and sediment thicknesses allows construction of palaeostratigraphic sections within which relative depositional water depths may be estimated after correction for compaction and tectonic strain. Angular relationships between successive palaeo-horizontals document relative tectonic tilting and sedimentary facies document the influence of base level changes. The analysis clarifies the depth range and depositional environment of the Allt-ddu Mudstones and the Nod Glas and proposes the correlation of the intra-Hirnantian glacioeustatic sea-level fall with the boundary between the Lower and Upper Garnedd-wen Beds of W.J. Pugh.

Introduction

Following the lead of Curtis (1970) and Vail *et al.* (1977), stratigraphers have increasingly thought of sedimentation in terms of relative sea-level movement. Positive or negative aggradation and progradation is now recognized not only in the transgressive/regressive sequences of shallow marine strata but also in their time-equivalents in deep water either by distinctive geometries (e.g. Bosellini, 1984) or by distinctive facies sequences (e.g. May *et al.*, 1984). Over the last decade it has also become increasingly appreciated that fluctuations of absolute sea-level related to global tectonic or climatic processes can be of great chronostratigraphic value - particularly in certain types of tectonic province (e.g. passive continental margins) where absolute and relative sea-level movements are often closely correlated. Moreover, fluctuations related to short period glacio-eustatic processes are often associated with distinctive sedimentary facies (or facies sequences) and are increasingly recognized as of chronostratigraphic significance (e.g. Brenchley and Newall, 1980; Williams and Wright, 1981).

After removal of the effects of compaction and (if necessary) tectonic strain, major thickness variations in time-equivalent strata relate either to filling of variable topographic relief or to variable rates of contemporaneous tectonic movement. Sedimentology, particularly in the identification of depositional surfaces approximating to the palaeo-horizontal (i.e. parallel to the plane of contemporary sea-level) and of facies sequences indicative of changing depositional base level, should allow distinction between these possibilities. An informative example of this type of approach in a tectonically active basin is given by Nagtegaal et al. (1983). It is commonly the case that the results of both end-member processes (i.e. static infill or variable subsidence beneath constant base level) are present in a thick sedimentary succession and in such cases it is particularly instructive to draw a sequence of palaeo-stratigraphic sections hung from palaeo-horizontals. If bulk strain effects can be removed, the geometry of such sections allows the relative water depths at deposition to be calculated and the effects of tectonic tilt between sections to be isolated.

This paper looks at some classic deep to moderately shallow water marine sequences of Upper Ordovician (Caradoc-Ashgill) age in north central Wales with the above considerations in mind. It will be found that several new insights result and that several problems are highlighted.

Mercian Geologist, vol. 10, no. 1, 1985, pp. 19-26, 3 figs.

The palaeo-stratigraphic sections

Basic data

The location of the sections is shown in fig. 1. The area discussed lies on the southeast flank of the Harlech Dome and the continuous Ashgill-Caradoc outcrops between Corris and Bala lie north of the Ashgill inliers of central Wales at and around Plynlimon (James, 1983a). Data to construct the sections given in fig. 2 have been drawn from: Bassett (1972), Bassett, Whittington & Williams (1966), James (1972), Lockley (1980), Pugh (1923, 1928, 1929) and Schiener (1970). The country southwest of Corris towards Towyn, studied by Jehu (1926) and James (1973), is not treated in fig. 2 since the problems of interpretation of the Ashgill-Caradoc are essentially the same as at Corris.

Palaeo-horizontals

Each of the sections in fig. 2 comprises a sedimentary package bounded at (or near) its top by a palaeo-horizontal. This, of necessity, is only approximate, the theoretical ideal being probably only approached by suspension deposits in ponded basins. Nevertheless, the palaeo-horizontals chosen are certainly of very low initial gradient, at least in the plane of section, and within the limits of precision of the thickness data used in fig. 2 may be treated as parallel to sea-level. The palaeo-horizontal criteria used include erosional unconformities in shallow marine sequences; thin, areally extensive, tuff horizons preserved in shallow water or partly subaerial sequences and top surfaces of turbidite bodies deposited from fully turbulent suspensions.

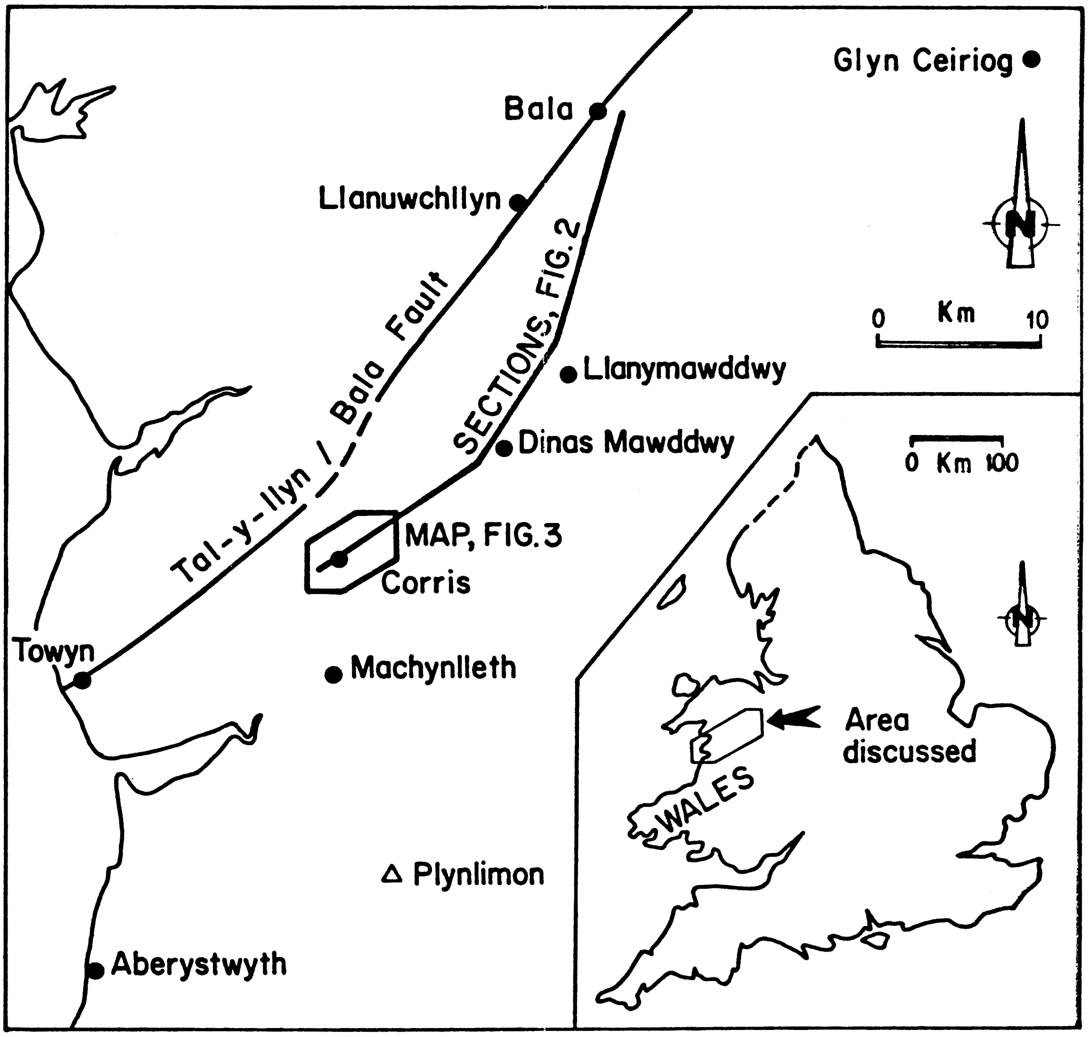

Fig. 1 Location maps for the Corris - Bala country.

Angular relationships

The data of fig. 2 is of course two-dimensional and all angular relationships shown therein are to variable extent minima. Nevertheless, within the plane of section relative tectonically induced tilts and relative water depths can in principle be calculated. To do this, corrections for overburden induced compaction (which may be differential) are required as also, since the strata are variably cleaved, are corrections for extension in tectonic *a*. Rigorous corrections of this nature are not possible since compaction is somewhat variable in different sedimentary provinces and also since no details of tectonic strain are available for the Upper Ordovician sequences studied. However, some approximations are possible and set useful limits on the likely magnitude of the corrections.

Cleavage attitude is taken to be approximately vertical, based on published information. We assume that pre-cleavage sedimentary dip is approximately horizontal and thickening thus maximal (see Rast 1969, p. 322-3 for discussion) and that the sedimentary packages can be treated essentially as mudstone. Regional strain data (Rast, 1969; Coward & Siddans, 1981) suggest that extensions of less than 30% and more than 60% are improbable for the strata under consideration. Regional data on burial history (Smith & George, 1961) and metamorphic grade (Bevins & Rowbotham, 1983) suggest, assuming palaeo-geothermal gradients of 35° C/km at shallow crustal depths, a maximum burial of about 9 km including tectonic extension. Since burial below 6 km does not significantly decrease the already extremely low porosity at that depth, the decompaction calculation is not particularly sensitive to the tectonic extension within the range quoted above. The curve of Baldwin (1971) has been used for decompaction. Results show that initial relief of the Ashgill-Caradoc sequences under consideration in the plane of fig. 2 is likely to have been in the range of 30–50% *greater* than the apparent relative relief as currently measured without extension/decompaction corrections. Such relief/water depth will be termed 'non-corrected' below.

With the above in mind we can turn to a discussion of the stratigraphic subdivisions of each of the three packages depicted in fig. 2.

Caradoc

Figure 2 shows that two sediment packages can be recognized separated by a mild tilt of 0.5 degrees. Assuming no flexuring of the thick volcanic sequences under the 1.2 km thick mudstones of the Ceiswyn Formation, about half of this tilt is probably due to differential compaction. Noteworthy in the lower package is the regressive/transgressive character of the Glyn Gower Siltstones and the slope environment of the recently defined Llaethnant Formation (Lockley, 1980). The upper package indicates renewed regression overall with muddy slope foresets and silty topsets in the Allt-ddu Mudstones. A minor transgression separates the extreme regressions of the Pont-y-Ceunant Ash and the sequence immediately underlying the Cwmerig Limestone. The erosion surface at the top of the package parallels the strata within the topsets to a degree that suggests negligible tectonic warping as a contribution to the relative sea-level fall that created it.

In both Caradoc packages the components of foreset slopes in the plane of section are consistent with the Soudleyan palaeogeography shown by Brenchley & Pickerill (1980, fig. 8). The *Sericoidea* fauna of the Allt-ddu Mudstones (Lockley, 1980, p. 38) appears to have lived (if in-situ) in non-corrected water depths of about 200 metres or somewhat more.

Nod Glas

The age of this formation is not clear. Bassett (*in* Williams *et al.*, 1972) points out that it may range from Marshbrookian to at least Onnian but that it has also been thought to be solely Onnian (Cave, 1965). Price (1984, p. 103) assigns it solely to the Caradoc and the overlying Ashgill to no older than the Rawtheyan. Since the underlying Ceiswyn or Allt-ddu Formations are Longvillian, various contrasting view points can include both continuity of sedimentation and boundaries which are non-sequences, either above or below, see also Lockley (1980, p. 37 and fig. 7).

Figure 2 indicates that erosional boundaries are improbable, the characteristic black shale facies, the Corris Shale of Lockley (1980), accumulating in non-corrected water depths in excess of 250 metres. Thus the possibilities of non-sequence must be via sediment starvation rather than erosion since thinning due to slumping does not appear to be documented. Some degree of non-sequence is probable in view of the frequently phosphatic character of the Nod Glas, and the spatially allied Cowarch Phosphate Bed (Lockley, 1980, p. 33) by analogy with similar deposits (Baird, 1978). Moreover, the water depth estimate is also consistent with the depths

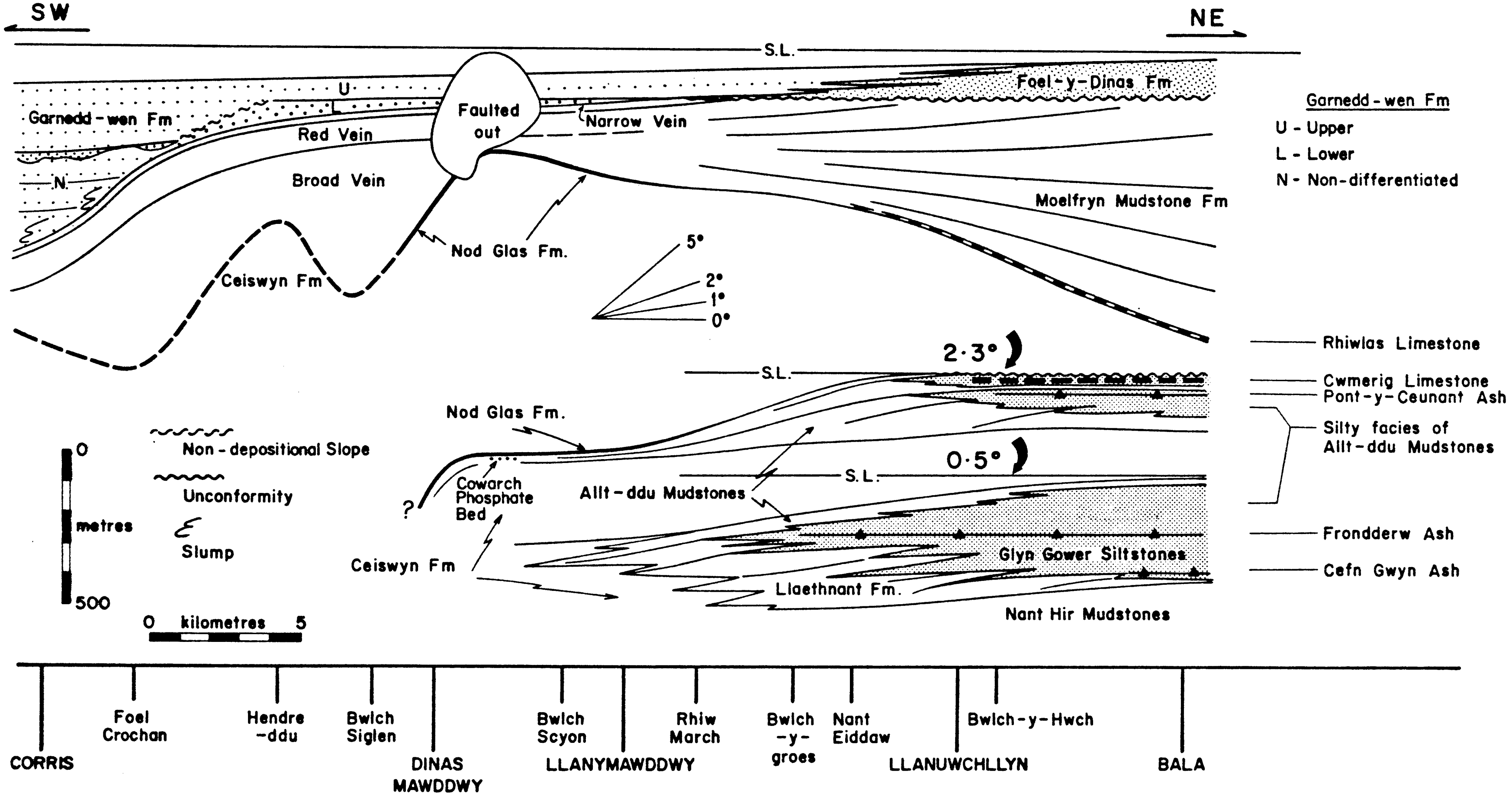

Fig. 2 Correlation and Sedimentological Restorations (Palaeostratigraphic sections) of Caradoc and Ashgill strata between Corris and Bala. Based on sources referenced in text. All thicknesses are present-day without differential tectonic thickening corrections and only the topmost portion of the Ceiswyn Formation is indicated. The lower two restorations, separated by only mild tilt, are Caradoc; the upper, overlying the major tilt, is Ashgill. The Nod Glas Formation is plotted in both Ashgill and Upper Caradoc restorations since it could well be of both ages in this area (Bassett, 1972, p. 27). Inset scale indicates angular relationships and strong arrows indicate sense and amount of rotation. S.L. Denotes sea-level.

of accumulation of modern examples (Bremner, 1980; Burnett, 1980; Marshall & Cook, 1980). In particular the upslope termination of the Nod Glas suggested by fig. 2 may be related to a depth limit below which nutrients were trapped by a thermocline (Leggett, 1980, p. 151). It is noteworthy that the area of transition between the distinctive facies of the Corris Shale and Dyfi Mudstone (Lockley, 1980, p. 36-39) corresponds with a rapid change of slope shown in fig. 2.

Ashgill

The major Nod Glas facies change in the vicinity of Dinas Mawddwy is mirrored thereabouts by changes within the lower part of the Ashgill; at higher levels the evident transgression post-dating the sub Foel-y-Dinas Formation unconformity at Bala (Bassett, Whittington & Williams, 1966) moves the area of facies transition to the NE.

The uniform nature and extremely variable thickness of the Moelfryn Mudstones, well illustrated by Lockley (1980), argues for differential tectonic subsidence SW of Bala; the identification of the sub Foel-y-Dinas unconformity as a palaeo-horizontal adds force to this suggestion. Whether or not the former slope area SW of Nant-Eiddaw at the termination of the Rhiwlas Limestone was ever onlapped by the Moelfryn Formation (a possibility not shown in fig. 2) awaits proof or otherwise of the continuity of Nod Glas sedimentation. It is interesting that the major angular discordance of 2.3° between the Ashgill and Caradoc packages was developed after an episode of faulting at Bala (Bassett, Whittington & Williams, 1966) which induced very local variation in the degree of pre-Rhiwlas Limestone erosion.

The Broad Vein (Abercwmeiddaw 'Group' of Pugh (1923)) poses problems for the restoration in fig. 2. The thicknesses are derived from Pugh's maps (1923, 1928) and appear very variable, in contrast with those for the Red and Narrow Veins which appear to be rather constant according to Pugh but which are not thick enough to redetermine with accuracy on the basis of his maps alone. Pugh did not mention variation of thickness and quoted only one figure, namely 457 metres (Pugh, 1923, p. 538). The uniform nature of the underlying Nod Glas might argue against infill of rugose topography; moreover the Broad Vein does not appear to be internally slumped. Where the writer has checked Pugh's maps, notably west of Corris where the Broad Vein appears to be only about 220 metres thick, the bounding formations appear accurately mapped and as yet unrecognized structural complications within the area of outcrop appear required for apparent major thickness variation. Further southwest of Corris similar problems appear in the ground mapped by R.M. Jehu (1926). The Broad Vein thickness is given by Jehu as 274-289 metres (*op. cit.*, p. 473) which is appreciably thinner than Pugh's estimate at Corris. However, Jehu's fig. 4 (*op. cit.*, p. 476) shows only 197-212 metres and further local apparent thinning was postulated as possibly due to internal strike faulting.

The Moelfryn Formation presumably passes laterally into the Broad Vein/Red Vein/Narrow Vein sequence with no major changes of depositional gradient between them. If the latter sequence were to onlap the Moelfryn Formation substantial depositional relief would be required around Rhiw March and the uniformity of facies mitigates against this. Faunal evidence is inconclusive but tends to support absence of appreciable onlap since the basal Ashgill appears always to be Rawtheyan in this area (Price, 1984, p. 103).

The *Foliomena* fauna of the basal Broad Vein (Harper, 1979, p. 440) appears consistent with the depositional depths exceeding 300 metres to be inferred from fig. 2 (*op. cit.*, p. 443).

Above the Narrow Vein, in the type area between Corris and Aberllefenni lie the Garnedd-wen 'Beds' and it is the internal geometry of these that is critical in postulating a chronostratigraphic correlation with the Foel-y-Dinas Formation. The key element in this geometry is the continuity of a prominent horizon of turbidites (a palaeo-horizontal) between Corris and Aberllefenni which both proves onlap against a slope and necessitates an extension of a component of this slope to the northeast since the turbidites are base-of-slope deposits displaying north-westerly transport (James, 1972). Map evidence for the continuity of this horizon has not previously been published and is given here as fig. 3b. It may be noted in passing that the new map removes the necessity for a violent twist in the axial trace of the Corris anticline (fig. 3a) about which Pugh was clearly uneasy (1923, p. 533).

This paper correlates the major arenite horizon, underlain by extensive slumped beds and overlain by rather uniform silty mudstones, with the boundary between the Upper and Lower Garnedd-wen 'Beds' (Pugh, 1928) which is seen as a regressive maximum. The succeeding transgression may conveniently be correlated with the first deposits above the intra-Ashgill unconformity at Bala (Bassett, Whittington & Williams, 1966); the overall regressive/transgressive couplet representing a response to late Hirnantian glacio-eustatic events. This correlation does not appear to have been made before and is not mentioned by Brenchley & Newall (1980, p. 27-28) in their discussion of the Hirnantian glacial event in Wales. If correct, it would refine correlation with other Ashgill sequences although the details of the sea-level fluctuations within the Hirnantian are not fully agreed (*cf* Brenchley & Newall, 1980, fig. 22 and Leggett *et al.*, 1981, fig. 1). It implies that the Narrow Vein is unlikely

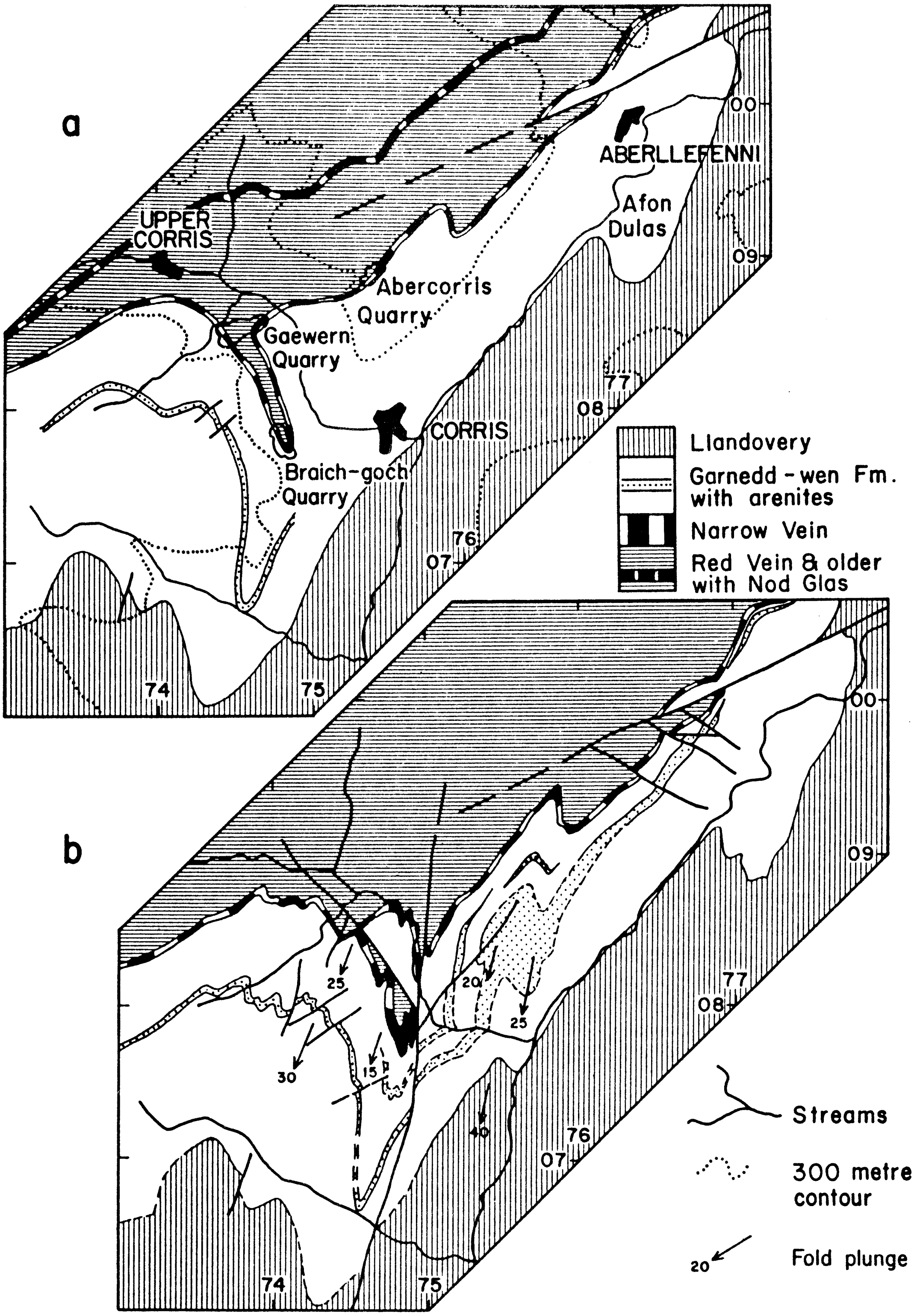

Fig. 3 Geological maps of the area between Corris and Aberllefenni; (a) after Pugh (1923) with topography and major quarries indicated, (b) based on present work demonstrating lateral continuity of the principal arenite unit in the Garnedd-wen Formation and a revised structural interpretation of the Corris anticline. (b) does not show the Nod Glas since it has not been remapped by the writer.

to be younger than early Hirnantian and this, together with increasing depth of erosion below the intra-Ashgill unconformity to the NE, is supported by a probable Rawtheyan age for the topmost Moelfryn Mudstones (Hiller, 1981). Since the Narrow Vein/Red Vein/Broad Vein sequence is of constant lithological type and great lateral extent and is clearly not foresetted in the plane of fig. 2; the Garnedd-wen onlap must be against a slope which was tectonically created (*cf* James & James, 1969). The lack of obvious thickness variation in the Narrow Vein also suggests that its upper surface is not incised by channels and that its present area of exposure was bypassed during Garnedd-wen sedimentation. Unless the Narrow Vein and the Red Vein are mud blankets occupying large depth ranges at deposition, the creation of the slope controlling Garnedd-wen deposition SW of Aberllefenni would have originated after their deposition. The slope appears to have had an inclination of about 58° and this would be consistent with the occurrence of slump and mass-flow deposits in the basal Garnedd-wen. A speculative contributory factor to the slumping, which is widespread at this time in the Welsh basinal Ashgill (James, 1983b), is melting of gas hydrates on the slope during glacio-eustatic sea-level fall (McIver, 1982). Cold basinal water at such a time might permit hydrate stability below about 400 metres water depth, and such a depth was likely on the Garnedd-wen slope near Corris prior to sea-level fall since the non-corrected depth estimate derived from fig. 2 approaches this figure. The organic rich sediments of the Nod Glas are a likely biogenic gas source.

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CLASSIFICATION OF THE SOUTH PENNINE OREFIELD

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Summary

The general characteristics of mineralisation in the South Pennine Orefield are compared with the common characteristics of Mississippi Valley-type ore deposits and it is concluded that the South Pennine Orefield should be considered to be an example of Mississippi Valley-type ore mineralisation. A comparative study of the South Pennine Orefield with two other major carbonate-hosted lead-zinc districts, namely, the English Northern Pennines and Central Ireland, has shown that, despite some similarities, they belong to three different classes of ore deposits.

Introduction

Since the first discovery of carbonate-hosted lead-zinc deposits in the Mississippi Valley region of the United States, the term "Mississippi Valley-type" ore deposits has been applied, in a general sense, to those base metal sulphide deposits formed in unmetamorphosed sedimentary carbonates. Over the years the genesis and the characteristics that differentiate the Mississippi Valley-type ore deposits as a group have been controversial. Although the current opinion on the genesis of these deposits is that, in most cases, the ore bodies are sedimentary and diagenetic in origin, there is still some confusion concerning the characteristics which have provided the basis for the classification of Mississippi Valley-type ore deposits. In this context the South Pennine Orefield is not an exception.

Although Ford (1976), Worley and Ford (1977) and Worley (1978) have "simply" cited the South Pennine Orefield as an example of Mississippi Valley-type ore deposits in the British Isles, Emblin (1978) has argued that there are three "essential differences between the conditions of the Pennine ore deposits and the Mississippi Valley type criteria". According to Emblin (1978), the three differences are:

a. The essential influence of successive phases of tectonic activity. In contrast, the absence of tectonic activity was one of the original Mississippi Valley criteria.

b. The ubiquitous presence of metasomatic mineralisation throughout the Pennines. The absence of concurrent wall-rock solution is geochemically essential in the Mississippi Valley classification.

c. Most Pennine orebodies are discordant but by definition those of the Mississippi Valley type are stratiform".

Because of these differences, Emblin (1978) proposed a new class of ore deposits, termed "Pennine-type", to characterise the ore deposits in the orefields of the Northern Pennines (Alston and Askrigg Blocks) and South Pennines (Derbyshire Dome). As discussed below, the nature and genesis of ore mineralisation in the Northern Pennine Orefield is different from that of the South Pennine Orefield and, although the two orefields show some similarities, in the author's opinion they belong to two different groups of ore deposits. Moreover, two important references defining the characteristics of Mississippi Valley-type ore deposits (Ohle, 1959; Brown, 1970) are at variance with the criteria proposed by Emblin (1978). The pioneer work of Ohle (1959), which summarised and reviewed the information available in 1957 on the geology of Mississippi Valley-type ore deposits in the United States and other countries was the first attempt to determine the common characteristics of these deposits. In 1970, Brown published a review and sequel to the Behre Symposium, held in New York in March, 1966, on the problems of the origin of Mississippi Valley-type ore deposits, in which he pointed out their distinctive

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characteristics in the central United States and discussed the different North American and European schools of thought concerning the origin of these deposits. These two publications, in the opinion of the author, indicate that the three differences cited by Emblin (1978) as a means of separating the Pennine orefields from Mississippi Valley-type ore deposits, can be regarded as either falling within the Mississippi Valley-type category or as relatively minor differences which may be found within ore bodies of almost any other category of ore deposit (White, 1968).

Some of the Mississippi Valley-type ore mineralisation has been found in the carbonates of foreland fold and thrust belts and in areas that have been strongly affected by orogenies (Anderson and Macqueen, 1982; Ohle, 1959). The influence of tectonic and structural activities on the deposition of sulphides in sedimentary rocks can be summarised as: (a) raising the geothermal gradient of the region; (b) orogenies providing additional forces for migration of the mineralising fluids, especially during the later phases of fluid migration (Mostaghel, 1983a); (c) faults providing channel-ways for migrating fluids which may be responsible for reopening, by hydraulic fracturing, pre-existing faults (Firman, 1977); and (d) folding providing positive structures which are favourable reservoirs for ore mineralisation (Mostaghel, 1984a). These factors do not affect or change the processes of ore deposition other than facilitating the process of ore fluid migration.

The presence of replacement mineralisation is not uncommon in Mississippi Valley-type ore deposits. Ohle (1959) pointed out that "most of the tonnage of Mississippi Valley type ore has come from bedded replacement deposits and in these the ore of each district shows great selectivity for certain favourable beds". The replacement of the limestone host rock by ore minerals, and especially by fluorite, has been documented in many Mississippi Valley-type orefields, for example in the southern Illinois area of the United States (Ohle, 1959).

It has been estimated that approximately 75 percent of the mineralisation in the South Pennine Orefield is in the form of discordant deposits and only 25 percent is stratiform (Mostaghel, 1984a). Although most of the Mississipppi Valley-type ore deposits are stratiform or strata-bound, some of the ore bodies of this group are discordant. In a review of the common characteristics of the lead-zinc districts in the central United States, Brown (1970) stated that "the ores ... occur mainly in certain preferred horizons or strata and are sufficiently comformable to bedding that they usually, though not always, may be described as stratiform or strata-bound" but "in Kentucky-Illinois the deposits are chiefly fissure veins". Ohle (1959) also gave examples of discordant deposits in the ore bodies which are classified as Mississippi Valley-type. Thus the author disagrees with Emblin's (1978) suggestion that the South Pennine Orefield differs significantly from Mississippi Valley-type ore deposits.

In a recent review of ore genesis in the English Pennines, Dunham (1983) suggested that the orefields of the South and Northern Pennine, Illinois-Kentucky, central Kentucky and Sweetwater should be recognised as a fluoritic subtype of the Mississippi Valley-type ore deposits on account of their distinguishing characteristics which include the presence of extensive fluorite mineralisation and association with deep-going fracture systems. As discussed below, the present author is of the opinion that, despite their general similarities, the genesis of ore mineralisation in the South Pennine Orefield is not entirely similar to that of the Northern Pennine orefield and the two orefields should not be classified into one subtype or one class of ore deposit. Although extensive fluorite mineralisation took place in the Pennine orefields, not all the deposits contain fluorite (Mostaghel, 1983b) and, in fact, the base metal sulphides have some preference for association with calcite throughout the South Pennine orefield (Mostaghel, 1984b). The subdivision of Mississippi Valley-type ore deposits on the basis of the presence or amount of a particular mineral would result in not only having a large number of subtypes but also in dividing the ore bodies of a single orefield into different subtypes with, presumably, a common origin.

To discuss the classification of the South Pennine Orefield, a review of general characteristics of Mississippi Valley-type ore deposits and the South Pennine Orefield is presented in this paper, together with a comparative study of carbonate-hosted lead-zinc deposits in the Pennine orefields and central Ireland.

Common characteristics of Mississippi Valley-type ore deposits

As stated by Brown (1970), "although no precise definition of a Mississippi Valley-type ore deposit exists, the term embraces a large number of common characteristics" and, as noted by Ohle (1959), "although not all of the ores from the different districts exhibit all of the characteristics, there are present invariably enough of the typical features so that most geologists quickly identify each area as a representative of the Mississippi Valley type". Several authors have attempted to identify the most common characteristics of these ore deposits. The contribution of Ohle (1959) has been updated by White (1968), Brown (1970), Heyl *et al.* (1974) and most recently, by Anderson and Macqueen (1982). Gustafson and Williams (1981) and Bjorlykke and Sangster (1981) also discussed the broader relationships between the different types of ore deposits hosted by sedimentary rocks. The following are characteristic of Mississippi Valley-type ore deposits:

1. According to Ohle (1959), "the one universal and fundamental characteristic shown by all of these deposits is a lack of nearby bodies of igneous rocks that are obvious or even likely sources of the ore solutions" and "this characteristic of Mississippi Valley type ore, of course, is the one that has confouned the hydrothermal school". Furthermore, Ohle (1959) stated that "most of the districts have no evidence whatever of igneous activity that is younger than the ore host rock". Brown (1970) also pointed out that "igneous activity is minor or lacking in most mineralized areas and, even where present, has little or no obvious connection with mineralization".

2. "Most rocks are not metamorphosed regionally and the deposits show no signs of having undergone any important physical alteration since deposition except for weathering on outcrop" (Brown, 1970). Anderson and Macqueen (1982) also pointed out that the host rocks of Mississippi Valley-type ore deposits are unmetamorphosed.

3. "Most deposits occur in carbonate rocks, with a strong bias toward dolomites" (Anderson and Macqueen, 1982). Minor mineralisation may take place in associated sandstones (Brown, 1970).

4. Although the ores are mainly stratiform or strata-bound, "a smaller but still important production has come from veins such as those in Central Kentucky and Tennessee, in England and in the Illinois-Kentucky fluorspar district" (Ohle, 1959).

5. "Individual deposits, similar to one another in their occurrence, tend to occur in districts which may be distributed over hundreds of square kilometres" and "this argues against strictly local sources for metals and sulphur" (Anderson and Macqueen, 1982).

6. "Deposits occur in most sedimentary basins in all parts of the world" and, "host rocks range in age from Proterozoic to Cretaceous, although many fewer deposits are known in the Proterozoic, Jurassic and Cretaceous than in the Cambro-Ordovician and Carboniferous" (Anderson and Macqueen, 1982).

7. "Deposits tend to be found at or near the edges of basins as presently preserved, or on arches between basins" (Anderson and Macqueen, 1982). "There is a definite tendency for the ore to occur in structurally positive areas" such as knob structures, folds, domes and the sedimentary depositional arches (Ohle, 1959).

8. The ore deposits "may occur in relatively undisturbed platformal carbonates, or within foreland fold and thrust belts" (Anderson and Macqueen, 1982). Ohle (1959) stated that the ore deposits of Mississippi Valley-type are mostly located in passive structural regions, and these regions "have not undergone strong mountain building activity since the ore-bearing beds were deposited". However, "this is not to imply ... that none of the districts lie in areas that have been affected by orogeny" (Ohle, 1959).

9. As noted by Anderson and Macqueen (1982), "some deposits appear to be strongly controlled by uncomformity-associated features such as paleokarst terrane" (e.g., East Tennessee, U.S.A.; Pine Point, Canada), and "some deposits tend to be localized along facies fronts between platformal carbonates and basinal shales" (e.g. Robb Lake, Canada).

10. "Although early workers commonly suggested that deposits were located within carbonate reef masses, subsequent work on many deposits demonstrates that actual reef-hosted deposits are minor" (Anderson and Macqueen, 1982).

11. There is evidence of ore mineralisation in solution and collapse structures (sink holes, collapsed caves) in a number of Mississippi Valley-type ore deposits (Ohle, 1959).

12. In some deposits "stratigraphic evidence suggests that mineralization took place at relatively shallow depths" (Anderson and Macqueen, 1982).

13. There is very little variation in the mineralogy of Mississippi Valley-type ore deposits, with galena and/or sphalerite as the principal sulphide and pyrite, marcasite and chalcopyrite as the accessory metalliferous minerals (Ohle, 1959; Brown, 1970; Anderson and Macqueen, 1982). Dolomite, calcite, fluorite and baryte are present in varying proportions. As noted by Anderson and Macqueen (1982), "commonly, galena is low in silver, and sphalerite is low in iron" in the Mississippi Valley-type ore deposits. Sphalerite occasionally shows colour banding which is "indicative of minor compositional variation" (Brown, 1970).

14. "Coarse crystallinity of sphalerite, galena and fluorite, especially in the usually abundant cavities, is characteristic" (Brown, 1970).

15. "The ores are relatively lean in precious metals, but high in various trace elements (Cu, Cd, Ge, Ga, Co, Ni, Hg, etc.) which differ in different deposits" (Brown, 1970).

16. "Studies of fluid inclusions within coarsely crystalline [fluorite,] sphalerite, barite and carbonates have established two important facts: (a) mineralization temperatures on average ranged from 80°C to 200°C, and (b) ore-bearing fluids were highly saline Na-Ca-Cl brines" (Anderson and Macqueen, 1982). These brines "are similar to but five to ten times as concentrated as sea water" (Brown, 1970).

17. "Organic materials in the form of kerogen or bitumen in the host rocks and/or petroleum in fluid inclusions is very commonly observed" in the Mississippi Valley-type ore deposits (Anderson and Macqueen, 1982). "The association between 'oil and ore' is so complete that ... it was inevitable that oil was involved as one of the ore-forming fluids" in formation of Mississippi Valley-type ore deposits (Dunsmore and Shearman, 1977).

18. Sulphur isotope studies of galena and sphalerite "show that sulphur is generally heavy and with fairly wide ranging values" which "establishs a crustal, ultimately sea-water origin involving sulphate-reduction at some time in the genetic story" (Anderson and Macqueen, 1982).

19. "Lead isotopes can also show a considerable range in any one district, and are commonly highly radiogenic, yielding future ages (negative model ages)" (Anderson and Macqueen, 1982).

20. "Open space, developed by a variety of mechanisms in carbonate rocks ... seems to be a prime requisite for the development of an economic deposit" (Anderson and Macqueen, 1982).

General characteristics of ore mineralisation in the South Pennine Orefield

The general characteristics of the ore deposits in the South Pennine Orefield are briefly discussed here employing the same order as is used in the preceding section for the Mississippi Valley-type ore deposits.

1. The igneous rocks in the South Pennine Orefield include basaltic lava flows, tuff and ash horizons, vents and occasional sills and dykes. Some thirty lava and tuff horizons are recognised in the orefield (Walters and Ineson, 1980) though many have no surface exposure. The volcanic activity occurred in the Lower Carboniferous prior to ore mineralisation. Although it was a long held general belief that ore minerals were rare within igenous rocks of the orefield, Walters and Ineson (1980) have compiled a list of localities in the orefield where ore is found in lava and tuff horizons.

2. The host rocks are not metamorphosed and the ore deposits have not undergone any important physical alteration other than weathering which has resulted in formation of secondary minerals (Mostaghel, 1984a).

3. The ore deposits are largely hosted by limestone. Some mineralisation is also found in dolomitised limestones and dolomites, especially in the southeast part of the orefield where the porosity of dolomites has been an important factor in controlling mineralisation, and a little in overlying Upper Carboniferous shales and sandstones.

4. Although the ores are strata-bound, only 25 percent are stratiform and the remaining 75 percent are discordant vein deposites (Mostaghel, 1984a).

5. The South Pennine Orefield occupies an area of about 900 Km^2 of exposed Lower Carboniferous limestones (Rogers, 1977). There is also evidence of ore mineralisation in the concealed eastward extension of the orefield (Ineson and Ford, 1982).

6. The age of the host rocks is Lower Carboniferous (Dinantian) which is divided into Courceyan, Chadian, Arundian, Holkerian, Asbian and Brigantian stages. The first three stages are known largely from deep boreholes whereas the other three stages are widespread at outcrop surfaces (Worley, 1978).

7. The South Pennine Orefield is located on a structural high between the North Sea Basin to the east and the Cheshire-Irish Sea Basin to the west.

8. The limestone host rocks were deposited in an active structural region on a pre-Carboniferous basement thought to have a graben structure in which the central block of the basement is downthrown relative to the northern and southern blocks (Maroof, 1976). The structure of this basement beneath the orefield has affected the structure of the overlying rocks. The predominant structural element of the orefield is the Derbyshire Dome with the Dinantian limestones as its core. The dome is an asymmetrical anticline with a flat north-south culmination toward its western margin. Superimposed on this structure are folds and faults within the limestones and the younger rocks. Folding developed during sedimentation of the limestones and resulted in the development of lagoonal and reef environments on the anticlines and basinal environments in the synclines (Ford, 1977). The earliest faults were initiated during the Dinantian and some illustrate subsequent reactivation during mineralisation. The main structural features of the orefield were produced during the Hercynian Orogeny in Permian times. A further period of structural deformation affected the orefield and the surrounding areas during the Alpine Orogeny in the Miocene resulting in renewed faulting and gentle folding (Frost and Smart, 1979).

9. The orefield is located below an erosion surface which was produced in late Dinantian or early Namurian prior to Upper Carboniferous sedimentation.

10. The reef-hosted deposits in the South Pennine Orefield form a minor proportion of the total ore mineralisation in the orefield.

11. A number of deposits in the orefield are found in solution and collapse structures.

12. Mineralisation in the South Pennine Orefield occurred at relatively shallow depths within the crust (Mostaghel, 1984a).

13. The principal sulphide mineral is galena which usually constitutes, with sphalerite and pyrite, less than 10 percent of the minerals present in most ore bodies. More than 90 percent of the deposits contain varying proportions of calcite, fluorite and baryte.

14. A number of minerals, especially calcite, fluorite and galena, show coarse crystallinity in some areas of the orefield.

15. The galenas from the orefield are low in silver (less than 10 ppm on average) and sphalerites are iron-poor with less than 0.7 mole percent of FeS_2 (Mostaghel, 1984a).

16. The ore fluid depositional temperature is estimated to have been between 50°C and 150°C and the ore fluids are thought to be concentrated saline brine dominated by Na, Ca and Cl (Atkinson *et al.*, 1982; Rogers, 1977).

17. Hydrocarbons are present in the form of asphalts, bitumen, pitch, or thick, heavy, unconsolidated oil and occasionally as bituments in fluid inclusions of fluorite (Atkinson, et al., 1982). These hydrocarbons are sometimes localised in the limestones to form a bitumen deposit but often disseminated through the pore spaces of the limestones either as a matrix component or as the bonding material (Mostaghel, 1984a). The presence of bitumen and asphalt traces in or near the ore bodies is common and many oil "shows" have been encountered in nearby colliery workings in addition to commercial oil and gas discoveries on both at the top of the Lower Carboniferous limestones and in the overlying Upper Carboniferous sediments, in te areas surrounding the orefield (Frost and Smart, 1979). The association between mineralisation and hydrocarbon generation leads to the conclusion that "oil" was involved in the ore forming process (Mostaghel, 1984a).

18. Robinson and Ineson (1979) found that galenas from the orefield have sulphur isotope composition of -23.2 to 6.6‰ whereas the analysed sphalerite and baryte samples show a spread of -16.0 to -9.5‰ and +4.4 to 22.6‰, respectively.

19. A study of lead isotope ratios in galenas from the orefield by Coomer and Ford (1975) has shown that the lead in these galenas is anamalous J-type and yields negative ages, though the ratios do not show a particularly wide spread.

20. Mineralisation in the South Pennine Orefield occurred in the open spaces in the Limestones; indeed a distribution map of the discordant (vein) deposits of the orefield is almost identical to a structural map of the faults. The ore fluids were apparently responsible for reopening, by hydraulic fracturing, pre-existing primary and secondary wrench faults. (Firman, 1977). The precipitation of ore minerals from these

solutions in faults and fractures resulted in formation of discordant deposits (rakes and scrins) which form a substantial part of the mineralisation.

Classification

The similarities between the general characteristics of the Mississippi Valley-type ore deposits and the ore deposits in the South Pennine Orefield are apparent when the preceding two sections are compared. Therefore, the inevitable conclusion is that the South Pennine Orefield belongs to the Mississippi Valley-type class of ore deposits. However, there are differences amongst the various types of ore deposits which may owe their genesis in some way to connate (formation) waters. Table 1 summarises the results of a comparison between the general characteristics of ore mineralisation in the South Pennine Orefield with those of carbonate-hosted lead-zinc deposits in the Northern Pennines and the Tournaisian of Central Ireland.

Although there are some common characteristics between the style and environment of mineralisation in the three orefields listed in Table 1, the deposits in these districts belong, in the writer's opinion, to three different groups. The South Pennine Orefield represents a group of ore deposits which were probably formed by refluxing connate brines during the diagenesis of the enclosing host rocks. The ore minerals of these deposits were precipitated from Na-Ca-Cl fluids at temperatures which were attained likely by deep sedimentary burial and were lower than those present during formation of the other two groups discussed here. The lead in galenas from these deposits has a range of isotopic compositions and, in most cases, is found to be enriched in the radiogenic isotopes.

The Tournaisian-hosted ore deposits in Ireland are considered by some authors to be carbonate-hosted submarine exhalative lead-zinc deposits (e.g., Large, 1981; Badham, 1981; Russell *et al.*, 1981). Badham (1981) stated that formation waters are "either dispersed or form ... secondary Pn-Zn deposits" in carbonate rocks; but "in areas of higher than normal heat flow and active tectonism such fluids may be expelled from the sedimentary column, particularly up faults" and "if this occurs beneath the sea into a euxinic environment, sulphide [minerals] may be precipitated". According to Badham (1981), "if expulsion continues for some time and if the sedimentation rate is low, considerable volumes of sulphide [minerals] may accumulate". Russell *et al.* (1981) pointed out that this group of ore deposits "formed in local basins on the sea floor as a result of protracted hydrothermal activity accompanying continental rifting". As in the case of Mississippi Valley-type ore deposits, formation (connate) waters and episodic basin dewatering are involved in formation of submarine exhalative lead-zinc deposits (Cathles and Smith, 1983; Sawkins, 1984). However, sea water and downward penetrating convection cells are also involved in the genesis of the sediment-hosted exhalative ore deposits according to Russell *et al.* (1981). As pointed out by Large (1981), Mississippi Valley-type ore deposits "genearlly lack many of the internal characteristics of the sediment-hosted, submarine exhaltive sulphides — no stratiform mineralisation [stratification in the ore bodies], little or no copper mineralisation, no distinctive metal zonation sequences, no hydrothermal alteration, as well as non-conformable (anomalous) and generally inhomogeneous Pb-isotope characteristics". Fluorite is considered to be rare in submarine exhalative mineraisation (Large, 1981). As noted by Sawkins (1984), in a general sense, the sediment-hosted exhalative lead-zinc deposits and Mississippi Valley-type ore deposits "can be viewed as end-member variants of the same general episodic sediment dewatering process, the former related mainly to rift basins, the latter to epicratonic basins". Therefore, although there are some similarities between the ore mineralisation in the South Pennine orefield and the Tournaisian of Ireland (Table 1), it is concluded that they belong to two different groups of ore deposits, the former is a Mississippi Valley-type ore deposit, the latter a submarine exhalative deposit.

In the author's opinion the Northern Pennine Orefield occupies an intermediate position between the Mississippi Valley-type ore deposits and the submarine exhalative ore bodies. The ore deposits of this area are believed to have been formed by interplay of connate waters, derived from the sediments in the adjacent sedimentary basins, and hydrothermal solutions rising through the Weardale Granite buried beneath the orefield (e.g., Sawkins, 1966; Ineson, 1976). The minerals in the Northern Pennine Orefield were precipitated from relatively potassium-rich Na-Ca-Cl brines at temperatures higher than those found in the Mississippi Valley-type ore deposits. The northern half of the orefield (Alston Block) exhibits an areal concentric zonation of fluorite surrounded by an outer zne of baryte and calcite (Ineson, 1976). This part of the orefield is also "vertically zoned with quartz-chalcopyrite-pyrrhotite at depth passing upwards to galena-sphalerite, fluorite-baryte and finally baryte" (Ineson, 1976). The zonation is believed to be related to the dual origin of the orefield (Ineson, 1976). As mentioned in the introduction, there are major differences between the two Pennine orefields. The most important of these dissimiliarities are the following (*cf.*, Dunham, 1983, for more detail):

1. Sphalerites in the North Pennine Orefield, and especially in the Alston Block, are rich in iron because of the higher formation temperature for mineral deposition in this orefield (Vaughan and Ixer, 1980) and leaching of the Whin Sill.

2. The mean Ag content of galenas is 150 ppm in Alston Block, 40 ppm in Askrigg Block and less than 10 ppm in the South Pennine Orefield (Dunham, 1983; Mostaghel, 1984a).

3. The Pb isotopes in galenas are inhomogeneous and anomalous (J-type) in the South Pennine Orefield whereas they are conformable and homogeneous in the Northern Pennine Orefield (Coomer and Ford, 1975; Dunham, 1983). Some Pb isotopes in galenas from the Askrigg Block are inhomogeneous and give negative model ages (Dunham, 1983).

4. The ore fluids had different chemsitry in the Pennine orefields. As noted by Rogers (1977), the mineralisation in the South Pennine Orefield "may represent the end member in a range of increasing temperature and potassium levels when compared to the mineralization of the Askrigg Block, which occupies the intermediate position, and of the Alston Block, with a strong enrichment of potassium".

5. As noted by Atkinson *et al.* (1982), there is a marked increase in the mean homogenisation temperature of fluid inclusions in fluorite crystals from the South Pennine Orefield (low), the Askrigg Block (intermediate) and the Alston Block (high). There are also a number of hot spots within the fluorite zone in the Alston Block (Dunham, 1983; Atkinson *et al.*, 1982).

6. The zonation of the non-metallic minerals is well defined in the Northern Pennine Orefield (Dunham, 1983). In the South Pennine Orefield, although most of the fluorite deposits are found near the eastern margin of the orefield they overlap and interdigitate with baryte and calcite deposits both of which have very irregular distribution patterns (Mostaghel, 1983b).

7. Metasomatism is a common phenomenon in the Northern Pennine Orefield, especially in strata adjacent to the veins and in quartz-dolerite sills and dykes (Ineson, 1976).

8. Unlike the South Pennine Orefield, diagenetic structures (solution collapse breccias and zones of secondary porosity) are unimportant as host structures in the Northern Pennine Orefield (Ineson, 1976).

9. Frequently dolomite, ankerite and quartz minerals are found, as principal minerals, within the ore deposits of the Northern Pennine Orefield indicating the presence of significant Mg and Si in the ore fluids responsible for sme deposition in this orefield. The veins of the Alston Block contain between 8 to 25 percent quartz (Ineson, 1976) whereas this mineral is generally rare in the ore deposits of the South Pennine Orefield.

10. Both witherite and ankerite occur in the Northern Pennine Orefield, especially in the Alston Block, but are absent from the South Pennine Orefield.

11. Smith (1974) has demonstrated that the yttrium content of fluorite is greatest in the Northern Pennine Orefield.

12. Fluorite is fluorescent in the North Pennine Orefield whereas, with minor exception, there is a general lack of fluorescense in the minerals of the South Pennine Orefield which may be attributable to the lack of rare earth elements, in these minerals.

13. The characteristics of the ore mineralisation of the southern half (Askrigg Block) of the Northern Pennine Orefield may be considered to have an intermediate style of ore mineralisation, with the other Pennine orefields as the two end-members.

Conclusions

1. The characteristics of ore mineralisation in the South Pennine Orefield are typical of Mississippi Valley-type ore deposits.

2. The present author is of the opinion that, despite some similarities, the ore deposits of the South Pennine Orefield and the Tournaisian of Ireland belong to two distinct classes of ore deposit, the former is a Mississippi Valley-type deposit, the latter a submarine exhalative deposit. An intermediate position between these two classes of ore deposit is occupied by the Northern Pennine Orefield which is thought to have a dual origin.

3. The mineralisation in the southern half of the Northern Pennine Orefield has characteristics between those of the South Pennine Orefield and the northern half of the Northern Pennine orefield.

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Table 1 Comparison of the general characteristics of the Pennine orefields with the Tournaisian-hosted deposits of Ireland.

Table 1 (part 1)	*South Pennine Orefield, U.K.*[1]	*Northern Pennine Orefield, U.K.*[2]	*Tournaisian-Hosted Pb-Zn Deposits, Ireland*[3]
I. *Host rock character*			
A. Mainly Carbonate rocks	***	***	***
B. Favourable stratigraphic horizons for ore precipitation	***	***	***
C. Presence of igneous rocks and tuff horizons	***	***	*
D. Unconformities	***	***	***
II. *Post-depositional modification*			
A. Dolomitisation	**	***	***
B. Re-crystallisation	***	***	***
C. Silicification	**	***	*
D. Karstification and cavity development	***	***	***
E. Local metasomatism	**	***	
III. *Regional mineralisation controls*			
A. Orefields located near sedimentary basins	***	***	***
B. Ore deposits localised by major structural features	***	***	***
C. Ore deposits located near facies boundaries of sedimentary or diagenetic origin	**	**	**
IV. *Local mineralisation controls*			
A. Sedimentary structures (reefs, bars, slump breccias, local facies, pinch-outs and lateral or vertical facies changes) were important in ore localisation	**	**	***
B. Tectonic structures (folding, faulting and fracturing) were important controls of ore mineralisation	***	***	**
C. Diagenetic structures (solution collapse breccias and zones of secondary porosity) are important ore hosts in some deposits	***	*	***
V. *Ore character*			
A. Coarse and well-developed crystals of ore and gangue minerals	***	***	**
B. Disseminated and/or replacement deposits	**	**	***
C. Most deposits in the orefields contain less than 10% sulphide	***	***	***
D. Main character of the ore deposits			
strata-bound	***	***	***
stratiform	**	*	***
E. Main morphology of the ore deposits			
vein (large vertical and laterial dimensions)	***	***	*
tabular (large lateral relative to vertical dimensions)	**	**	***

Table 1 (part 2)	*South Pennine Orefield, U.K.*[1]	*Northern Pennine Orefield, U.K.*[2]	*Tournaisian-Hosted Pb-Zn Deposits, Ireland*[3]
VI. *Ore mineralogy and paragenesis*			
A. Sulphide minerals			
galena	***	***	**
sphalerite	**	**	***
B. Non-metallic minerals			
baryte	***	***	***
fluorite	***	***	
quartz (silica)	*	***	***
dolomite	**	***	***
calcite	***	**	***
witherite		**	
ankerite		**	
C. Ore deposits have simple mineralogy	***	**[4]	***
D. Local and/or regional zonation of minerals or metals	**	***	***
E. Repetetive deposition of minerals	***	***	***
F. Simple regional paragenesis	***	**[4]	***
VII. *Chemical constituents of the ore*			
A. Major elements			
Pb, Zn, Fe, Ca, S, C and O	***	***	***
Cu	**	***	***
Mg	**	***	***
Si	**	***	***
Ba	***	***	***
F	***	***	
B. Reported minor and trace elements in galena[5]			
Ag and Sb	***	***	***[6]
Zn, Cu and Fe	***		
Bi and Ca	***		
C. Reported minor and trace elements in sphalerite[5]			
Fe	***	***	***[6]
Pb, Cu and Cd	***	***	***
Mn		***	***
Ag, Ge, Ga, In and Co		***	***
Ca and Sb	***	***	***
Bi	***		
Si and Hg		***	***
Ni, Ti, Ba and Mg			***
VIII. *Isotopic composition of the ore*			
A. Wide range in lead isotope composition of galena			***
B. Radiogenic lead isotopes enrichment (J-type)	***	**	
C. Wide range in sulphur isotope composition of sulphides	***	***	***

Table 1 (part 3)	*South Pennine Orefield, U.K.*[1]	*Northern Pennine Orefield, U.K.*[2]	*Tournaisian-Hosted Pb-Zn Deposits, Ireland*[3]
IX. *Mineralising fluid character*			
A. Concentrated saline brine dominated by:			
Na, Ca and Cl	***		***
Na, Ca, K and Cl		***	
B. Homogenisation temperatures of fluid inclusions			
50 - 150°C	***		
50 - more than 150°C		***	***
C. Density greater than nomral water	***	***	***
X. *Postulated genesis*			
A. Sedimentary-diagenetic origin	***		
B. Dual origin: ore mineralisation by juvenile hydrothermal solutions and connate water		***	
C. Polygenetic; mainly submarine exhalative			***

Table 1 — Key and footnotes

***	commonly present
**	occasionally, or in part, present
*	rare
1	after Mostaghel (1984a)
2	after Dunham *et al.* (1965), Sawkins (1966), Bishara (1966), Solomon *et al.* (1971), Ineson (1976), Rogers (1978), and Vaughan and Ixer (1980)
3	after Morrissey *et al.* (1971), Coomer and Robinson (1976), Watling (1976), Sheridan (1977), Russell (1978), Riedel (1980), Deeny (1981), Larter et al. (1981), Badham, (1981), Large (1981), Boast et al. (1981) and Boast, Coleman and Halls (1981)
4	According to Vaughan and Ixer (1980), the southern half of the Northern Pennine Orefield (the Askrigg Block) has a simple and uniform mineralogy and paragenesis whereas the northern half (the Alston Block) exhibits a more complex and varied mineralogy and paragenesis.
5	The galena and sphalerite samples from the orefields were not analysed for all the elements listed.
6	Data for minor and trace elements in galena and sphalerite are for the Keel deposit only.

THE MINERALOGY AND PARAGENESIS OF SPEEDWELL MINE, CASTLETON, DERBYSHIRE

by

David G. Quirk

Summary

A paragenetic study of the mineral veins in Speedwell Cavern and Mine, Castleton, is presented following field and microscopic examination and X-ray diffraction analysis.

It is suggested that the cavity-fills and veins can be divided into two areas recording a similar mineralization history depending principally on the order fluorite before barite or barite before fluorite. Calcite occurs as the earliest gangue mineral in the pipe and minor veins but is absent as an early phase in the two major fracture veins. Two late calcite phases are ubiquitous. Galena is a common but minor early mineral, whilst sphalerite is rare. The widespread occurrence of minor iron sulphides throughout the paragenesis is connected to periods when free growth of other minerals was limited. Wulfenite and an unusual blue fluorite variety are also recorded. Goethite/mud concretions on the cave walls are related to mineralized styolites and speleogenesis. The broadly east-west veins recognizable on the surface, some 150 metres above the mine and cave passages, are only partly recognizable underground.

Introduction

This report results from observations made in the far reaches of Speedwell Cavern and Mine, Castleton, North Derbyshire, and subsequent microscopic and XRD study.

The mineral deposits consist of vertical fissure veins and elongated bodies of variable dimensions known as pipes, consisting primarily of coarse calcite occupying solution cavities. Owing to problems of access, only one visit was permitted for fieldwork and to obtain material for a paragenetic study of the minerals present. Their sequence of deposition is presented in the following pages.

Other than Ford's (1956) brief note on "four feet of calcite in Faucet Rake" no previous description of the mineral deposits in Speedwell Mine has been traced. The minerals present in the veins near Winnats Pass have only been briefly noted in the Geological Survey Memoirs (Carruthers and Strahan, 1923; Stevenson and Gaunt, 1971).

Description of mineralization

The Main Canal

A major E-W vein, Faucet Rake, is encountered in the Bottomless Pit cavern at the end of Speedwell Main Canal (location 1, Fig. 17). The vertical rake is about 1.5 m wide and consists primarily of comb-textured white calcite ('7' to 'X' in Fig. 1).

In a fissure vein early minerals are usually marginal owing to a process of symmetric inward growth from the walls. Late crystals tend to occur in the centre, except where there has been asymmetric re-opening. In Faucet Rake the earliest mineral phases are seen on the north wall ('Ln', Fig. 1). Barite ('2') lies between two layers of purple fluorite ('ls') and ('ln') which occur on the unaltered limestone wall (Ln) and as a thinner surface on the

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north side of the main part of the vein ('X'). The fluorite layer is also represented by a discontinuous coating on the south wall of the rake ('ls"). Therefore the initial opening of the fissure was followed by a few millimetres free growth of purple cubic fluorite ('ls' and 'ln') from the two planar limestone surfaces ('Ls' and 'Ln') and then precipitation of barite ('2'). Further opening was accommodated by a fracture along the south contact ('Ls/ls'). An inward growth of calcite ('3s' and '3n') was followed by purple fluorite ('4') in vugs at the centre. The beginning of the major opening phase was a limited dilation on the north side of the calcite at the early purple fluorite boundary ('3n/ls'). This was filled by fluorite ('5') and later barite ('6'), and sealed with a few calcite crystals. The north wall continued to part at this purple fluorite contact ('ls') with the deposition of thicker layers of calcite (eg. '7s' and '7n'). A minor influx of iron-rich fluoritizing solution caused fine brown fluorite replacement of layer '8' (Fig. 1). This was probably followed by splitting along this replacement suture and the fracture was healed with a thin layer of calcite (9). The main part of the vein is thick calcite formed during progressive fissure dilations. A late veinlet running irregularly through the massive calcite on the southern half is bordered by brown, turbid and stained calcite (see Fig. 1). Dissolution probably preceded the secondary growth of the vuggy scalenohedra and was caused by a fracture briefly introducing fluid that was initially undersaturated.

High level workings indicate that Faucet Rake was mined for galena, although none was seen in the accessible part. The mineral parageneses described later in this paper suggest galena in Faucet Rake was deposited early in the sequence. Table 1 represents the probable paragenesis, with time as a horizontal dimension. The latest phases are on the right, the earliest mineralization event is the line furthest to the left in the table.

The Near Bung Hole Passage

At the end of the Far Canal a mostly natural stream passage trends ENE downstream of the Bung Hole (see Fig. 17). On the east side of Block Hall (location 2, Fig. 17) a small ENE-WSW vein, that probably controlled development of the chamber, shows early sparry orange-coloured calcite followed inwards by barite and with late white calcite in the centre (see Table 2). The late calcite also shows some vuggy scalenohedral development in the orange calcite.

150 m further down Near Bung Hole Passage (location 3, Fig. 17), stopes above the stream can be followed upwards for 10 to 20 m to boulder chokes, although there is some evidence of higher inaccessible workings to the north-east. Location 3 is about 175 m directly beneath Hurdlow Barn (385 m O.D.), and therefore may be a deep extension of the NW-SE Nether Pipe recorded on the Oakden plan of 1779 (see Ford, 1982). A typical mineralized area is shown in Fig. 2 and consists of botryoidal barite, overgrowing large corroded calcite crystals. The barite in turn lies beneath columnar calcite and later pipe-type calcite which is similar in shape to the early calcite. The habit of the late calcite is to occur as large single scalenohedra, sometimes with the unit rhombohedron giving modified terminations to the blocky crystals. Twinning is common, sometimes multiple and parallel to the long C-axis, yielding doubly-terminated groups of scalenohedra. The final cavity filling produces a metre or so in thickness of calcite. Purple/pale blue fluorite appears only once in the paragenetic sequence. The fluorite often occurs as a mosaic of cubic crystals; to "support" this texture, host rock dissolution prior to and during fluorite growth must have occurred. Interstitial barite and micro-vugs filled with barite have a fine cockscomb surface with platy crystals about 1 mm long. Galena occurs between and with the fluorite and barite. The paragenesis in Table 3 is rarely seen complete in any one area.

Whirlpool Passage

Upstream of the Bung Hole, at the Whirlpool a tributary stream enters the Main Stream Passage from the north-west. After following this passage for 130 m, a NE-SW veinlet is encountered (location 4, Fig. 17), about 1 cm wide, with mud at its centre (see Fig. 3).

At the Whirlpool Stopes (location 11, Fig. 17) it is possible to see cockade-textured galena, about 1 cm thick, on top of corroded, early calcite, with an intervening thin layer of goethite. Presumably oxidation of pyrite produced enough sulphuric acid to cause slight dissolution of the underlying calcite. Coarse, white, massive and columnar calcite also occurs above the galena layer and is obviously a later phase.

On the SE side of the stream at location 5 (Fig. 17) mineral gravel lies on a stone-built ore-processing floor. Specimens from here were dissimilar to the mineralization seen in the rest of Whirlpool Passage: (i) A loose pebble showed barite and calcite lying beneath later fluorite containing iron sulphide inclusions; (ii) dark purple fluorite cubes (1 cm) were found with calcite imbedded and included in their surface (see Discussion, 1)); (iii) stubby, multi-faceted crystals of calcite on galena probably originate from the mined passage nearby at locality 11 (these show a combination of the unit rhombohedron and scalenohedron, and partial development of the hexagonal prism with sides parallel to the C-axis).

Fig. 8 (location 11) is a sketch of goethite pseudomorphs after marcasite but with a pyritic central core. Therefore it seems that pyrite was changed to, or encrusted by, late marcasite which in turn altered to goethite in oxidizing aqueous conditions.

Fig. 4 shows a cross-section of the WSW-ENE vein at location 6 (Fig. 17) and Table 6 is the inferred paragenesis. Several metres further up the passage on the north-west wall at location 7 there is a circular vug shown in Fig. 5. The minerals have grown concentrically into the cavity and therefore dissolution must have occurred before mineralization. Table 7 indicates the paragenesis. The same order of events is recorded in an intermittent pipe-type body that continues at least as far as location 8 (Fig. 17). Here, early calcite, pyrite and galena are not present presumably due to the absence of a pre-mineralization cavity (see Table 8). When these four events are excluded from the paragenesis it is interesting to notice how closely matched Table 7 and Table 8 are. Thus early dissolution at location 7 allowed a greater spread in the timing and number of mineral phases but broadly the paragenesis remains the same.

A stratiform mineral body occurs in the walls below the low passage roof around location 9 (Fig. 17). A field sketch is shown in Fig. 6 and the interpreted paragenesis in Table 9. Large quantities of late calcite are still observed. Relic calcite anhedra, rimmed and partially replaced by barite, may be the earliest mineral (near the base of the pipe), with cubic, coloured fluorite occurring in fractures and the flat surface beneath the calcite clasts. Therefore the calcite may have formed as coarse, bed-parallel crystals replacing the limestone along a bedding plane. Later dissolution started beneath and around their grain boundaries. The fluid responsible for this resorption may have been introduced by fracturing (with subsequent growth of fluorite). The fluorite was followed by barite as the pipe developed. Fine fluorite deposition (or metasomatism of the roof) above the horizon was followed and preceded by dissolution and galena crystallized on the exposed surfaces. Galena, followed above by manganese wad and goethite occur within three layers of the typical yellow chalky barite. This is overlain by columnar calcite and late blocky calcite. A 'muddy' base to the calcite probably represents a halt in precipitation between the barite and calcite phases.

At location 10 (Fig. 17) a veinlet about 1 cm wide and shown in Fig. 7 has a simple paragenesis (Table 10) of galena -› fluorite -› barite.

The passage continues NW to Whirlpool Rising where the stream rises from a deep flooded pothole. Beyond this, at location 12 (Fig. 17) a vein about 60 cm wide is found on the floor. Fig. 9 depicts the SW half and the paragenesis is shown in Table 11.

Several specimens were also collected here, and one boulder was found to have a small encrustation of wulfenite crystals (see Discussion, and Fig. 15). The paragenesis of the boulder is shown in Table 12. The specimen (Fig. 10) is also interesting for the reniform (convex up) fluorite which shows a replacement texture; however, cubic surfaces, which are often purple, are also present. These crescent-shaped vugs arise at culminations in the reniform layers. Probably partial dissolution occurred directly above a replacement front, followed by fluoritization (brown, purple and black) and the growth of free fluorite crystals as the metasomatism moved upwards. Finally galena partially infilled these spaces. This cycle happened again with more complete vug development, and was followed by further overhead dissolution and precipitation of barite on the upper fluorite surface. The third and last galena growth is within the barite and this shows goethite and tarnished pyrite inclusions with a goethite coating and a thin layer of purple fluorite on top. Another mineral specimen from location 12 (Fig. 17) shows a more restricted paragenesis (see Table 13), equivalent to only the middle portion of the stages in Table 12, and with no galena. Both Table 12 and Table 13 represent parts of the paragenesis of the Whirlpool Pipe that continues NW beyond the Whirlpool Rising. One finally reaches a WSW vein, shown in Fig. 11, at the end of the passage. The similarity to Faucet Rake (Fig. 1, Table 1) is striking and it is concluded that location 13 intersects a westerly branch off Faucet Rake. Location 13 on the underground survey appears to correlate with Quick Scrin on the surface according to Oakden's 1779 plan of the Speedwell area. This minor vein trends WSW but cannot be seen to join Faucet Rake on the surface. Table 14 shows the paragenesis. There are only minor differences compared to Table 1 (Faucet Rake), the chief being the presence of galena (with early fluorite and barite) and large pipe-type blocky calcite in the centre of a much reduced thickness (compared to location 1) of columnar and faintly pink calcite. It is puzzling why the galena layer (2 cm thick) adjacent to the limestone wall (see Fig. 11) was not exploited by the miners, as nowhere else in Speedwell Mine was ore of this thickness observed.

The Main Stream Passage

Rejoining the Main Stream Passage the next area of mineralization upstream is at the Boulder Piles, location 14 (Fig. 17). Early barite clasts are included in pinkish, columnar, polygonal calcite which in turn is traversed by discontinuous veinlets of barite. The suggested paragenesis is shown in Table 15. Mineral gravel, essentially fluorite, barite and galena (see Table 16), was also found and it is probable that these were derived from overhead stopes that are now blocked by large, unstable boulders.

After the Blackpool Sands a few small irregular veins of coarsely crystalline calcite were seen. At location 15 (Fig. 17) consolidated dark brown silt occurred interstitially between subhedral calcite crystals. The silt grains were mostly quartz although it is suspected that some fine goethite is also present. The quartz silt, rather than a specific mineral precipitate, was probably derived from the host limestone. Table 15 records the mineral order in these veinlets.

From after the Boulder Piles to the Main Rising curious botryoidal, mud-coated concretions were found along the passage walls. Internally they consist of banded mud and silt (manganese- and iron-rich) and goethite, with a hard central core of granular quartz and goethite. The formation of these recent speleothems probably occurred as follows: Areas of partial silicification along stylolites (see Fig. 12) and joints probably became porous later by dissolution of early calcite (formed contemporaneously with the quartz replacement) and permitted the flow of iron-rich water. Reniform goethite outgrowth from the limestone wall (after speleogenesis) was interrupted or supplemented by sediment coatings from the stream during periods of flood.

Cliff Passage

A vein trending 070/075° can be seen above the waterfall at the entrance into Cliff Passage (location 16 on Fig. 16). This is about 150 m directly beneath New Rake, with a similar ENE trend on the surface. In fact the whole Main Stream Passage is closely parallel to New Rake. Fig. 13 shows early tension gashes filled with barite then galena, found on the south side of the main fracture that mostly consists of calcite. The vein is displaced 25 cm to the south below a shale layer near the floor in Cliff Passage. A few metres back along the Main Stream Passage a simple veinlet consists of barite on the outside and central calcite. Vertically-layered goethitic mud lies on the NW side and partially fills the centre of the vein. A thin layer of flowstone coats the surface.

The calcite pipes seen in Cliff Passage are controlled by a shaley layer about 1 cm thick, with calcite crystals generally beneath and occurring as small bodies tapering downwards or lensatic in shape as lenses. A typical example (Fig. 14) has a cavity lining of fluorite followed by barite, and filled with blocky calcite. Around location 18 (Fig. 17), the second pipe encountered has late iron-rich cubic fluorite grown from the flat surfaces of the large modified calcite scalenohedra. A third pipe shows evidence of late intersertal fluoritization (or fine fluorite deposition) and galena growth along planar calcite compromise boundaries.

Near location 17 (Fig. 17) there are numerous thin goethite/fluorite veinlets (with perhaps barite) only a few millimetres thick. They often trend NW or sub-horizontally and crosscut calcite veinlets.

Higher up in Cliff Cavern (location 19, Fig. 17) a calcite pipe is disrupted by numerous stylolites but there are no clay layers at this upper level.

In conclusion Cliff Passage shows cavity-fill (palaeo-karst?) mineralization and some coarse metasomatic calcite replacement of the limestone.

Discussion

Blue Fluorite

In the Whirlpool Passage, at location 5 (Fig. 17), some loose mineral gravel was collected, including some dark purple interpenetrant fluorite cubes (>1 cm) with calcite grains imbedded on their surface. On later microscopic and chemical investigation it was found that apparently pure splinters of fluorite taken from the specimen were mainly colourless but "laced" and spotted with a blue coloration. In fluorite from other areas in Derbyshire a purple edge coloration often occurs adjacent to another mineral — usually barite, or calcite, or micro-inclusions of chalcopyrite, pyrite, arsenopyrite, bornite, bravoite, and goethite. Braithwaite et al (1973) maintained that purple coloration in fluorite from Derbyshire was due to colloidal calcium. However this would tend to produce a more diffuse and even colour than that observed. Although the splintrs had no apparent carbonate inclusions the fluorite effervesced with the addition of hydrochloric acid. The fluorite was investigated to reveal whether the purple/blue coloration could be explained by one of two theories: lattice distortion possibly due to radiation from or exsolution of another mineral, or the presence of blue-coloured microscopic inclusions.

No alpha, beta or gamma radiation was detected from the specimen.

XRD analysis showed that the crushed splinters contained about 5% calcite, and that the intensity ratio of the fluorite d-spacing peaks 3.15 and 1.93 is approximately 100:30 respectively compared with 93:100 for synthetic fluorite (Berry, 1974). Replacive and secondary fluorite from Matlock Bath also produces a more intense 3.15

lattice diffraction than the 1.93 spacing, whereas unequivocal primary fluorite has a ratio similar to the 93 to 100 of pure synthetic fluorite — both having an undistorted lattice. The specimens are all prepared in a similar way by hand crushing to a fine powder with pestle and mortar and making smear-slides with acetone. Two thin sections (see Fig. 15) under the microscope revealed hydrocarbon and glauconite concentrated along crystal boundaries and late fractures. Calcite, quartz, epidote and pyrite also occur as late inclusion zones in the fluorite associated with several purple bitumen-stained layers. Hydrocarbon occurs at the boundaries between the radiating columns of the interpenetrant twins, and the incorporation of other inclusions is preferentially along the locus of edge growth of the fluorite (see Fig. 15). Glauconite occurs in intimate association with the bitumen and occurs slightly lamellar and parallel to the fluorite walls. The hydrocarbon also shows lamination and cracks due to shrinkage and is opaque to brown translucent at some edges. It imparts a purple stain along some cleavage zones formed by strained growth in the fluorite. The external surface of the fluorite is rough but regular cubic, however, internally the structure consists of zoned growth with areas of polygonal and cubic sub-crystals (see Fig. 15). Calcite has a more broad distribution than the other inclusions that occur only in the final fluorite zones, although calcite too occurs *mainly* as a late inclusion. Some calcite crystals are embayed and partially replaced by fluorite, others are rounded calcite rhombs or occur as irregular crystals. The epidote prisms are colorless but characteristically highly birefringent. Partial replacement by quartz inclusions show slightly strained extinction in crossed polarizers and are probably detrital. It appears that most of the included crystals were released by dissolution of adjacent limestone and occur in greater concentration at the edges and final growth zones of the fluorite. However, many of the zones of elongate calcite inclusions (see Fig. 15) probably indicate competetive growth between the fluorite surface and coprecipitating calcite, and certainly the secondary calcite shown in Fig. 15 grew in fractures in the fluorite. The centre of the specimen is a cubic mosaic of turbid fluorite crystals which may indicate initial growth was by replacement. Probably the source of the hydrocarbon was also the limestone and this bitumen is the cause of the coloration in the fluorite.

Wulfenite

Minute (‹1 mm) wax-yellow, twinned and striated, tetragonal prisms of the lead molybate, wulfenite ($PbMoO_4$), were found coating a fluorite surface at location 12 (Fig. 17) near Whirlpool Rising (see Fig. 10 and Table 12). Mineral identity was confirmed by XRD analysis. Similar crystals have been recorded by King (1980) from Tickow Lane Mine, near Shepshed.

Ford and Sarjeant discussed wulfenite in the Peak District Mineral Index (1964):

"Wulfenite ...... was recorded by Mawe (1802) at Odin Mine, Castleton, but has not yet been confirmed. Molybdenum was found in the Buxton spa waters (Stephens, 1929). Wulfenite is definitely known in the Magnesian Limestone of Bulwell, Notts., in association with galena and hydrocarbons (Deans, 1961), and has been found in the dolomitised Carboniferous Limestone of Breedon, Leics., by R. J. King".

Nichol et al (1970) record high molybdenum concentrations from the Namurian shales near Castleton. It is suggested that the wulfenite was formed from downward percolating meteoric water while overlying shale still covered the area above Winnats Pass and Longcliffe (probably pre-glaciation). Wulfenite is not an uncommon minor mineral in oxidized lead ore deposits but it would seem that this is the first definite confirmation of wulfenite in the South Pennine Orefield.

Paragenesis

In the fracture veins and mineralised pipe deposits of Speedwell Cavern wallrock alteration outside the limestone/mineral boundary is not common. The primary gangue minerals are calcite, chalky barite, and fluorite, in order of importance. Galena is common, but does not occur in great quantities; pyrite is generally microscopic. Smithsonite after sphalerite is only seen in the stopes of the Near Bung Hole Passage (Table 3). No evidence is seen for "thermal zonation" in this part of the Derbyshire orefield: the quantity of fluorite, barite and calcite, and ore minerals bear no relation to longitude in Speedwell Cavern.

(a) *The Main Stream Passage*

Two general parageneses can be constructed for Speedwell Cavern primarily on the order of fluorite/barite alone (Tables 22 and 23). The whole of the Main Stream Passage, from Cliff Cavern and Main Rising to the Bung Hole Near Series, shows a mineral sequence: calcite (the oldest) → barite → fluorite → columnar calcite → blocky calcite (the youngest). Galena is mainly associated with fluorite or also appears slightly before or after the fluorite episode.

Cliff Passage does not show development of early calcite. Here the mineralisation is mainly in calcite pipes, usually with an early cavity coating of barite, then fluorite. Late fluorite and galena is also seen in spaces between some large blocky calcite crystals. A final (purple) fluorite layer is also seen in a vein at the south-east end of the Whirlpool Passage.

Little fluorite is observed in the rest of the stream passage until the Bung Hole Stopes are reached downstream. Here, early calcite is partially corroded by dissolution and an overgrowth of iron-rich barite. A middle calcite layer is followed by purple fluorite and a second generation of barite. Galena and pyrite grew intermittently throughout.the formation of these gangue minerals but sphalerite only occurs once, beneath the purple fluorite. The columnar, then blocky, overgrowths of two calcite generations fill the remaining cavities in the pipes. Some speleothem deposits occur on the mineral veins in the Main Stream Passage. Early quartz, calcite, and goethite concentrated along stylolitic boundaries are emphasized by botryoidal muddy iron-rich concretions on the walls of the upper parts of the Main Stream Passage.

(b) *The Main Stream Passage/Whirlpool Passage Transition*

A pebble found at the Boulder Piles shows the order fluorite replacement + pyrite → fluorite + galena → and, finally, barite. This is characteristic of the fluorite/barite paragenesis in the Whirlpool Passage and Faucet Rake (see Table 22). Conversely a loose pebble found at location 5 (Fig. 17) at the Whirlpool Stopes shows a sequence of minerals barite → calcite → included fluorite. This sort of paragenetic order is only seen at the Near Bung Hole Stopes and suggests that the gravel at location 5 has its origin in unexplored mine workings (near the Whirlpool Stopes) with a paragenesis similar to the lower regions of the Main Stream Passage. The stopes above the Boulder Piles probably worked mineralization similar to that found in The Whirlpool Passage.

(c) *The Whirlpool Passage and Faucet Rake*

The rest of the Whirlpool Passage consists of pipes, stratiform bodies, and veins. The first mineral deposited after cavity formation is pyrite, and it has an intermittent appearance throughout the mineralization history, mainly at the start of renewed episodes of mineral growth, and is particularly common at the base of the late columnar calcite. This suggests that pyrite supercedes and/or is contemporaneous with a phase of dissolution of the limestone—frequently the roof. Early calcite is sometimes present, and is followed by fluorite, which is often purple due probably to microscopic inclusions of hydrocarbon. The fluorite is followed by about three colloform layers of barite—an order in reverse of that seen in the Main Stream Passage. Galena often occurs with the fluorite (and there may be several generations of both) but its time of growth is not greatly constrained and it sometimes interlayers with early calcite and often with later barite. Three layers of galena are often present, with the latest stringer usually incompletely developed. The ubiquitous columnar calcite and blocky vug calcite form coarse overgrowths. Both Faucet Rake and the vein at the end of Whirlpool Passage (location 13) show the same general fluorite, then barite, then calcite relationship. There is a minor repeat of this sequence in Faucet Rake, and then the main vein fill is thick layers of comb-textured calcite. The vein at the end of Whirlpool Passage is filled more with the later phase of blocky calcite but both are crosscut by a small vuggy calcite veinlet. A thick galena layer occurs between early fluorite, and it is proposed that galena formed at the same stage in Faucet Rake. Neither vein possesses early calcite, presumably because fault dilation was later than the time of formation of this phase. Early calcite deposition is recorded in some of the pipes and veinlets deeper in the system.

Conclusion

The mineral veins and cavity-fill deposits in Speedwell Cavern consist primarily of several generations of white calcite, chalky barite, and fluorite. Galena is a widespread early mineral but following mining activity is no longer visible in any quantity. The distribution of minor iron minerals throughout the paragenesis has been recognized, and frequently these microscopic inclusions correspond to periods of dissolution or cessation of gangue mineral growth. The blue coloration in some fluorite seems to be due to the inclusion of bitumen.

The system can be divided into two areas with a characteristic paragenesis and a general order of events: early calcite → fluorite/barite/galena → columnar calcite → blocky calcite (Tables 22 and 23). Later cave development has led to the development of speleothem deposits and the growth of secondary minerals; of particular interest is the first scientific confirmation of wulfenite from the South Pennine Orefield.

Acknowledgments

Heartfelt thanks to Mr P.E. Laffar for the use of his computer and word-processor and to Mr John Harrison for access to the mine. This study is part of a 3 year research project on the mineral paragenesis of the South Pennine Orefield, and I am grateful to the Isle of Man Board of Education for the encouragement and sponsorship. Thanks.also to Dr T.D. Ford for all his help and supervision.

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Key to paragenetic tables

c	–	corrosion	colm.	–	columnar
p	–	purple	blky	–	blocky
( )	–	not always present	r	–	replacement
?	–	probable phase	⌒		prolonged mineralisation

LOCATION 1

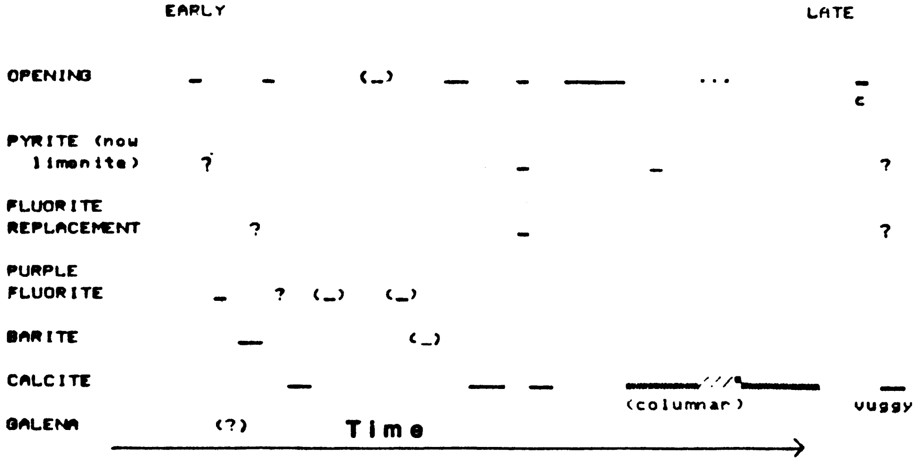

Table 1. Location 1, Faucet Rake, in Bottomless Pit Cavern.

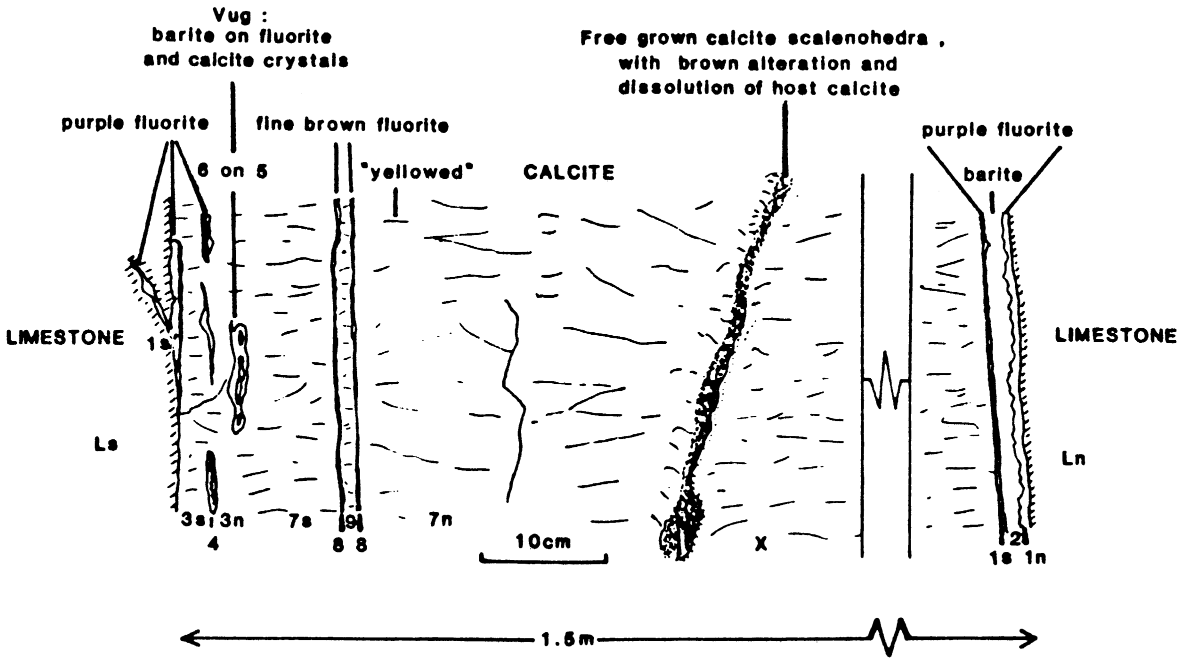

Fig.1. Faucet Rake, Location 1, Speedwell Cavern. Section through vein, looking west.

LOCATION 2

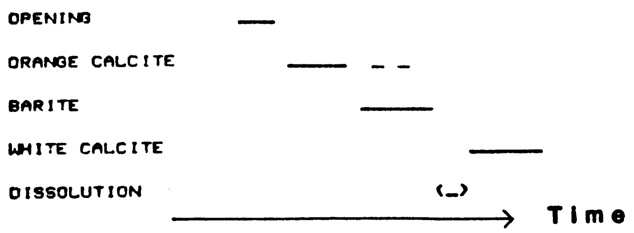

Table 2. Location 2, Block Hall.

LOCATION 3

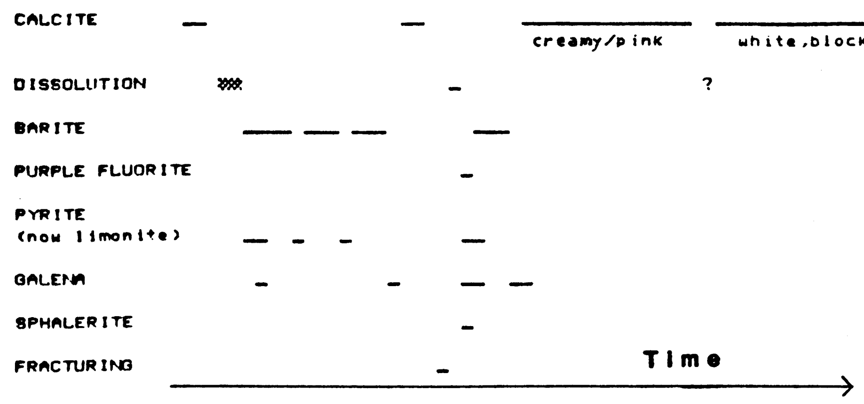

Table 3. Location 3, near Bung Hole Passage.

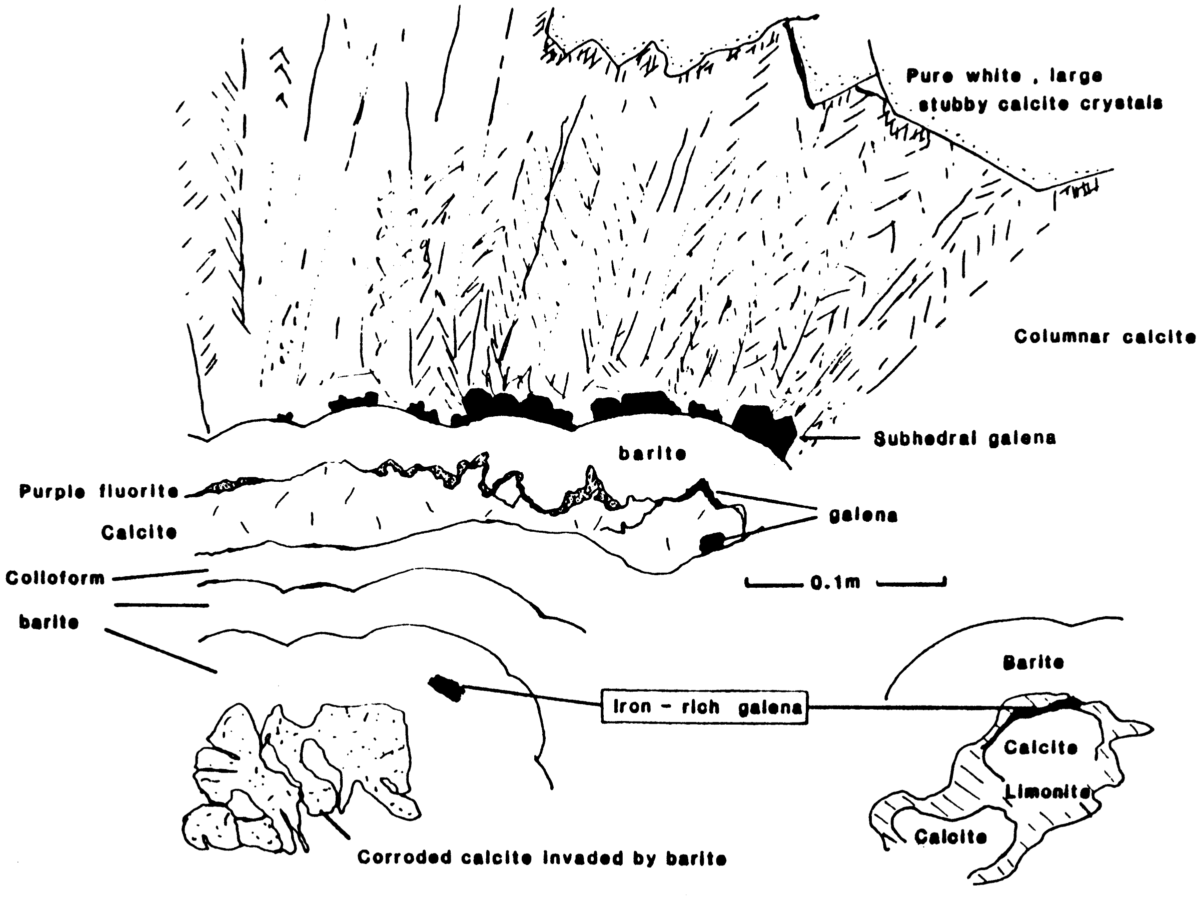

Fig.2. Mineralised area near Bung Hole Stopes, Location 3.

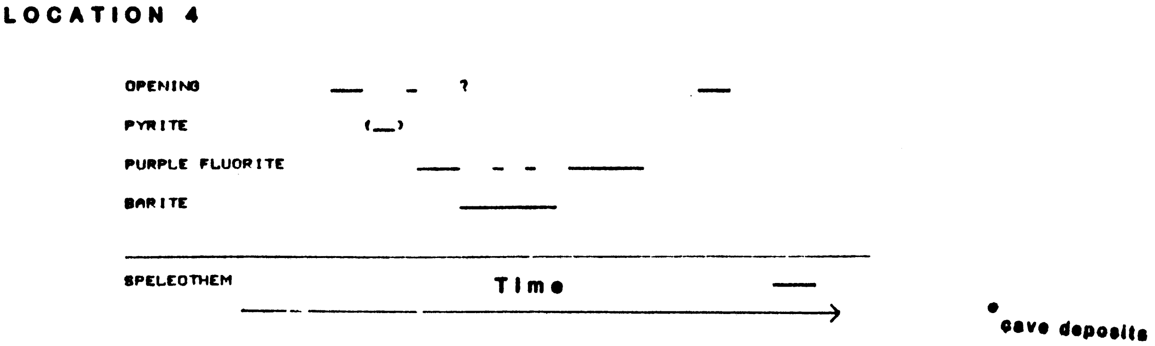

Table 4. Location 4, N.E. of Whirlpool Stopes.

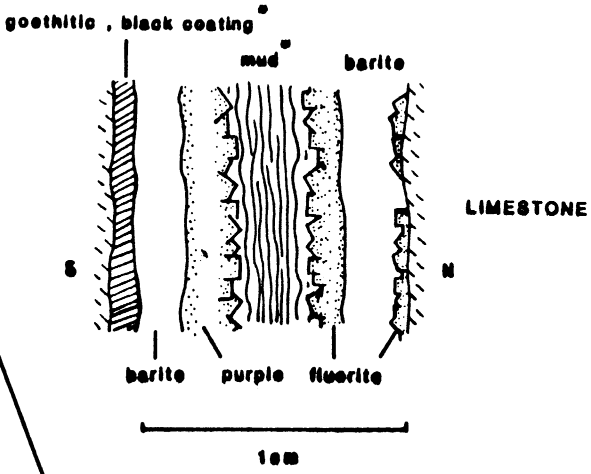

Fig.3. Location 4. Vein crossing passage northeast of Whirlpool Stopes.

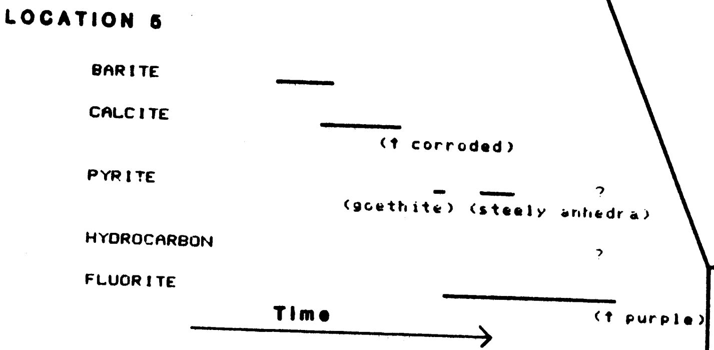

Table 5. Location 5, Exotic Pebble at Whirlpool Stopes.

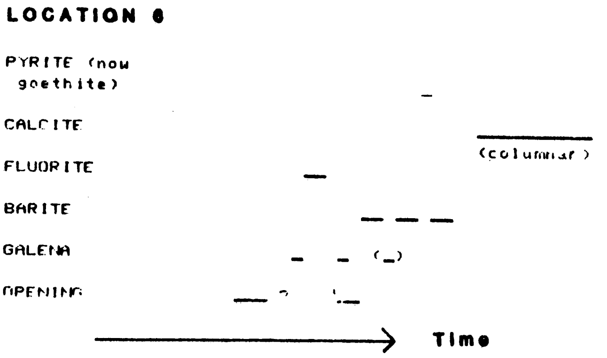

Table 6. Location 6, Whirlpool Passage.

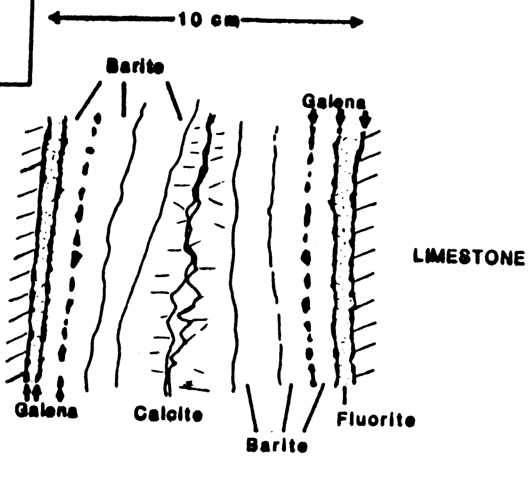

Fig.4. Vein, Location 6, Whirlpool Passage.

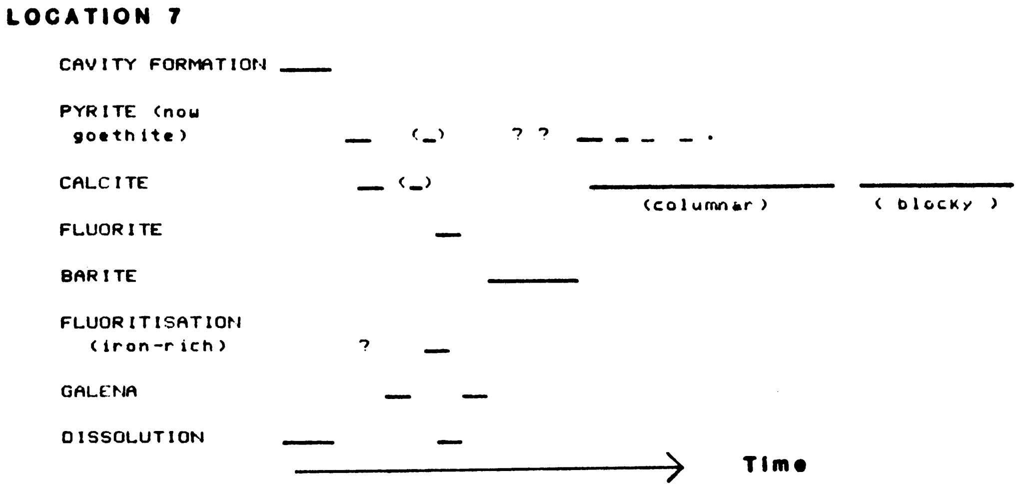

Table 7. Location 7, Whirlpool Passage.

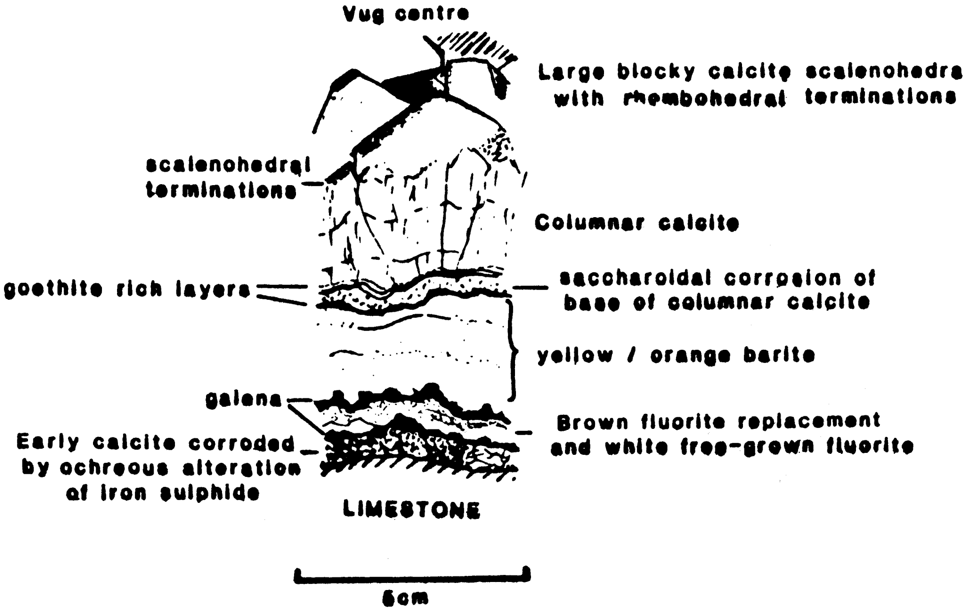

Fig.5. Lower segment of concentric, circular pipe near Location 7, Whirlpool Passage.

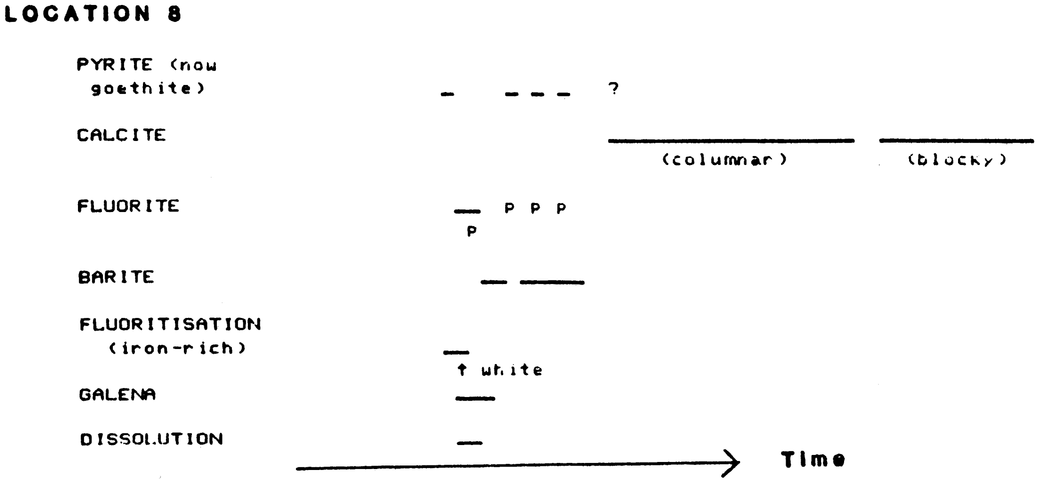

Table 8. Location 8, Whirlpool Passage.

LOCATION 9

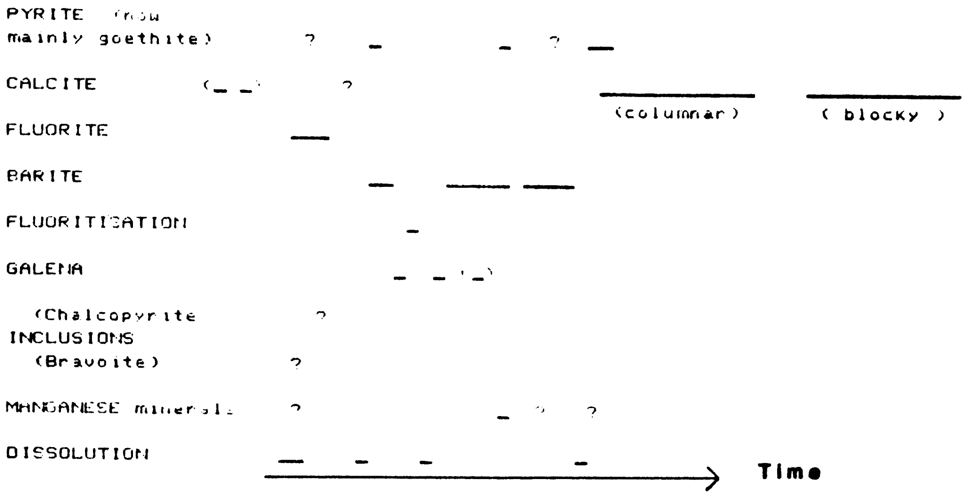

Table 9. Location 9, Whirlpool Passage.

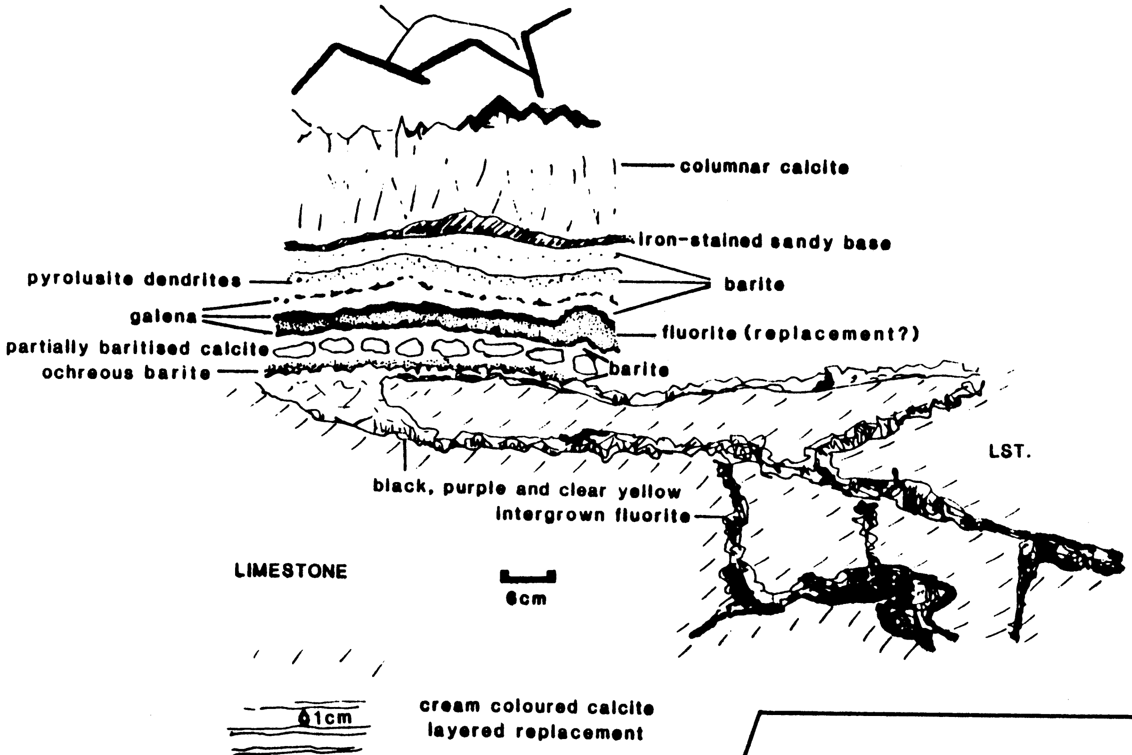

Fig.6. Stratiform body, about 1.5 m thick.

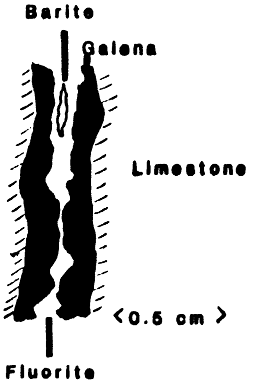

Fig.7. Location 10.
Veinlet crossing Whirlpool Passage.

LOCATION 10

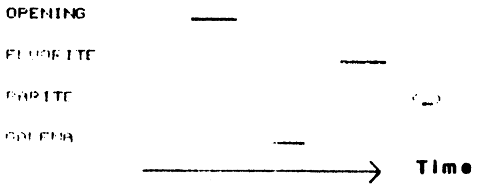

Table 10. Location 10, Whirlpool Passage.

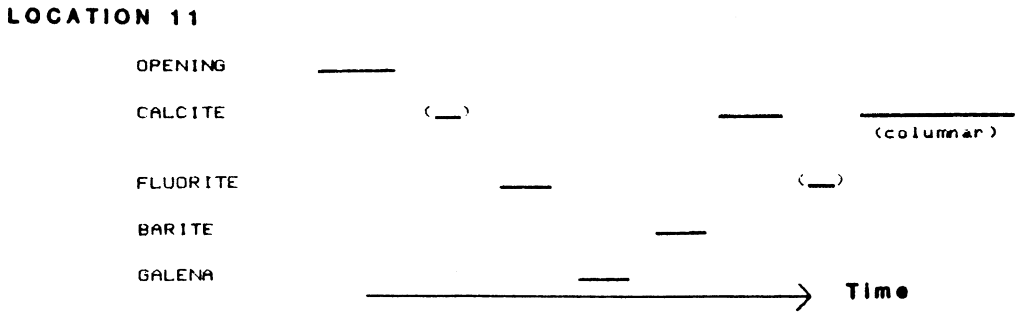

Table 11. Location 12, Whirlpool Passage.

Fig.8.Iron minerals in specimen from Location 11, Whirlpool Passage.

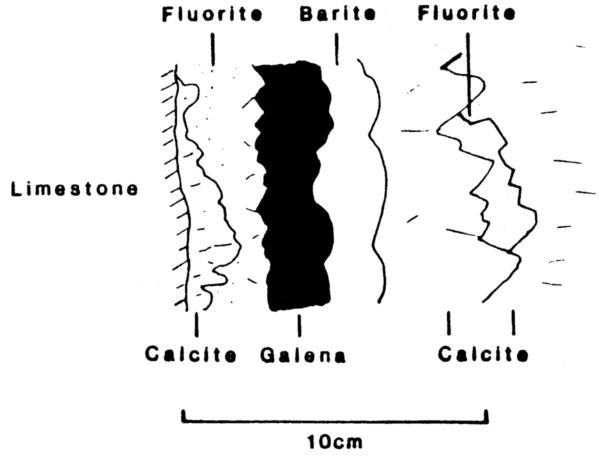

Fig.9.Location 11. Southeast side of vein at Whirlpool Rising.

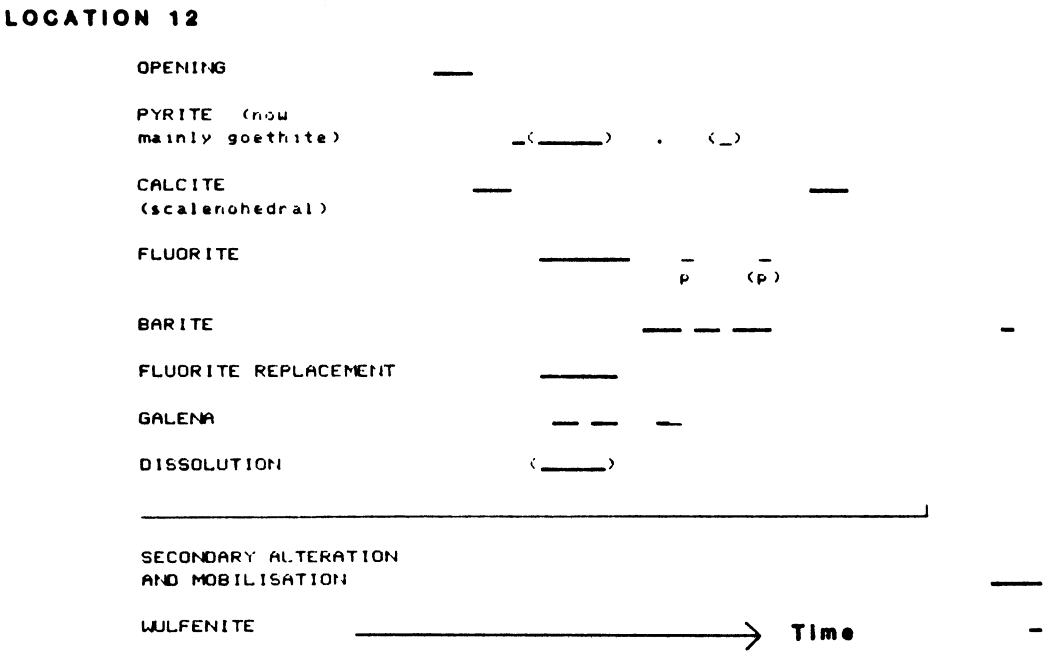

Table 12. Location 12, Loose Boulder, Whirlpool Rising.

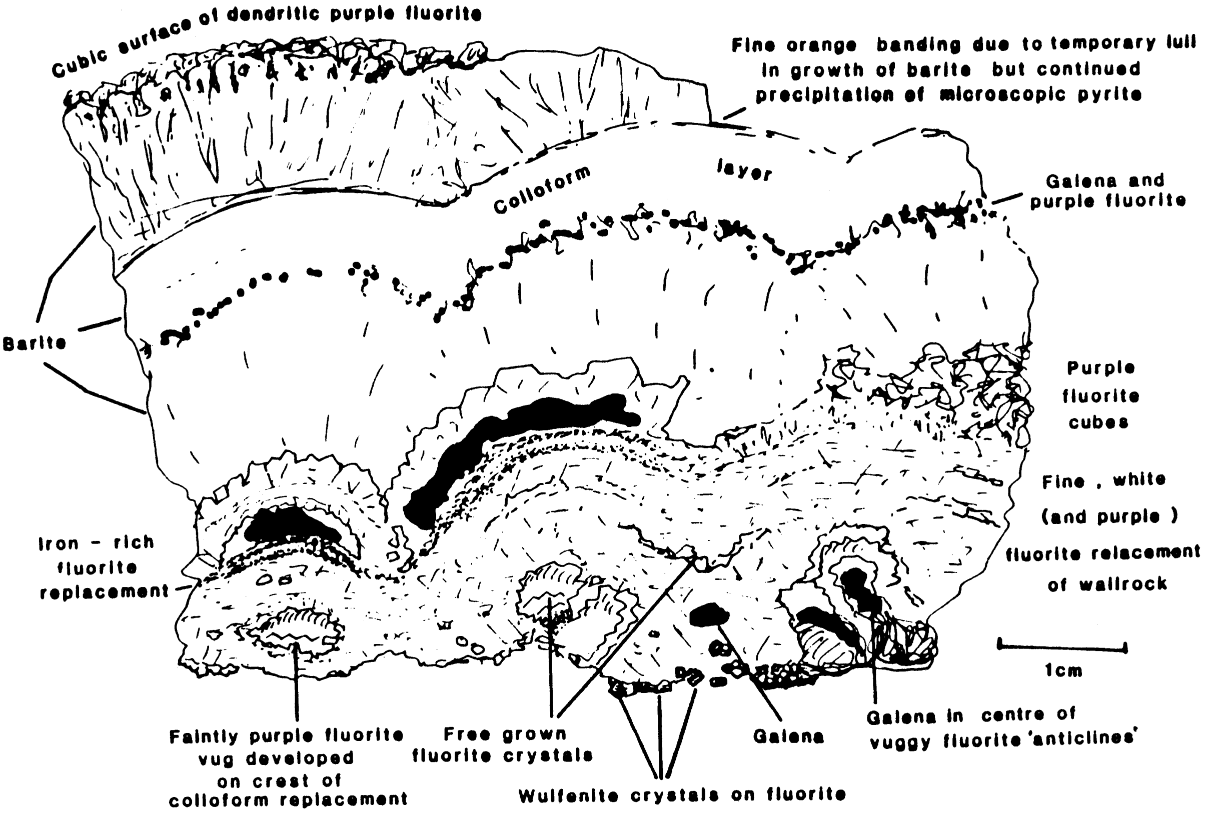

Fig.10. Location 12. Specimen from Whirlpool Rising showing reniform banding, replacement, contemporaneous dissolution and vug development. Note secondary wulfenite coating the fluorite/limonitic basal surface (see Fig. 16).

LOCATION 12 (continued)

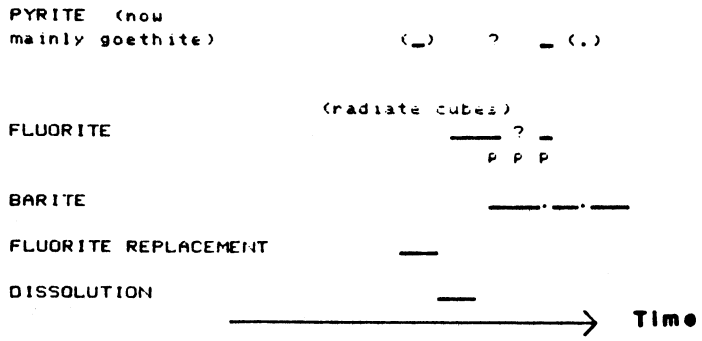

Table 13. Location 12, Loose Boulder, Whirlpool Rising.

LOCATION 13

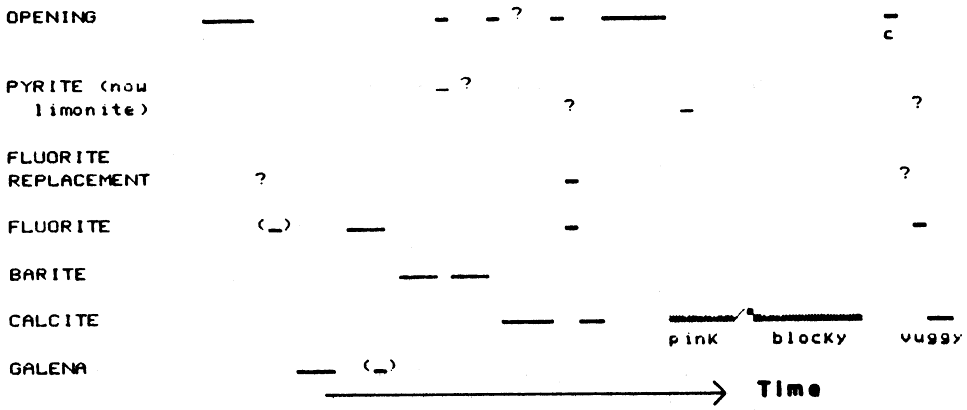

Table 14. Location 13, Branch off Faucet Rake (?) end of Whirlpool Passage.

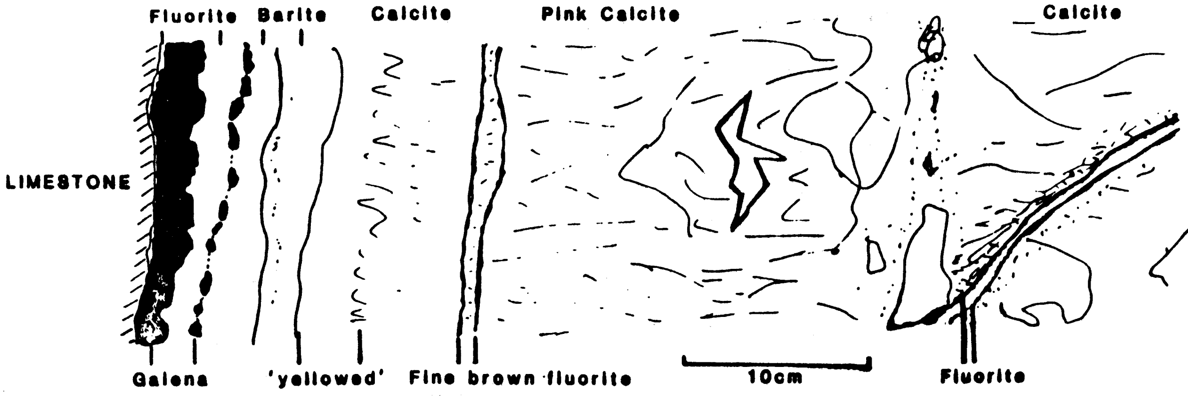

Fig.11. Location 13. Southeast side of vein at end of Whirlpool Passage, approximately 60cm wide.

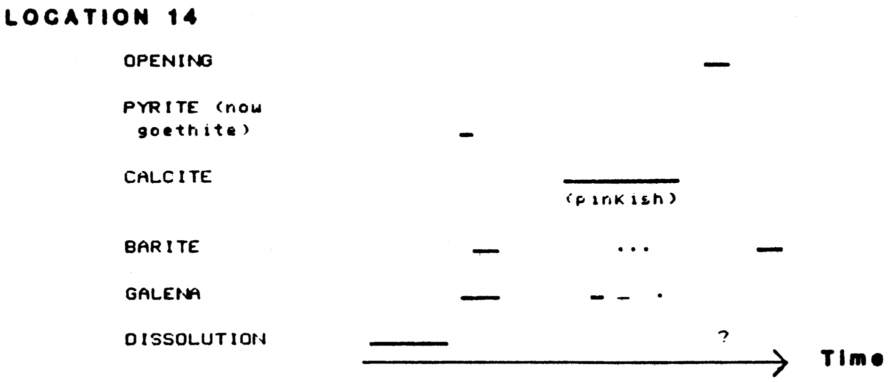

Table 15. Location 14, Main Stream Passage, Boulder Piles.

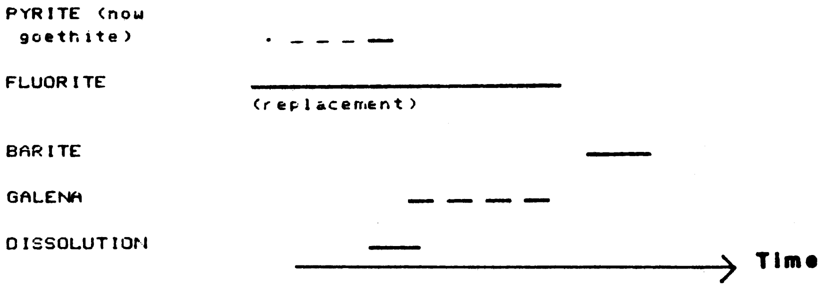

Table 16. Location 14, Pebble from Main Stream Passage, Boulder Piles.

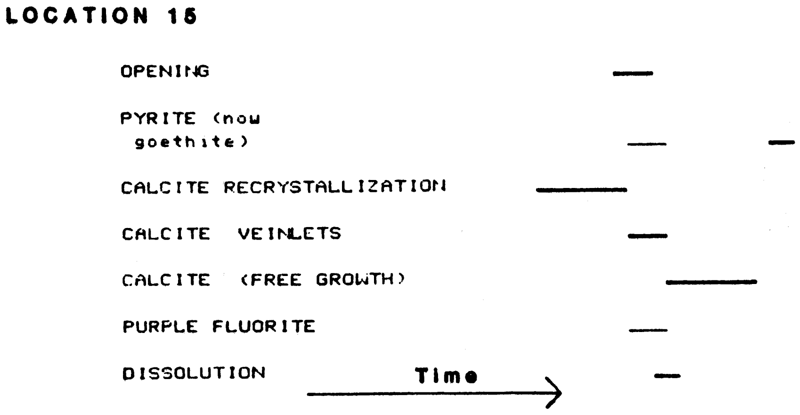

Table 17. Location 15, Main Stream Passage.

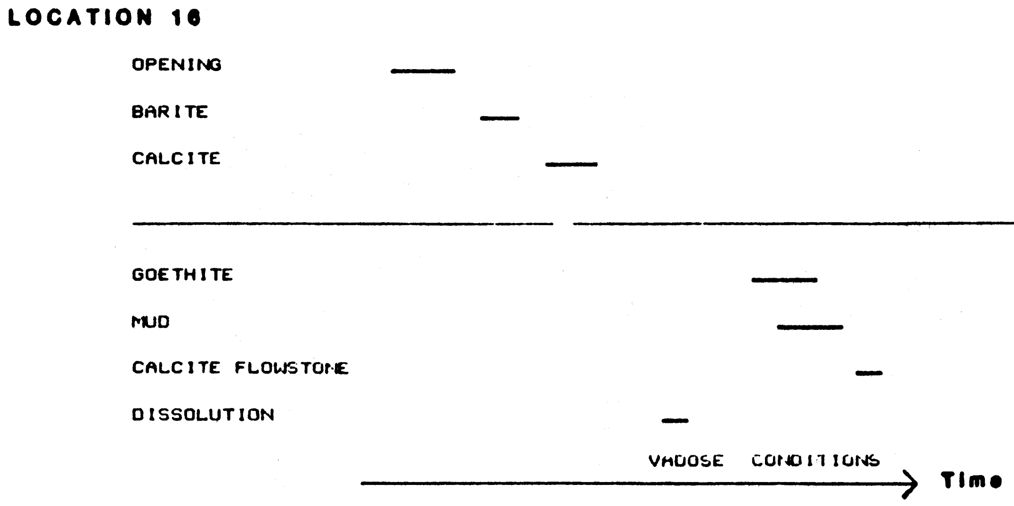

Table 18. Location 16, Main Stream Passage.

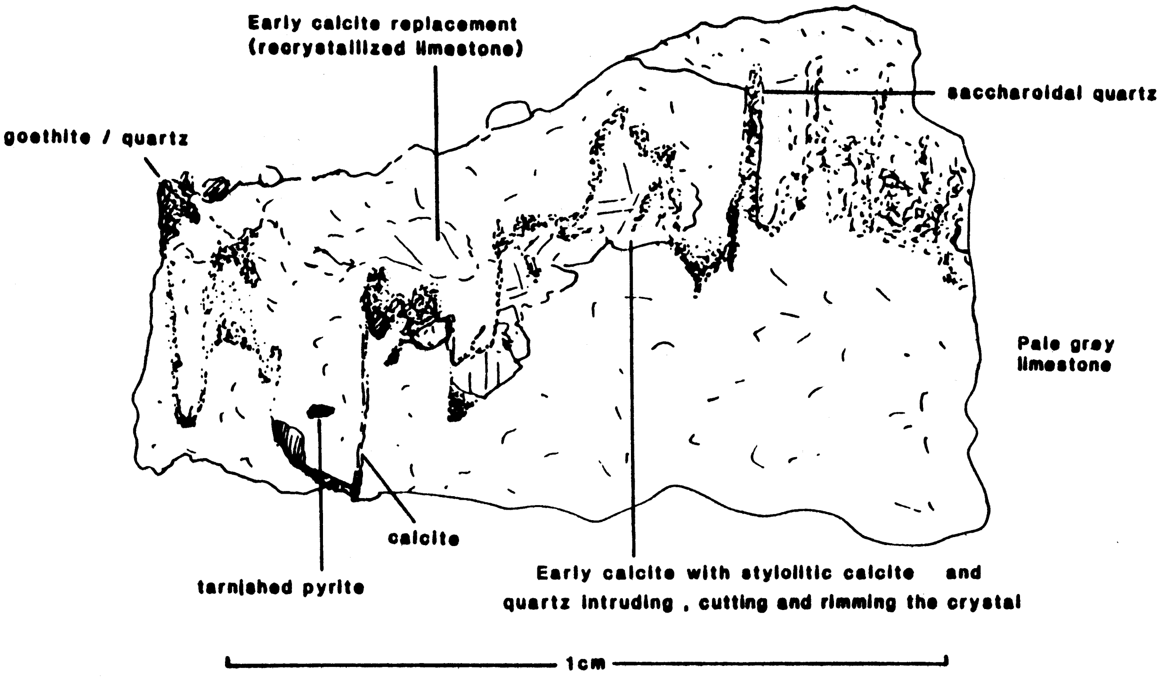

Fig.12. Location 16, Main Stream Passage. Section through wallrock beneath goethite/mud concretions. Quartz, pyrite, calcite stylolite crosscutting early calcite in recrystallized limestone.

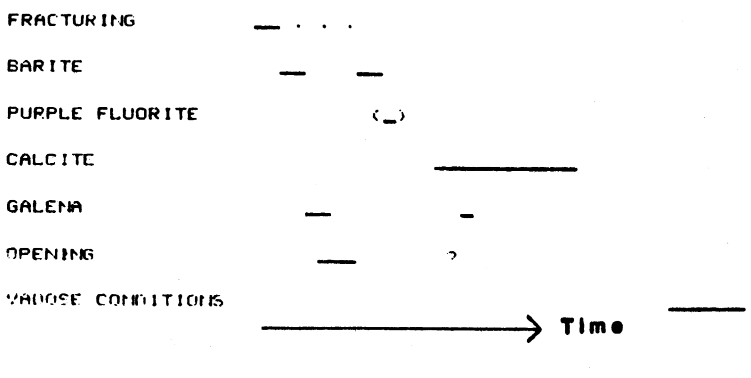

Table 19. Location 16, Vein at entrance to Cliff Passage.

LOCATION 16 (continued)

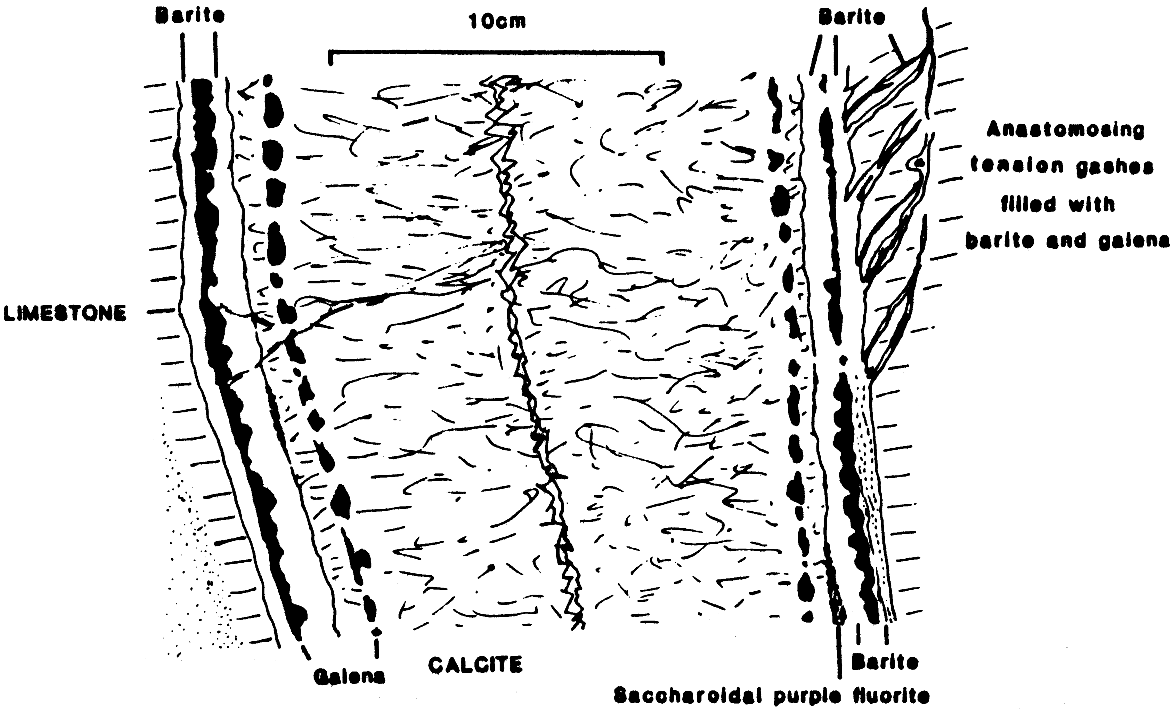

Fig.13. Location 16. Symmetric vein crossing entrance to Cliff Passage.

LOCATION 17

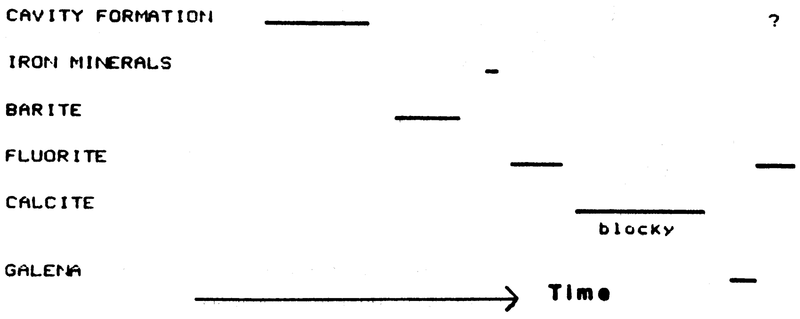

Table 20. Location 17, Calcite pipe in Cliff Passage.

LOCATION 19

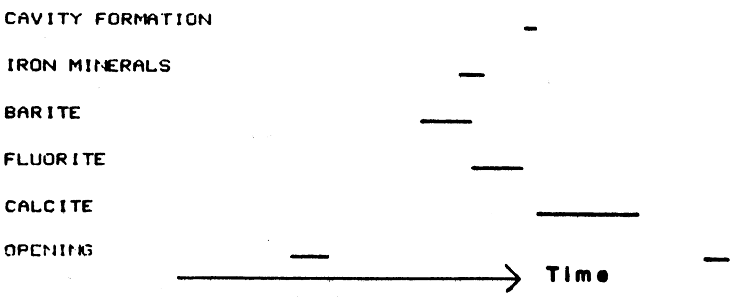

Table 21. Location 19, Cliff Cavern.

LOCATION 17 (continued)

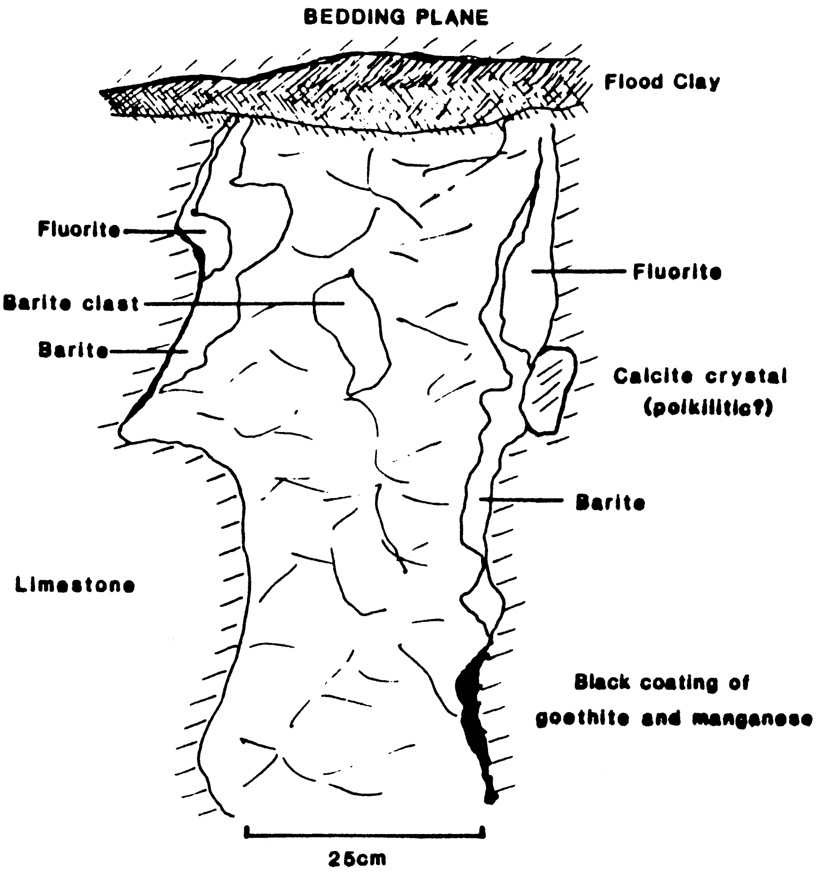

Fig.14. First calcite pipe, trending northwest. Location 17, Cliff Passage.

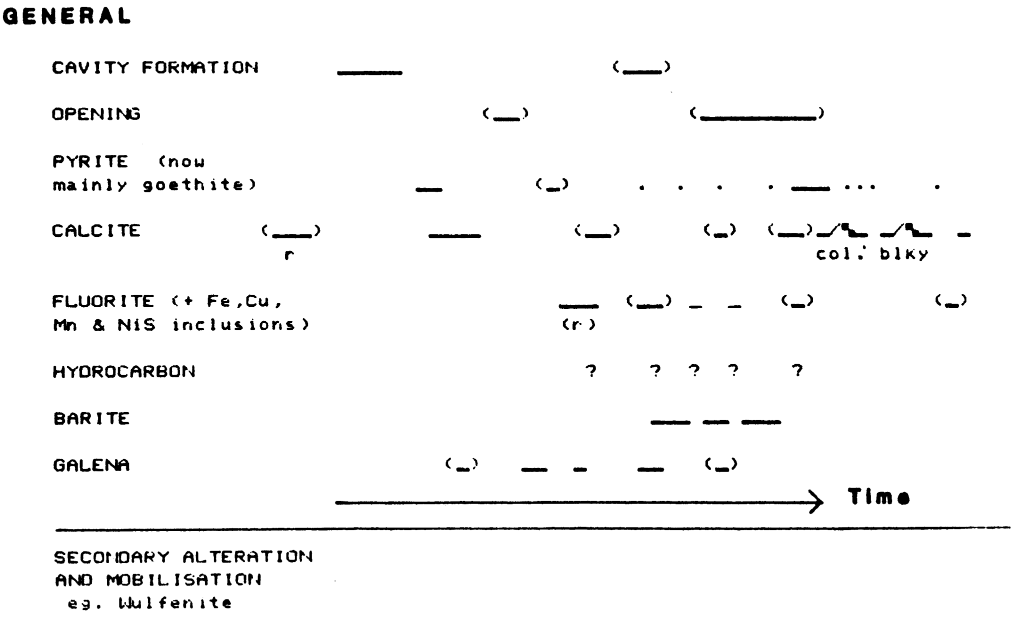

Table 22. General paragenesis for the Whirlpool Passage and Faucet Rake.

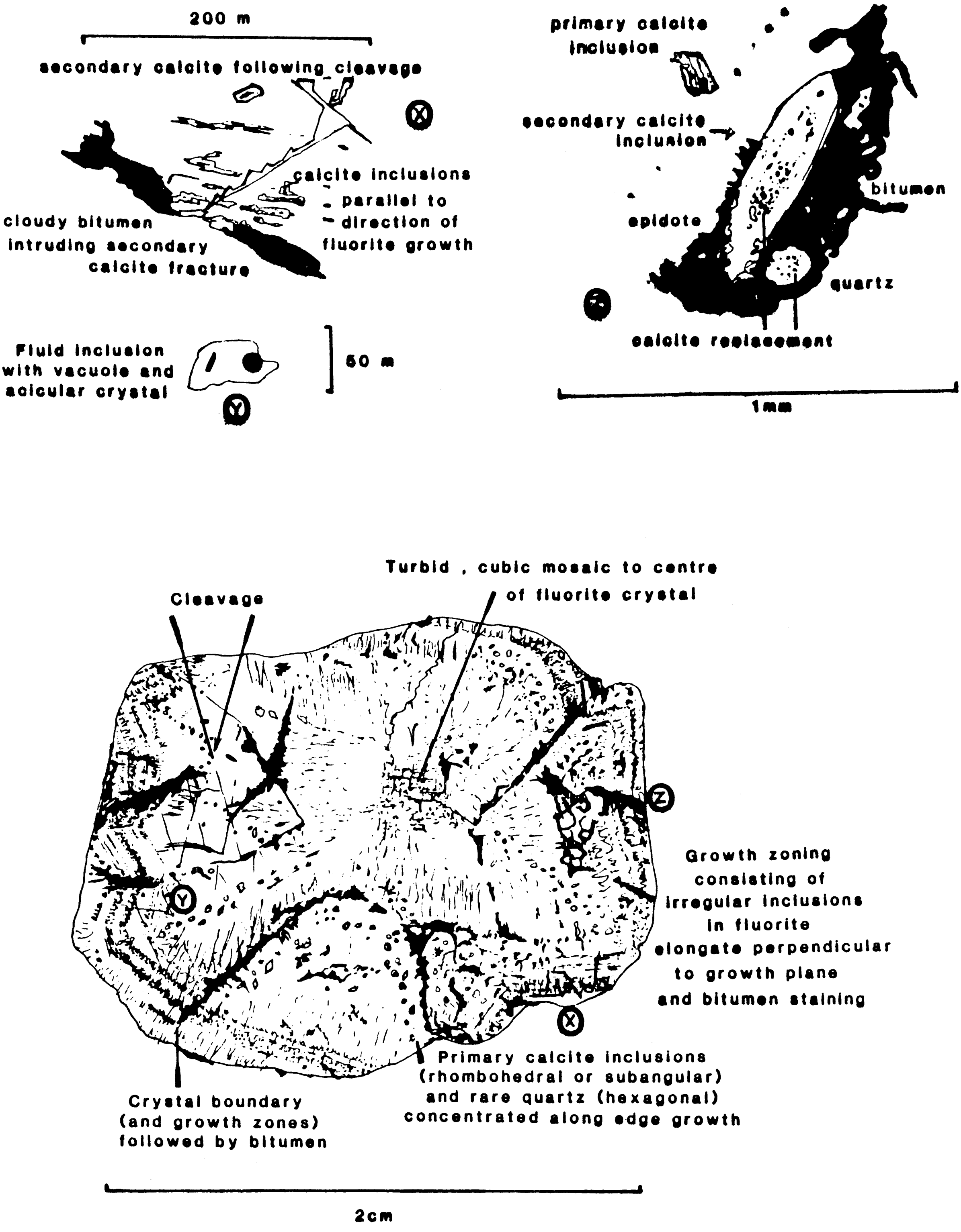

Fig.15. Polished thin section of cubes of dark blue fluorite, from mineral gravel found at Location 5, Whirlpool Passage. Note growth zoning depicted by elongate calcite inclusions and emphasized by hydrocarbon staining at edge of crystal faces. Bitumen is concentrated principally along crystal boundaries and minor fractures that displace the growth zones. Triangular secondary calcite inclusions are constrained by fluorite cleavage. Rare fluid inclusions are present. Details shown on the top, are all in a fluorite matrix.

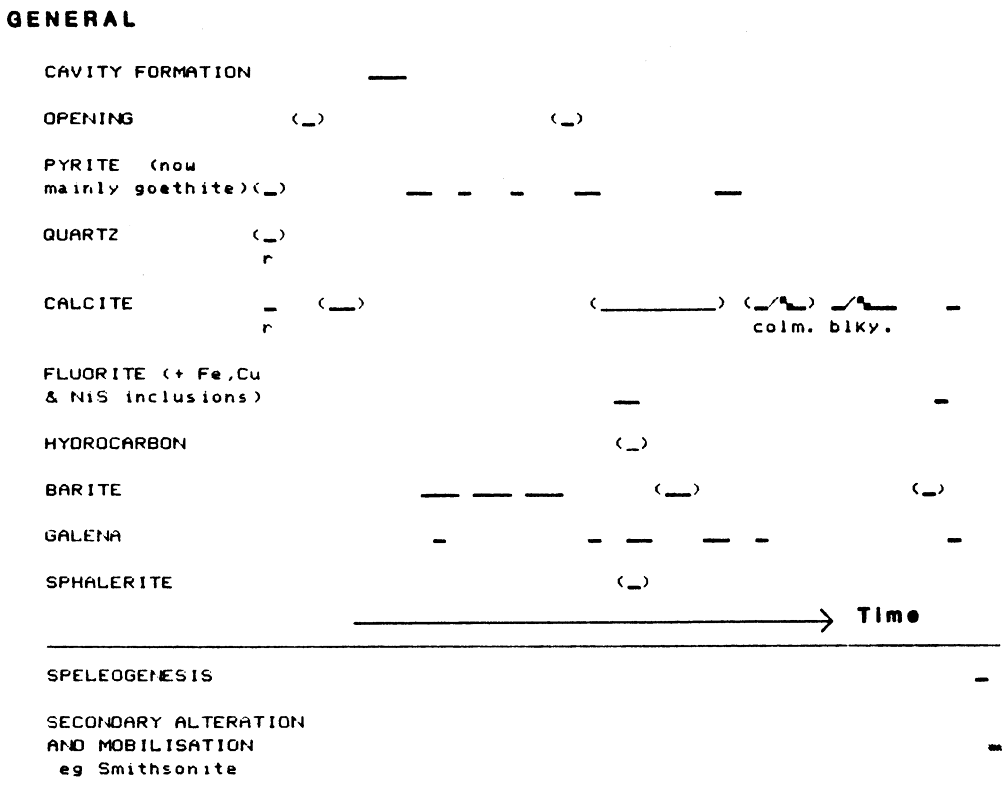

Table 23. General paragenesis for the Main Stream Passage, near Bung Hole Passage and Cliff Passage.

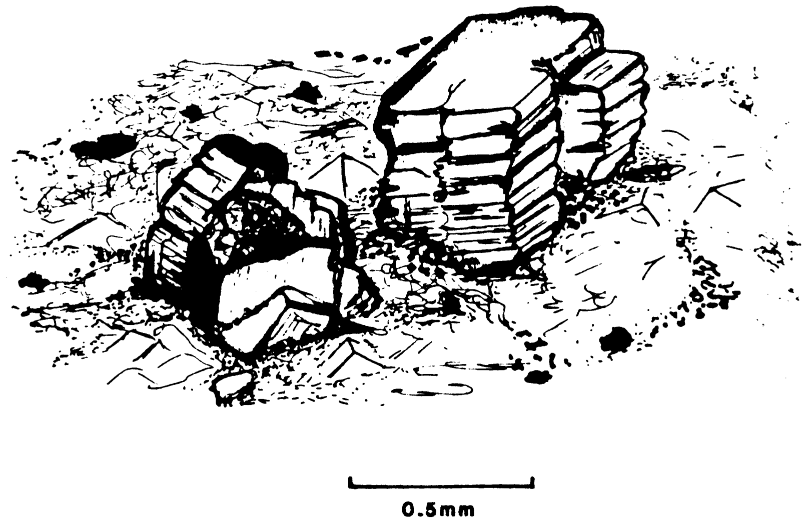

Fig.16. Multifaceted, tetragonal crystals of wulfenite, beeswax yellow in colour, on a limonitic fluorite surface (see Fig. 10). The prisms are horizontally striated at right angles to their length (C axis) due to bevelled (011) modification and development of (021) faces.

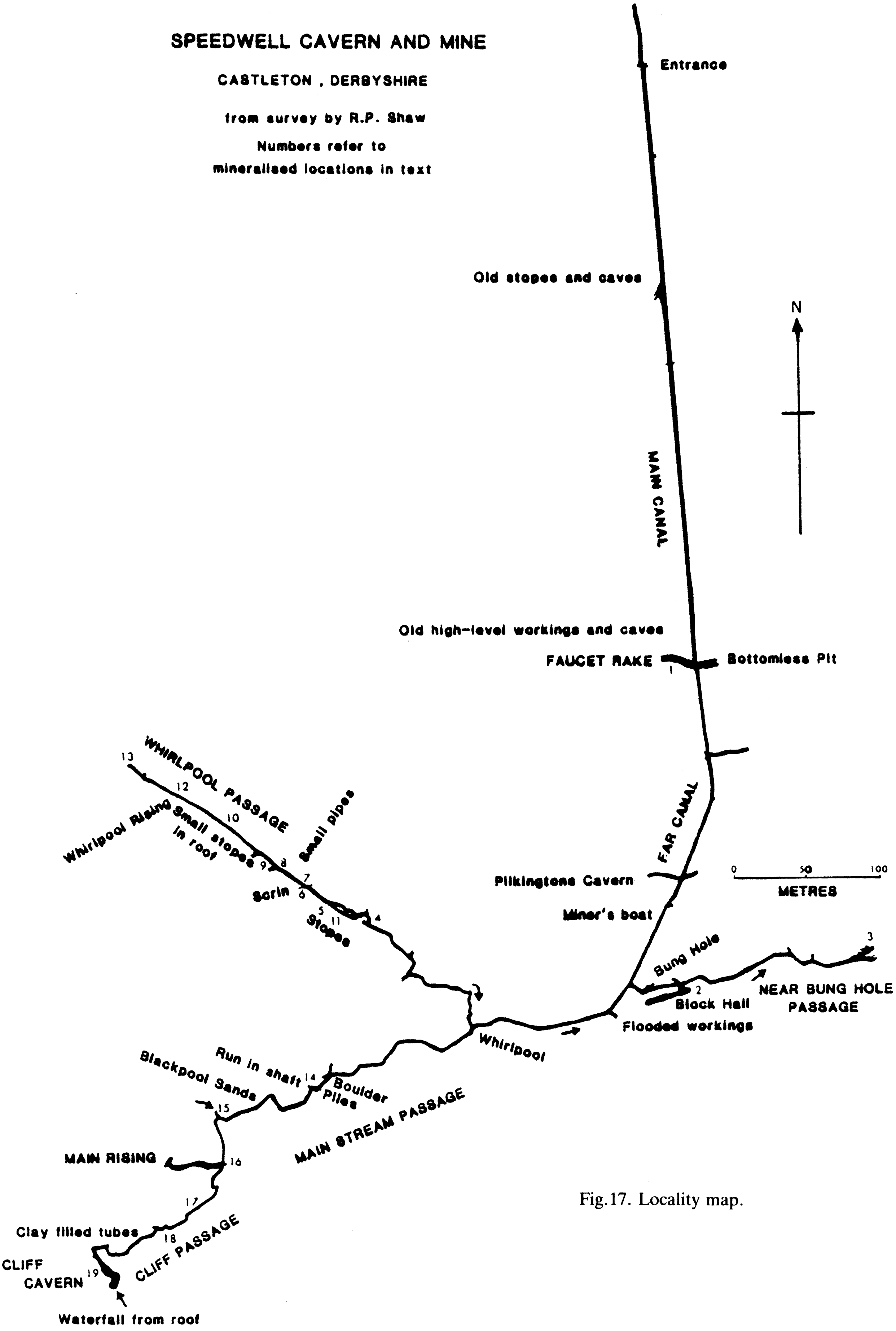

Fig.17. Locality map.

REVIEWS

SCHROEDER-LANZ, H. *Late- and Postglacial Oscillations of Glaciers: Glacial and Periglacial Forms*. 1983. A.A. Balkema, P.O. Box 1675, 3000 BR Rotterdam. Netherlands. £19.80. ISBN 90 6191 5171.

This book is a collection of 26 papers dedicated to the memory of Hans Kinzl, Professor of Geography at the University of Innsbruck in honour of the contribution made by him to the study glacier-forelands. It is a compilation of papers read at a conference at Trier in Germany on the 15-17th May 1980, organised to coincide with a visiting Professorship of Dr. J-L. Sollid to the University of Trier. Unfortunately the meeting was beset by misfortune: Professor Sollid was badly injured doing fieldwork and could not attend, and Professor Kinzl died during its preparation. It would be a pleasure to say that despite these set-backs the published volume is a great success, making-up for earlier distress and disappointments, but unfortunately this is not the case. In many respects the book is unsatisfactory: many of the papers are trivial and some are irrelevant to the theme, there is little attempt to produce coherent synthesis, and despite a brave attempt by the publisher to produce a text suitable for readers of German, French and English language, the tri-lingual format is clumsy and far from attractive.

The aim of the book is to give "an overview of the methodological and regional state of [glacier-foreland studies]" (Editor, p IX). It is arranged into five sections dealing respectively with evidence from the Alps, Norway, the Pyrenees and Iberia, the Massif Central (which seems to include the Black Forest!), and the rest of the world outside Europe (Antarctica, Mexico, Arctic Canada, Greenland and the North American Rockies). A final section that is entitled "Chronological Questions" includes two short papers; one on secular variations in oak growth in middle Europe and the other on the establishment of lichen growth curves. Thirteen of the papers are in German, eight in English and five in French. All papers include an abstract in each of these languages and the captions to all the photographs and diagrams are similarly trilingual. Text is typeset and attractive, with a liberal use of space, proof reading has generally been good so that errors in the text are relatively few. However, many of the photographs are poorly reproduced.

Of the papers dealing with glacier variations all adopt an approach based on combinations of geomorphological mapping and dating using radiocarbon ages, topographic freshness lichenometry and historical records. Some of the geomorphological maps, like that of the French Southern Alps by Jorda (p 42), and that of the terraces of Doralen in Norway by Gehrenkemper and Treter (p 175) record precise information which is of considerable interest, but in general the treatments are far from successful. Some, such as that relating to Visdalen in the Jotunheimen by the editor, that by Hazera concerning the western Pyrenees, and that by Beeler dealing with the region of the Bernina Pass in the Alps are simply too brief to communicate the information needed by the reader. Others, such as that by Habbe and Walz concerning the glaciation of Val Viola in the Italian Alps, or that by Clapperton and Sugden on the glacier fluctuations of West Antarctica have an inadequate temporal control from radiocarbon dates. That by Muller, Kerschner and Kuttel on the Val de Switzerland is dependent largely on one virtually irrelevant pollen diagram and the perceived "freshness" of the moraines. The result is that most works succeed in fitting the glacial history of the area studied into pre-existing schemes of glacial activity without a stringent or even valid scientific test. Consequently, for the Alps, we learn on several occasions of the importance of the Egesen Advance, which is the equivalent of the Loch Lomond Readvance of the British Isles that formed during Younger Dryas time about 11,000 to 10,000 years B.P., despite the fact that Watts (1980) has shown that the atmospheric driving force for this event is much less in central Europe than in western Europe adjacent to the Atlantic ocean. Research to test the existence of such a glacial event would have been of more value than simple perpetuating an established belief. Inevitably part of this problem arises from the delay in publication, but also, it reflects the intellectually complacent tone of much of the book.

From a more positive point of view two elements do stand out. Firstly it is pleasant to see a relatively frequent use of glacier reconstructions, at least in the Alpine region of Europe, and the reference to estimations of past snow-line elevations; and secondly it is of great interest to see the frequent reference to rock glaciers emphasizing their importance as typical, rather than rare, periglacial/glacial landforms. Unfortunately, with the exception of an article examining the climate of the Younger Dryas in the western Tyrol by Kerschner, neither of these topics are considered in any detail.

However, one paper does stand out above all the rest for its content and intellectual significance. This is the consideration of lateglacial shoreline displacement by Anundsen and Fjeldskaar. This paper is detailed and comprehensive, with information necessary to follow the scientific argument. The results demonstrate that a limited glacial readvance will cause measurable crustal loading that can be recognised in the shoreline displacement studies. An understanding of this process can therefore provide a theoretical basis for the use of shoreline displacement curves to interpret the glacial history of an adjacent region, and in particular identify otherwise unrecorded glacier readvances. The precise description, detailed chronologies and thorough treatment adopted by this study should be a standard by which to judge the rest of the papers in the book. The only problem is, that as presented, this paper is only incidentally relevant to the theme of the volume and would have been more at home in a volume on, for instance, isostatic shorelines.

All other points worth mentioning are critical of the volume. Certain of the papers are, quite simply irrelevant. For example it is very difficult to find any justification for the inclusion of the article by Schunke on the temporally independent study of thufurs and palsas, or for the inclusion of the inconsequential study of the sediments in the drained lake basin in the San Juan Mountains, Colorado. This paper gives no evidence for the existence of glaciers other than a till in one section, and the dates which form the basis of the age which is proposed for deglacierization as early as 15,00 years B.P. come from another publication. Equally unsatisfactory is the fact that several papers are concerned solely with a timescale that is beyond the range indicated in the title of the book and have no bearing on the topic. For instance, Hannss' article on the French northern Alps, and Schmidt-Thome's article on northwestern Iberia. One could go on finding more complaints, but perhaps it is worth ending with the most serious. There is no attempt to produce either a synthesis of the work included in the text or an overview of current understanding of the nature of Late- and Postglacial oscillations of glaciers. Such a review is needed from the points of view of methodology, regional development and variations, climatic reconstructions and geomorphological/geological significance. This information would have served to highlight the relevance of those papers which do at least have something to offer, and reflect the current state of knowledge. As an academic contribution this book is but a shadow of "Studies in the Scottish Lateglacial Environment" by Gray and Lowe (1977), and "Studies in the Lateglacial of North-west Europe" by Lowe, Gray and Robinson (1980). This is particularly disappointing in view of the high standards set by Professors Sollid and Kinzl, in whose honour the colloquim was initiated and the volume dedicated and for the need for a volume of this kind dealing with areas such as the Alps which are not typically represented by publications in English.

References

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Lowe, J.J., Gray, J.M., & Robinson, J.E. 1980. *Studies in the Lateglacial of North-west Europe*, 204 pp, Oxford, Pergamon Press.

Watts, W.A. 1980. Regional variation in the response of vegetation to Lateglacial climatic changes in Europe. In Lowe *et al.* (eds) *Studies in the Lateglacial of North-west Europe*, 1-21.

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CRAVEN, M., and STANLEY, M. *The Derbyshire Country House*, published by the Derbyshire Museum Service, Matlock, Derbyshire. Volume 1 (1982) 99 pages, Vol. 2, (1984) 111 pages. Vol. 1 £2.50. Vol. 2. £3.50. ISBN 0 906753 01 5.

The authors of these two volumes have out-pevsnered Pevsner's Derbyshire Volume of the "Buildings of England", (Penguin Books). Each volume catalogues some 300 stately homes, manor houses, and other large buildings such as castles, but not churches. Most of these still stand though purposes have changed and some are now offices, hotels, hostels or colleges, but a remarkable number have been demolished over the years. They mention some 700 "seats" in the introduction. The volumes are concise to say the least. There are black and white photos of three buildings on almost every page. The notes cover the present use, and give a one-paragraph summary of when the building was constructed or modified, a brief account of the family(ies) who live there and a few bibliographic references. Architectural details are summarized and, unlike most compilations of this nature, a special effort has been made to identify the building materials and their source(s). Volume 1 has an introductory section of 8 pages summarizing the geology (with emphasis on building stones), history, architecture and materials. Volume 2 adds a further 5 pages of introduction on the history of building materials, the nomenclature of country seats, and on moated sites.

The entries are arranged alphabetically and I found a little difficulty in locating some until I realised that there was an index of Grid References in the back of volume 1 (not in volume 2, presumably because so many have been demolished). Very little detail is given of contents of houses in the way of furnishings, art treasures etc.

One small criticism is the small size of print which I found difficult to read, particularly in the introductions. A few extra pages or a larger format would have solved this problem.

It is often said that the best Ph.D. thesis breeds half a dozen more by virtue of the new avenues of enquiry it opens up. Whilst this excellent compilation is not a thesis, it does open up new lines for research. The identification of building stones and the quarries which provided them is all too often uncertain as seen in the notes of these two volumes. One research line could be to look at the criteria for more accurate identification of source rocks by heavy mineral grains or detailed petrography; another could be a thorough archival study of quarries and their history. In fact, there is no comprehensive history of quarrying in our much quarried country available. These gaps in knowledge show only too well that, with rare exceptions, geologists have generally ignored the uses of the rocks they love. Why? The authors are to be congratulated on the start they have made in this task. No other county can boast such volumes.

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PARKER, A. and SELLWOOD, B. W. (eds.). *Sediment diagenesis*. NATO Advanced Sciences Institute Series C: Mathematical and Physical Sciences, vol. 115, 427 pp. D. Reidel, Dordrecht. Dfl. 140 (c. £35), hardback. ISBN 90 277 1677 3.

Diagenesis, particularly of clastic sediments, is a relatively young discipline. That sedimentary *rocks* clearly differ from recently deposited *sediments* is an obvious observation, however, the rigorous investigation of the precise mechanisms whereby unconsolidated sediments are transformed into rocks has begun in earnest in only the last 20 to 30 years. This discipline has seen especially rapid advancement in recent years with the application of new techniques such as scanning electron microscopy and cathodoluminescence to petrographic studies. Much of the impetus for this new research has been provided by the hydrocarbon industry since diagenesis is often of major importance in determining the ease with which oil and gas may be won from reservoir rocks. Consequently diagenetic studies are a rapidly expanding branch of geology with a concomittantly rapid turnover of new information and ideas. This book contains 'Keynote' papers from a NATO Advanced Study Institute held in Reading during July, 1981 and hence represents a 'state of the art' summary. As such it consists almost entirely of reviews and summaries of existing literature rather than presenting new ideas or data.

Chapters by T. Elliot and N. James respectively review terrigenous clastic and carbonate sedimentary environments and facies. Both of these reviews are useful as a guide to the existing literature for diagentisists who are unfamiliar with these subject areas, but, due principally to space constraints, lack sufficient detail to be used in isolation. G.V. Chilinganan reviews compactional diagenesis largely by synthesis of his previously published summaries. Similarly K. Bjorlykke draws largely on his own studies of North Sea hydrocarbon reservoirs in a review of sandstone diagenesis. B. Velde provides a review of clay mineral diagenesis, principally in terms of geochemical phase diagrams. H. Fuchtbauer discusses facies control of sandstone diagenesis and this is paralleled by a review of early carbonate diagenesis by R.G.C. Bathurst. The final chapter presents a review of fluvial diagenesis of limestones by H.R. Wanless. The chapter by Bathurst provides a useful update of ideas expressed in his textbook whilst the contribution by Wanless is a description largely of the effects of pressure solution and dolomitisation.

Overall the volume contains a series of sound summaries of specific subject areas. Unfortunately these remain as individual papers and little attempt has been made to synthesise these into an integral text other than the provision of an index. Perhaps a more serious failing of the book, which no doubt results from its rapid publication, are the frequent typographical errors and several 'cited but not listed' references. Despite these failings the book provides a useful reference source which many researchers will wish to use as a guide through the bewildering number of works recently published on this subject.

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N. EYLES (ed.). *Glacial Geology: An introduction for engineers and earth scientists*. Pergamon Press, Oxford. 1984. 409 pp. Price £9.95, (Flexicover). ISBN 0 08 030263 7.

The past two decades have witnessed major advances in our understanding of the relationships between cold climate processes and sediment properties and between cold climate sediments and landforms. On this basis general models of erosion, debris removal and deposition have become established, each characterised by recurring associations of landforms and sedimentary sequences (ie 'land systems'). Such models are potentially important as interpretative tools for various geological and engineering investigations in areas such as Britain and North America that were subject to a range of cold climate environments during the Pleistocene. The publication of a text embracing both the theory and practical applications of a landsystem approach in a glaciated terrain has been long overdue, and the work under review represents a timely attempt to fill the gap.

An introductory "rationale" indicates that the book was designed for mid- to senior-level undergraduates, college students and industry and government employees who need a "basic introduction to the geology of glaciated terrains". Its theme is that the comprehension of a small number of glacial landsystem models can form a suitable foundation for the successful interpretation of ground conditions in formerly glaciated areas. The book comprises 15 papers written by "active specialists in university and industry" and is considered by its editor to be "a distillation of a very large and diverse literature that crosses traditional discipline boundaries and areas of individual expertise". There is an extensive list of references amounting to 32 pages at the end of the text.

The first 9 chapters of the book are largely concerned with the 'Landsystems Approach' and include reviews of the depositional processes operating at glacier margins. An introductory overview (18 pages) is followed by papers on the subglacial (52 pages), supraglacial (20 pages) and glaciated valley (20 pages) landsystems. These precede accounts of periglacial landforms and sediments (29 pages) glaciolacustrine and glaciomarine deposition (28 pages) and glaciofluvial transport and deposition (15 pages). There are also chapters dealing with the geotechnical properties of lodgement till (29 pages) and the distribution of glacial landsystems in Britain and North America (16 pages). A notable and pleasing aspect of this first part of the book is the use of block diagrams to give a three-dimensional illustration of the associations of landforms and sedimentary sequences under discussion. However, it is unfortunate that many of these detailed diagrams have been reduced to less than half-page size which minimises their impact on the reader.

The final 6 chapters of the book focus on engineering aspects of glacial geology. These comprise papers on engineering geological mapping (18 pages), site investigation procedures (28 pages), foundation engineering (27 pages), road construction (16 pages), dam and reservoir construction (31 pages) and hydrogeology (20 pages). However, there is little attempt to follow the landsystems theme advocated in the opening part of the book. For example, the account of site investigation procedures (Chapter 11) tends to concentrate on relatively expensive methods of subsurface exploration using sophisticated engineering equipment. The potential value of employing a glacial geologist to undertake a landsystems interpretation is not discussed, although it is acknowledged that university and college departments might be able to provide detailed local information. It is a pity that, throughout the book, greater emphasis was not given to engineering case histories where a landsystems approach had been successfully used. Without such evidence, site investigation engineers of the future may remain unconvinced of the value of this new interpretative tool.

The standard of production of the text is a disappointment. This results partly from the policy of reproducing the author's original typescript (in reduced form) and partly because of inadequate proof checking. On some pages the print is uncomfortably faint, and there are instances where it is poorly aligned (e.g. p107). The readers attention is further distracted by irregular word spacings (e.g. p105), missing technical symbols (e.g. p300 and p304) and uncorrected typographic errors (e.g. three errors in the caption to Fig 9.3). On p262 a substantial passage has been omitted. A general lack of uniformity in the presentation of the diagrams detracts from the aesthetic appeal in the book. The unnecessarily large format of certain figures contrasts with the excessive reduction of others. There are wide variations in cartographic standards and styles. Some diagrams lack an indication of scale (e.g. Fig 3.8) and others have incomplete legends (e.g. Figs 1.8 and 10.3). In Fig 9.1 there is a mis-match between the map and its key because of differential reduction. In Figs 9.5, 9.6 and 9.7 the amount of information intended to be shown is inappropriate to the size of the final maps, and much detail has been lost in the reduction process. The captions to many figures fail to stand out from the text such that it is not always immediately obvious where captions end and text continues (e.g. p5 and p99). In some cases, small fragments of text are lost amongst a sequence of diagrams (e.g. p35).

Overall the book is a useful review of the field of glacial geology. The aims and objectives are commendable, but they are not fully achieved because of an unfortunate abandonment of the landsystems theme in the later chapters. I have reservations about its suitability as an under-graduate text: it extends beyond the level of the "basic introduction" intended, and some of the chapters are quite heavy going. The poor standard of production is a major distraction. Nevertheless, the book is a welcome addition to the literature and it should serve as a valuable reference source for engineers and geologists alike.

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McQUILLAN, R., BACON, M. & BARCLAY, W., (with contributions by R.E. Sheriff, R. McEvoy & R. Steele). *An Introduction to Seismic Interpretation*: Reflection Seismics in Petroleum Exploration. Graham and Trotman Ltd, London, 1984. 256pp. ISBN 0 86010 455 9 (Hardback) £29.50, ISBN 0 86010 496 6 (Soft cover) £16.00.

The first edition of this title appeared in 1979. Then it was considered an excellent contribution to the subject of reflection seismics in hydrocarbon exploration and as such a very welcome addition to the bookshelves. Since its publication there have been many advances and a shift in emphasis at undergraduate level towards increased teaching of the subject. This reworked and expanded new edition is the fruit of these changes and as such again receives a warm welcome. In revising the original version the page format is smaller, while both the text and illustrations have been expanded. As such this second edition represents both a revision of the original material and a new appraisal of the subject.

The overall approach of the book remains essentially the same with sections on data acquisition, data processing, geophysical and geological interpretation, sandwiched between the basic theory and case histories. Additional chapters on the use of well-log data and other geophysical methods together with a contribution on seismic stratigraphy and hydrocarbon detection (R.E. Sheriff) are interspersed to complete the coverage. Within this scheme there is now a greater emphasis placed on the fundamental theory which should appeal to the students of applied geophysics courses, as will the appendices (8 of them!) covering everything from physical properties of rocks and the interconversion of units, to sample questions from British University and North American examination papers. Even with the reorientation of the book so that it doubles as a student text (with a greater depth being given to the theoretical aspects underlying the technique) the mathematical treatment does not dominate the book and so the less-numerical reader wishing to concentrate on the interpretation or case histories should fear little. Though on a slightly sour note the change to a smaller format is accompanied by a loss of quality in some of the diagrams which is disappointing. While the majority remain crisp and clear, and the colour reproductions excel, a small number of previously acceptable black and white diagrams are now rendered either too dark or too faint. This will cause little problem for those directly involved in the subject, but for the novice or amateur some aspects may be unclear.

The choice of case histories provides a wealth of informative reading, particularly in showing the application of the earlier chapters to real ground. The integrated application of the geophysical techniques in the Moray Firth study, the use of CDP shooting in the Rainbow Lake stratigraphic trap evaluation and the velocity problems at the Kingfish Oilfield - currently Australia's largest producing oilfield - help bring together the different elements and emphasis that all is not nearly quite so simple as we may earlier have thought. The final study of the Hewett Gas Field briefly traces the development of seismic acquisition and interpretation techniques over much of the 1960s and 1970s. The advances made over the period have improved beyond any expectation and the techniques of twenty years ago are now obsolete. If the future follows that trend we may expect further developments over the next decade and the introduction of techniques which will outdate those currently in use. Perhaps, in this, we can look forward to a third edition of this text at the end of the decade to keep us abreast of these advances.

As an introduction to the subject this new edition provides a most useful insight into the world of reflection seismics in petroleum exploration and on balance improves on the original version, itself a welcome and most useful reference. Perhaps the only reservation concerns the increase in price. The original hardback was priced at £16.50; the new hardback is £29.50. I guess for 1985 such a price is considered most reasonable and we should be grateful for a student soft cover at the same price as the 1979 original.

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BIGNOT, G. *Elements of Micropalaeontology* 1985. Graham & Trotman, London, xii + 217pp. £25 hardback (ISBN 0 86010 485 0); £9.95 soft cover ISBN 0 86010 490 7.

On those rare occasions when palaeontology hits the national headlines, it is the spectacularly large fossils, the dinosaur's claw or the Bolsover dragonfly, that are usually involved. However, as everyone's Mum used to say, the nicest things come in small packages, and nowadays there is an increasing general awareness of the beauty and importance of microscopic fossils. Most undergraduate geology courses now contain a component of micropalaeontology and evening class students are commonly introduced to several of the more accessible groups. Wash a handful of Leicestershire Lias in hot water and you can recover a rich and diverse assemblage of foraminifera and ostracods, while a block of Carboniferous Limestone from Derbyshire can be treated with dilute acetic acid to yield abundant conodont elements. These fossils can be readily examined with a basic binocular microscope, but others, such as diatoms and dinoflagellete algal cysts, require more sophisticated equipment. Some, like the coccoliths, are so small that they can only be studied adequately using electron microscopes.

The upsurge of interest in microfossils has created a need for relevant textbooks, and in recent years two rather different volumes (Brasier 1980, Haq & Boersma 1978) have ensnared the market. Now a third contender has become available with the translation of Professor Bignot's work, originally published in French in 1982. This book differs from the others in being divided into two major sections, one introducing the main microfossil groups and the other outlining the geological and palaeobiological applications of micropalaeontology. The text has been translated by Aget Language Services under the scientific guidance of Dr Sally Radford, who between them have done an excellent job in producing a flowing English text with very few patches of clumsy phraseology. There are a few curiosities, though, such as the occasional use of "carbonate" when "carbonaceous" is meant.

After an introduction and a rather unsatisfactory outline of techniques of collection, preparation and identification, the first section proceeds with a largely morphological survey of the major microfossil groups under the Chapter headings: Foraminifera, Ostracods, Calpionellids and Related Microfossils, Siliceous Microfossils, Conodonts and Palynology. There is a wealth of detail in these pages, accompanied by hundreds of line drawings, but the author shows a consistent tendency to introduce jargon without adequate definition or explanation. In places, too, the detail is unnecessarily complex. For example, is it really worthwhile presenting the formula of conodont elements as: $Ca_5Na_{0.14}(PO_4)_{3.01}(CO_3)_{0.16}F_{0.73}(H_2O)_{0.85}$? The author's approach means that, while the text-book may be a useful adjunct to a taught course, it does not provide an understandable introduction for the uninitiated reader. Another shortcoming is the curious mixture of dated and up-to-the-minute information given in many chapters, giving the impression of an old text rather hurriedly revised for this edition. The updating of the bibliographies given at the end of each chapter, however, is certainly useful.

The second section of the book, dealing with applications of micropalaeontology, comprises about one-third of the text, with the topics covered including preservation, evolution, the earliest life, biostratigraphy, palaeoecology and palaeobiogeography. This set of chapters varies from the interesting to the idiosyncratic, but does contain several good examples of the uses of microfossils. Some of the arguments, though, are rather vaguely presented and I encountered one howler (unless there has been a major scientific advance of which I am unaware), on p. 163, where it is suggested that the age of Precambrian deposits has been established by radiocarbon dating.

In all, although this book contains a considerable amount of information, I found it a little disappointing. I do not think I can recommend it to most of the readership of this journal. It will have value, perhaps, for the teacher of micropalaeontology who requires quick access to detailed morphological data and to examples of applications; my thanks, therefore, to the editor of the *Mercian Geologist* for allowing me to acquire a copy by writing this review.

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N.B. *An Introduction to Seismic Interpretation* and *Elements of Micropalaeontology* may be obtained at the prices given above, plus postage, directly from Graham & Trotman Ltd, Sterling House, 66 Wilton Road, London SW1V 1DE. Telephone 01 821 1123. Telex: 298878 Gramco G.

SHIMOZURU, D. and YOKOYAMA., I. (eds.). *Arc Volcanism: Physics and Tectonics*. 1983. Terra Scientific Publ. Co. Tokyo; D. Reidel Publ. Co. Dordrecht/Boston/London; vii + 263pp. US $65, ISBN 90 227 1612 9.

This is a selection of fifteen papers presented during the Symposium on Arc Volcanism held in Tokyo and Hakone in 1981. The volume supposedly brings together contributions on a particular aspect of the meeting though in reality the papers are linked by a somewhat slender thematic thread. Most of the papers are by Japanese authors and deal mainly with volcanoes in Japan and the western Pacific region. There are plenty of new data and several original models and ideas to satisfy the determined specialist but it is definitely not a book for the undergraduate or reader with a more general interest. Even the specialist will be deterred by the exorbitant price!

The volume is divided into two sections with seven papers under Physics and eight under Tectonics, although the division between these is not altogether clear. One of the more interesting papers in the first section is that of Yokoyama who uses gravity and drilling data on four Japanese calderas to conclude that explosion rather than collapse must be the dominant mechanism in their formation. In a study of volcanic earthquakes, Okada finds evidence that magnitude 5 events often trigger sector collapse where sufficient gravitational instability has developed. Imai proposes a mechanism for successive eruptions at Asama Volcano involving shallow implosion earthquakes with a downward first motion. One interpretation is based on two phase flow, liquid plus gas, and another involves a syphoning mechanism — the coffee percolator model. Other topics addressed in the first section of the volume include rates of magma supply; thermal energy and the ratio between intrusive and extrusive magmatism; and a theoretical model for tephra dispersion.

The second part is concerned largely with models of subduction processes and magma generation. Honda and Uyeda review the thermal structure of subduction zones, favouring the possibility that release of volatiles and mechanical weakening of the slab may be important in determining preferential paths for magma ascent. Shimozuru and Kubo examine the relationship between spacing of volcanoes along an arc system and the dip of the subducting slab. In the ‘Chilean type’ there is strong coupling between upper and lower plates, greater seismicity and more closely spaced volcanic centres. In contrast, in the ‘Marianas type’ there is more effective decoupling, little seismicity and a lower linear concentration of volcanic centres. Kobayashi discusses fore-arc volcanism and the role of boninites, which develop during the initial stages of subduction when volatiles are first introduced into the asthenosphere. Accretion and obduction may bring together fragments of oceanic crust, the fore-arc assemblage and the arc volcanics.

Ida integrates changing thermal and mechanical regimes in a model of subduction zone evolution progressing from arc to marginal basin volcanism. Honza sees an inverse relationship between the intensity of arc and marginal basin volcanism based on a convection current model. In the segmented eastern Aleutian arc (Kienle et al.) andesite predominates at intrasegment volcanoes and dacites, domes, ash flows and calderas are characteristic of segment boundaries. Volcanism ceases towards the eastern part of the Aleutian arc system, perhaps because of the development of a large fore-arc accretionary wedge. The Solomon Islands have deveoped in response to the complex interaction of the Australian and Pacific Plates, further complicated by the subduction of the Woodlark Basin and its spreading centre, resulting in eruption of the unusual basic lavas of the New Georgia Group (Dunkley). The final paper (Keating et al.) is concerned with palaeomagnetic studies of the Bonin and Mariana arcs. Clockwise rotation and northward drift are related to onset of subduction of the Pacific plate beneath the Philippine Sea.

The volume does not purport to give an overview of arc volcanism nor does it provide a systematic coverage of the physics and tectonics of island arcs. An assortment of loosely related papers, the only justification for publication in this form is as a record of some of the proceedings of a particular symposium. In a sense it is an unnecessary volume since most of the papers could have been readily accommodated in appropriate scientific journals.

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EAST MIDLANDS GEOLOGICAL SOCIETY

SECRETARY'S REPORT FOR 1982

The membership of the Society during its 19th year remained around 500, with some 20 per cent of the non-Institutional members taking an active part in field and indoor meetings. There were 6 indoor, 1 full day Joint meeting with Matlock Field Club, 1 week-end, 1 week, 5 day and 1 afternoon field excursions. As usual leaders and speakers maintained the high standard we now expect.

The Annual General Meeting on 6 March in the Swinnerton Laboratory, was attended by around 50 members. Dr T.D. Ford was elected by the Council as the new President, Mrs Morrow having completed 3 years in that office. During the meeting the proposed restrictions on fossil collecting at Charmouth were brought to members' notice and they were urged to write in protest to protect the site for students' use. The Treasurer was pleased to report that a forecast deficit of £400-£500 was instead, a surplus of £50, for which he blamed an increase in the number of subscriptions, a boost in sales of the Journals, Bank Interest remaining high, reduction in the price of printing the Journal and finally, everyone in their efforts to reduce costs. There were no adverse comments at the meeting which proceeded smoothly, finishing at 7.00 p.m. It was followed by the *Collector's Meeting* at which members wishing to mount an exhibit had set out their displays before the AGM including the popular "Bring and Buy" stall run by Mr J.H. SYkes, making £43.00, which he generously donated to Society funds. There were several new members who not only attended but also exhibited.

The exhibitors and their displays were as follows:-

A.E.G. Allsop	Having a closer look at pebbles England's green and pleasant land Photographs of the Carsington Reservoir Project Hammering with a camera in Norway
Mr & Mrs J. Beaumont	The Darkness beckons - Underground in the Limestone of Yorkshire
Mr & Mrs T.F. Bridges	Minerals in Cardiff
The Editor	The Complete Mercian Geologist
T.I. Fairgrieve	Collection from Ravenscar Peak Fault
L. Grundy	Cornish Minerals
Mr Oakland	Lapidary
Miss E.A. Ramsell	Petrified Wood
The Secretary	Leaflets and Information sent to the Society Two polished specimens of ammonites from Whitby
Dr F.M. Taylor	Two Blue Minerals

Saturday 20th March was the occasion of the Joint Meeting with Matlock Field Club, the subject being "Slope Stability in Derbyshire" given by Mr Steve Penn of Trent Polytechnic, Nottingham. The meeting began with a lecture attended by 30 people in the Peak District Mining Museum, Matlock Bath. After lunch, the effects of landslip, at Mam Tor and especially on the now closed A625 were examined. The ascent of Mam Tor was made in a snowstorm, but luckily the descent was in sunshine. It was shown that no amount of road repair could prevent the landslip, and in fact aggravated the situation.

The last indoor meeting of the session on 24th April, was given by Dr P.R. Ineson of the University of Sheffield, a prolific contributor to the Mercian Geologist, who spoke on the "Igneous Horizons of Derbyshire and why they are studied". He enlarged on his previously published paper in the Journal about the poor exposures giving little clue to the extent and depth of igneous material in the area.

The May week-end excursion from 21-23, was spent in the Malverns and led by Dr R.J. Aldridge of the University of Nottingham. The headquaters was the Thornbury Hotel in Great Malvern which accommodated 24 members, several others joining each day's excursion. On the Saturday, the Precambrian in the large quarries adjacent to the Clock Tower were examined. Sunday's locations concentrated on the Cambrian and Silurian strata and fossils of the area. Following the excursion, several members rang the Secretary to say how much they had enjoyed the week-end. A reminder to the membership that constructive criticism is also welcomed.

Mr W.S. Moffatt of Loughborough University, with Dr R.J.O. Hamblin of British Geological Survey at Keyworth, took 26 members to Ironbridge for Industrial Archaeology as well as its geology on 13th June. The party first visited Blists Hill Museum, a fascinating reconstruction of life in the 19 century, with its cottages, shops, chapel and machinery. The afternoon, led by Dr Hamblin, who had surveyed the area, was spent looking round the town, the Bridge and the slope failures which have occured in recent years. The Ironbridge itself helping to keep the two sides of the Valley apart.

On Sunday 18th July, the "Jurassic Scarplands" excursion was led by Sir Peter Kent, the coach party meeting the car contingent at the summit of Ab Kettleby Hill for a vantage point view of the Scarp. The Nature Reserve at Holwell was then visited for the Middle and Upper Lias, Harlaxton Quarry, and then after lunch at Great Ponton, a quarry with shelly Upper Lincolnshire Limestone, near Sproxton. Here an extra exposure of nude bathers on a glorious sunny afternoon was surprised by 40 members, as well as the Grantham Formation and Lincolnshire Limestone. The return journey was made via Waltham and Bingham for a general view of the scarps.

The week's field excursion was spent in Northumberland from 24th-31st July, the headquarters being the Sunningdale Hotel at Bamburgh, 22 staying in the hotel, and joined by 6 others staying locally. Led by Mr A.K. James, who had hoped to work up the succession of rocks, had the tide levels not dictated otherwise.

On Sunday the party travelled to the nothernmost location of the week. After parking the cars at St Abbs, we walked to St Abbs Head examining the lavas, Lower Old Red Sandstone conglomerate, Silurian greywackes and shales on the shore below. Passing Mire Loch, which is on the St Abbs Head fault line, seeing several faults cutting the cliffs and stacks, dip slopes in the tops of the lava flows, and at Pettico Wick, rocks of Silurian Llandovery age containing some graptolites. Returning to the cars for lunch above the harbour, with coastguards, police cars and an ambulance, and hearing messages about helicopters going out to rescue a diver. After lunch, a short walk across fields to Siccar Point for the well displayed unconformity, with its vertical shales and greywackes covered by gently dipping dull red breccia and sandstone of the Lower Carboniferous. Then to Pease Bay and Cove, the path to the shore line passes through a tunnel cut in Cove Harbour Sandstone. The generally NE dip of the rocks enables over a 1,000 ft of sediment to be followed. At the Granthouse quarry, grooves, flats and ripple markings were found in the greywackes and shales.

North Northumberland was the target on Monday with the coast section between Scremeston and Spittal, where some good examples of Lithostrotian were found. Then to Berwick on Tweed with a cliff top walk from which the Middle Limestone Group structures could be clearly seen, and retracing our steps along the beach to examine them more closely. Finally the day finished with a visit to Holy Island, the dyke providing the foundation for Lindisfarne Castle and a protective wall for the Priory and village. Everyone managed to leave the island before being cut off by the tide.

Tuesday was spent in the Tyne and Wear area, firstly in Downhill Quarry in unconsolidated Yellow Sands. Fulwell provided the party with some good examples of Canonball Limestone, which were then seen on the promenade and shore at Roker. The erosional features and stacks were observed from above at Marsden Bay and Tynemouth was viewed from the shore for the Permian succession, finishing at Seaton Sluice, a sequence in the Middle Coal Measures.

On Wednesday, a visit to the Farne Islands in the morning, sailing from Seahouses, outwards in drizzle, but bright sunshine on landing. The birds definitely let everyone know whose territory it was! The classic site of Howick with the Whin Sill, folds, faults and intrusions in sediments of the Middle and Upper Limestone Groups, was visited after lunch. Craster and Dunstanburgh were the final locations of the day, again the Whin Sill predominating the scene.

A day was spent inland on Thursday at Roddam Dene to see the basal conglomerate of the Carboniferous Cementstone Group including a steep descent to the river section with the extra hazards of adders and nettles. At Fawden Dene and Shawdon Dene, near Ingram, glacial overflow channels and then Harden Redstone Quarry, Biddlestone, in a minor intrusion of Felsite associated with the emplacement of the Cheviot granite were seen. Huge mounds of various sized chippings are stockpiled, some travelling as far South as Torquay. The Coquet Gorge was OUT - the MOD were firing! The alternative was a shore section in the Middle Limestone Group at Beadnell.

Friday, another day spent inland, first at Doddington Quarry in the Fell Sandstone Group which is used as a building stone, for example in Chester Cathedral and then Pin Well, which was approached through a deep channel eroded by meltwater, leading to the disused quarry in andesitic lavas. After lunch, the long narrow road in Harthope Burn was visited, the party following the Hawsen Burn upstream to find the baked margin in the gorge walls. The disused airfield at Milfield, now worked for sand and gravel, was visited and then Mindrumill Crag andesitic lavas which form an upstanding crag and tail feature. Returning to Bamburgh, the party drove by Flodden Field, Ford Castle and made a short stop to view the Cup and Ring markings at Roughtinglinn.

A pleasant evening was spent with the whole party at the hotel before leaving for home the next day. A warm and sunny week with excellent geology and splendid scenery.

The field trip on 12th September was a Fossil Hunt in North Buckinghamshire and Oxfordshire led by Mr A. Horton of NERC. The rendezvous was the London Brick Company's Calvert Brick Works, where 30 members met the leader and Mr J. Horrell, the LBC Geologist, who kindly allowed us access. Some splendid specimens of ammonites were found in the quarry debris. At Ardley in the Middle Jurassic the quarry floor is riddled with worm burrows and bores. Duns Tew Sandpit was visited and finally the quarry behind the Cross Hands Inn near Chipping Norton provided some good specimens of echinoids.

On 10th October a small party visited West Mine, Alderley Edge, owned by Mr P.V.R. Sorenson, who with Dr Ford, escorted the group down the mine. Dating from 1857, it closed again in 1874, but was reopened during the 1914-18 War. All were equipped with lamps and batteries and descended 2 ladders to the galleries and caverns below. Malachite and azurite were found occuring together, and in one cavern, an unusual purple fungus, which tests have shown has no sustenance and yet thrives in complete darkness. Emerging eventually, and after a hurried lunch, Dr Ford led the party along Alderley Edge itself.

The proposal by British Rail to replace the bridge spanning Duckmanton Railway Cutting Reserve (Wilcockson Reserve) by an embankment, had been defeated. This would have covered the Clay Cross Marine Band, one of the most important marker horizons in the Coal Measures. Terry Judge, the Warden, had been contacted, and on a Saturday afternoon 23th October led members through the cutting explaining the work which he, and groups of volunteers had already achieved. The Society has donated £50 shortly before and he showed that the money had enabled steps to be constructed making an easier descent into the Reserve. Mr Judge's enthusiasm and anecdotes were much appreciated.

The winter indoor session began on 6th November when Professor Oxburgh of Cambridge lectured on "Geothermal Energy - Fact or Fantasy?" Talking of the energy emitted naturally from the earth, he had become interested in ways to assess this energy available far below. In certain parts of France, water for domestic heating is pumped down through boreholes, and the warmed water extracted. Possible areas in Britain with higher temperatures are Hampshire, Lincolnshire and Nottinghamshire. He suggested power stations would benefit from this heating boost.

On 11th December a social occasion as well as a lecture was held. Dr I.D. Sutton of Nottingham Adult Education Department, talked on "The Arid Lands of Western USA". Interspersing his lecture with geological diagrams and slides of spectacular scenery, he explained the reasons why the area had become so arid.

Afterwards, the 75 people adjourned to the Swinnerton Laboratory for an American style evening - cheesecake, pumpkin pie, various cheeses and Californian wine. Raffle prizes were awarded to 3 lucky winners.

Following the visit to the Duckmanton Reserve, a small area to the east of the new bridge needed researching before it was covered to find the Second Ell coal seam, which Mr Judge did not believe existed just there. Armed with spades and retaining ropes, the small party dug trenches in the steep sides of the cutting to prove that, in fact, no such seam occurs at that point. This was undertaken on 15th January 1983.

Nine years ago Dr Aldridge had lectured on the subject of Conodonts, and on 22nd January he brought members up-to-date with the "Conodont Animal - a tale of the unexpected?" Firstly reading some of the details of his previous talk, he then went on to describe the worm-like creature found in a sample from the banks of the Firth of Forth, which, on close examination, seemed to have conodonts in pairs in the mouth region, and also in the right positions. Further samples would have to be examined for confirmation, but hopefully, the Conodont Animal may have been traced at last. Dr Aldridge kindly fetched his precious sample for members to look at.

Dr Ford gave his Presidential Address on 5th February, the subject being "Precambrian Fossils of Charnwood Forest". He and Mrs Ford were entertained by Council Members to dinner before the meeting. He recalled the occasion in 1958 when a young boy had approached him saying he had noticed an impression of a frond-like fossil in a quarry at Charnwood. Searching further, others were found, and various lighting angles had revealed different aspects of these and other fossils. The problem, as always, is preservation from those irresponsible enough to want to extract them. As usual the President liberally illustrated his Address with slides.

The Presidential Address ended a very successful year of excursions and meetings. Our appreciation to Dr Ford and all the speakers, Mr S. Penn, Dr P.R. Ineson, Professor E.R. Oxburgh, Dr I.D. Sutton, Dr R.J. Aldridge, and leaders, Dr Aldridge, Mr W.S. Moffatt, Sir Peter Kent, Mr A.K. James, Mr A. Horton, Mr. P.V.R. Sorensen, the President, and Mr T. Judge. The Society is indebted to each one for their willingness to be involved in the year's programme.

Eleven circulars had been produced during 1982 and had kept members informed of news, events and publications. The list of members who so kindly hand delivered does change as their circumstances alter, but there is usually someone willing to take over when this happens and we are very grateful for this service which they render.

Six Council Meetings had been held at the Secretary's home, where Society affairs were discussed and the programme for the coming seasons planned. Items for the agenda may be sent to the Secretary, and should be received no later than 2 weeks before the next meeting, the date being published in the circular.

Society Membership was as follows:

Honorary	Ordinary	Joint	Junior	Institutional
2	251	118	4	115

A total of 490.

The Mercian Geologist had been published twice, but because of problems at the University with new machinery, typists and also with the printers and plates, Vol. 9 No. 1 had only just scraped into the current year. The Editor acknowledges the effort that collators and the distribution team make in the production of the Journal.

The Society Exhibit had been taken out of circulation as it was in need of up-dating and renovation, the work being undertaken by its original designer, Mr M.F. Stanley at Matlock.

The Society project at Headstone Cutting, Monsal Head, had been completed by Mr M.G. Lodge and helpers, the samples having been delivered to the University of Nottingham for examination.

It was with sincere thanks that we acknowledged the debt both to the University of Nottingham and Professor Baker for the use of the Department of Geology for meetings and activities. The Society is fortunate indeed in having such understanding bodies to gratify our needs.

Finally, in my report for 1982, my thanks for the continued support of every member, especially those on Council, also all speakers and leaders, which made it another successful year for the Society.

W. Madge Wright.

LETTERS TO THE EDITOR

Lithostratigraphy of the Peel Sandstones, Isle of Man

16th May, 1985

Dear Sir,

In a recent account of the Society's field excursion to the Isle of Man Dr. T.D. Ford very briefly outlined several problematical aspects regarding the outcrop stratigraphy and age of the Peel Sandstones. Both problems have resulted in some disagreement in the published literature (see review by Ford, 1971). The age of the succession has proved to be particularly enigmatic in the absence of a dateable contemporaneous fauna or flora and has lead to a variety of assumed dates of sedimentation, ranging from Old Red Sandstone (ORS) to Carboniferous and Permo-Triassic. In view of the Society's recent interest in the Peel Sandstones the aim is to briefly examine published data and new evidence which may help to resolve these problems.

Outcrop Sratigraphy

The Peel Sandstones, outcropping on the northwest coast of the Isle of Man (see Fig.1), were originally described by Boyd Dawkins (1902) and Lamplugh (1903). In his paper, Boyd Dawkins (1902) erected an outcrop stratigraphy and proposed the occurrence of a total stratigraphic thickness of approximately 500 m (including an inferred unexposed sequence of approximately 150 m projected inland). A cross section illustrating the outcrop stratigraphy suggested that the coastal exposure represented the fault repetition of the succession, based on observed gross lithological similarities between the rocks exposed either side of Traie Fogog bay and those exposed further north at Whitestrand. Ford (1984), however, pointed out that the Whitestrand succession, although lithologically similar, is "a repetition of depositional facies rather than a faulted recurrence of the same beds in Traie Fogog" and that the succession has, therefore, not been fault repeated to any significant extent. This assertion may be confirmed by:

1. Examination of clast petrography and identification of derived fossils (see also Gill, 1903; Lewis, 1934) has established that the younger the conglomerate the older are its clasts. This well developed inverted clast stratigraphy, most obviously defined by the restricted occurrence of Wenlock faunas to The Stack conglomerates (supported by the work of Lewis, 1934 and my own recent collection of approximately 70 fossiliferous clasts examined by Dr. C.T. Scrutton) and Ashgillian faunas to the Whitestrand conglomerates (supported by Gill, 1903; Lewis, 1934) and the presence of Ordovician related crinoid ossicles identified in one derived limestone clast by Dr. S.K. Donovan). This strongly suggests that the conglomerates exposed at Whitestrand are stratigraphically younger than those exposed at The Stack. Segregation of a wide range of clast types further supports this argument, particularly noteable is the restricted occurrence, in The Stack conglomerates, of numerous clasts of relatively unaltered acid lavas, pyroclastics and the presence of similar pyroclastic material in some derived Wenlock limestone clasts, whilst the Whitestrand conglomerates do not contain any clasts of this type, but do contain an abundance of intensely altered (?) volcanoclastic detritus of a type not recognised in The Stack conglomerates. Further distinct variations in clast composition also exists between the two units described above and the exotic conglomeratic clasts which contribute to the thin gravel bases of fluvial channel sandstone bodies exposed towards the base of the succession.
2. Although the succession is intensely dissected by fractures and small faults the thickness of The Stack conglomerate is approximately an order of magnitude greater than the conglomeratic unit exposed at Whitestrand.
3. The occurrence of distinct variations in profile type, degree of profile development and thickness of the pedogenic carbonates between the two conglomeratic units.

Further differences, in the form of minor facies variations (as suggested by Ford, 1984), also support the argument for an outcrop pattern not repeated by faulting, but the evidence is less immediately conclusive than that outlined above.

Therefore, despite a moderate degree of deformation, it appears that the present Peel Sandstone exposure represents a sediment package of the order of 1000 m, approximately twice that originally suggested by Boyd

Dawkins (1902). Furthermore, since no outcrop evidence exists defining the base and top of the Peel Sandstones the complete succession may originally have been substantially thicker, the present exposure existing at a remnant of a once significant clastic wedge.

Age of the Peel Sandstones

Available lithostratigraphic and structural evidence indicates that the Peel Sandstones were deposited:

1. Later than the derived Wenlock limestone clasts contained within The Stack conglomerates.
2. Prior to the tectonic uplift of the Cambro-Ordovician Manx Carboniferous (Arundian) basal, red bed conglomerates exposed at Langness and their complete absence from the Peel Sandstone conglomerates.
3. Prior to the tectonic deformation of the Manx Carboniferous (Arundian-Brigantian) succession, as evidenced by the significantly greater degree of tectonic deformation (with dips in the Peel Sandstone exceeding those in the Manx Carboniferous by up to 30°-40°) suffered by the Peel Sandstones.

The age of the Peel Sandstones, therefore, falls into a time slot between the Upper Silurian and Lower Carboniferous and can therefore be considered ORS in age as defined by Allen (1977, pg 40-42).

Clearly the date of the earliest phase of deformation to affect the Peel Sandstone becomes critical in defining the age of the rocks more precisely. Examination of the regional deformation history of the British Isles between the Upper Silurian-Lower Carboniferous (e.g. Allen, 1974; Bluck, 1984; Powell & Phillips, 1985) suggests that the Peel Sandstones could have been affected by either or both of two potential tectonic events, the first of these occurring during the end Silurian (Downtonian) to Lower Devonian (Gedinnian-Siegenian ?) and the second during the Middle to Upper Devonian (late Emsian to Famennian). The degree of structural deformation of the Peel Sandstones suggests that the succession was unlikely to have been deposited prior to the end Silurian-Lower Devonian event since rocks as young as Lower Downtonian in the Lake District zone are observed to have been overprinted by an end Caledonian cleavage event (Ingham et al. 1978), an effect not recorded in the Peel Sandstones. Evidence provided by the structural and stratigraphic relationships of the Shap Granite (Boulter & Soper, 1973; Wadge *et al*, 1978) suggests that this phase of deformation had been completed by earliest Devonian times. A more likely scenario is that the Peel Sandstones were deposited after the phase of end Caledonian deformation and later deformed by a mild regional tectonic event during the Middle and early Upper Devonian. The period was represented by a major hiatus in sedimentation over much of northern and central Britain, prior to the deposition of an Upper Devonian or Lower Carboniferous uncomformable cover on previously deformed Lower ORS. This view, although equivocal, of the occurrence of Lower Devonian, post orogenic clastic successions, within the paratectonic Caledonian zone, deformed during the Middle Devonian is supported by, and in agreement with, the observations of Capewell (1955) (see also Boulter & Soper, 1973, table 1) on the supposed Lower Devonian Mell Fell Conglomerate of the Lake District.

The assertion that the Peel Sandstones are of Lower Devonian age may be further supported by recourse to the petrological evidence. The variable, but high detrital, garnet content of the sandstones (as noted by Lewis, 1930 and confirmed by Crowley, 1981) originally lead to the speculation (Crowley, 1981) that the Peel Sandstones formed part of a southerly flowing (supported by palaeocurrent data, Crowley, 1981) regional (extending from present-day N. Ireland to S. Wales) early Lower ORS (Downtonian-early Gedinnian) fluvial dispersal system described by Allen (1974), Allen & Crowley (1983) and Simon & Bluck (1982), which consisted of sandstones and conglomerates characterised by a high content of metamorphic detritus dervied from high grade rocks of the orthotectonic Calendonides of (?) northern Britain. This suggestion is now, however, considered to be incorrent for the following reasons:

1. The relative absence in both the sandstones and conglomerates of detrital metamorphic debris other than garnet.
2. The relatively short distance of sediment transport (approximately 5-10 km) inferred from the angularity and coarseness of much of the conglomeratic debris.
3. The inferred alluvial fan-alluvial plain type sedimentology which suggests that the Peel Sandstones did not form part of a major trunk distributary system.

A more likely picture capable of accounting for the association of detrital garnet and the relative absence of other related metamorphic detritus is one in which the earlier regional fluvial dispersal system was segmented and locally uplifted in response to the gradual tectonic evolution of the Caledonides (see Allen, 1974; Allen & Crowley, 1983), resulting in the reworking of earlier, metamorphic-rich Lower ORS sequences along with Lower Palaeozoic upper crustal lithologies. A similar situation is envisaged by Allen (1974) to account for the composition of the later Lower ORS (late Gedinnian-early Emsian) in the Welsh Borders.

In summary it is suggested that the Peel Sandstones represent a fragment of an originally substantial package of sediments deposited during the late Lower Devonian (Seigenian-Emsian) as a series of coalescing alluvial fans and adjacent alluvial plains. Contrary to popular belief regarding Ordovician and Silurian palaeogeographies the Peel Sandstones were derived from a thick, upper level crustal succession of Lower Palaeozoic shallow marine carbonates, volcanics (lavas, pyroclastics and volcanoclastics) and coarse grained clastic lithologies (probably including metamorphic-rich earlier Lower ORS sediments) lying to the NW of the Isle of Man, the resultant detritus being deposited in a (?) simple, isolated intractratonic sag basin possibly initiated in response to marginal uplift induced by the intrustion of the c. 400 Ma granites into the surrounding crust.

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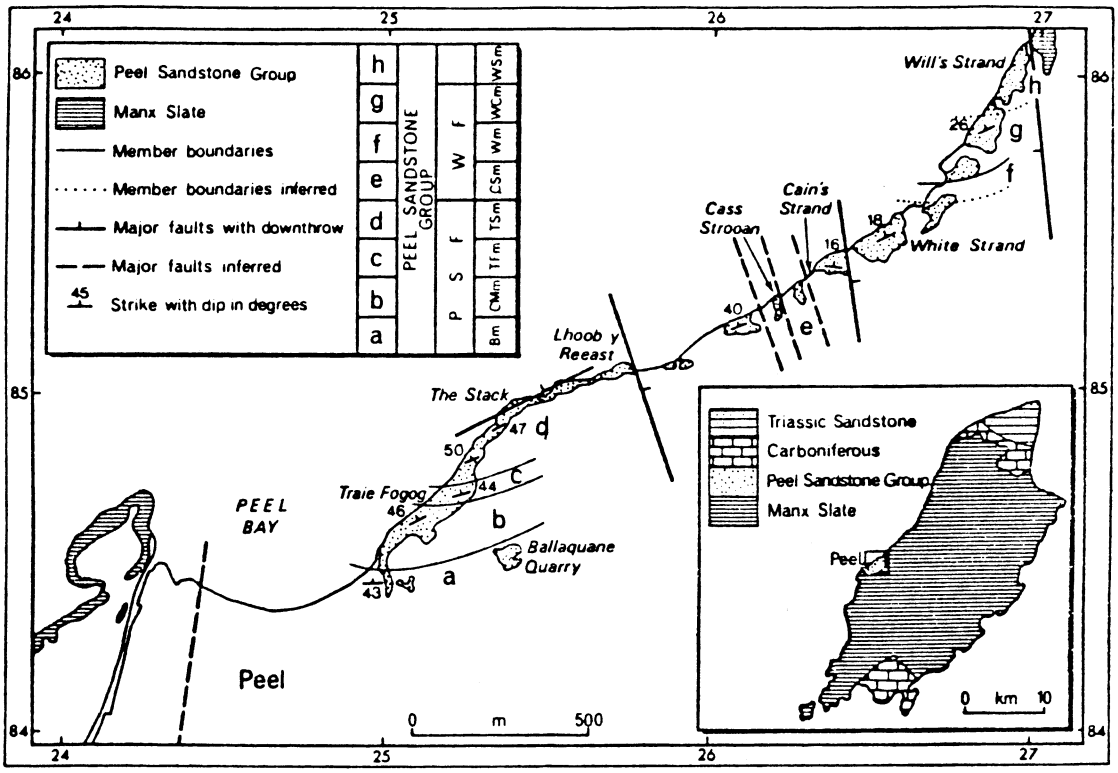

Fig.1. Outcrop and simplified structural map of the Peel Sandstones showing provisional lithostratigraphy.

PSF– Peel Sandstone Formation; WF– Whitestrand Formation; Bm– Ballaquane member (conglomerate and sandstone dominated low sinuosity channels; sheet flood sandstones); CMm– Creg Malin Member (stacked fining upwards cycles– active low sinuosity streams); TFm– Traie Fogog Member– (distal to medial alluvial fan conglomerates, sandstones and siltstones/mudstones; abundant dessication features, sparse pedogenic carbonate profiles); TSm– The Stack Member (medial alluvial fan conglomerates, pebbly sandstones and sandstones; abundant pedogenic carbonate profiles); CSm– Cain's Strand Member (sandstone dominated low sinuosity streams); Wm– Whitestrand Member (distal alluvial fan conglomerates, sandstones and siltstones; abundant dessication features, sparse pedogenic profiles); WCm– Whitestrand Conglomerate Member (distal alluvial fan conglomerates and pebbly sandstones); WSm– Will's Strand Member (sandstone dominated low sinuosity streams; intense structural deformation).

Inset. Simplified geological map of the Isle of Man (after Taylor *et al.*, 1971).

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29th May, 1985

Dear Sir,

Having introduced Mr. Crowley to the Peel Sandstone on a student field course several years ago, I welcome this expansion of knowledge concerning these exposures of the Old Red Sandstone. I fully support his deductions concerning the stratigraphic succession and thickness. He has raised an important point concerning the source of the fossiliferous Ordovician and Silurian clasts in the conglomerates: he suggests the possible presence of a Lower Palaeozoic carbonate platform "5 to 10 km N.W. of the Isle of Man". This would require revision of current ideas of contemporary palaeogeography, and I can only hope that Mr Crowley will soon publish the evidence on which his deductions are based in full.

Yours sincerely,

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THE MERCIAN GEOLOGIST

Journal of the East Midlands Geological Society

The journal first appeared in December 1964 and since that time 36 parts, comprising 9 volumes have been issued; the last, Vol. 9 No. 4 in Dec., 1984. The Mercian Geologist publishes articles especially on the geology of the Midlands of England, but other articles have been published which are of current interest to geology generally. Contents include original papers, review articles, biographies, bibliographies, excursion reports, book reviews and the Secretary's report on Society activities.

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Text-figs. normally occupy a full page of the journal, but part diagrams can be fitted into the typed page. Double page diagrams have been published with a single fold but each printed page has to be folded by hand. The standard reduction by our present printing process is approximately × 0.75. Thus the optimum size for the original diagram, including space for caption, index and explanation if required on the diagram, should be 285×190 mm (285×380 mm with a single fold). Greater reduction is possible but care must be taken with the original to ensure that at the final reduced size (230×155 mm; or 230×310 mm) the smallest letters are no smaller than 1 mm and that there is a similar minimum spacing between letters and lines. Bar scales (metric) should be provided as the exact reduction cannot be guaranteed.

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Year 1985

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