THE GEOLOGY OF THE AREA AROUND MALHAM TARN, YORKSHIRE

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Introduction

Much has been written about the geology of the area around Malham Tarn, but it is scattered in numerous publications. This paper is an attempt to collect together some of the information for the use of those working at the field centre and to provide a bibliography. A description of the Lower Palaeozoic and Pre-Cambrian rocks of the Ribblesdale and Ingleton inliers has been included since these areas are frequently visited by students from the centre and the Silurian inlier at Malham Tarn is more easily understood in relation to the Ordovician and Silurian rocks of Silverdale and Ribblesdale. Otherwise, the area described is limited to that shown on the folded map, about 40 square miles around Malham Tarn.

Fountains Fell in the north west rises to a height of 2,191 feet, whilst in the north east High Mark, Proctor High Mark, etc. form a high limestone area at about 1,500 feet rising to 1,765 feet at Parson's Pulpit. South of this the land drops to an extensive platform around the Tarn at about 1,250 feet. Continuing southwards there is a steep drop across the Mid-Craven fault to 650 feet at Malham and 550 feet at Settle. The important Aire/Ribble watershed runs between Malham and Settle along Kirkby Fell, Black Hill and Fountains Fell. Rising on the west of Black Hill, Cowside Beck (Ribble) drains westwards, whilst the Smelt Mill stream, the Tarn outflow and Gordale Beck, rising to the east of this watershed, drain into the Aire. To the north, Darnbrook Beck, on the north-eastern flank of Fountains Fell, flows into another Cowside Beck (Skirfare) and finally into Littondale.

Streams that flow over limestone tend to make their way underground through a series of widened joints and sinkholes. Since most of the area around the Tarn is limestone, many valleys are wholly or partly dry; for instance, the Tarn outflow, after crossing the North Craven fault on to the limestone, flows a short distance down the valley and disappears at Water Sinks (894655). In dry weather it disappears further up the valley but after periods of heavy rain the underground drainage cannot take the larger volume of water and the stream has flowed right down the valley to the old waterfall at Comb Hill. Darnbrook Beck on Fountains Fell behaves similarly. Generally it flows overground to its confluence with Cowside Beck, but during a long period of drought it sank at about the level of the Cockpits (886712), reappeared as a trickle from 888712 and finally sank at 895710 just above Darnbrook farm.

The Yorkshire Geological and Polytechnic Society (1900) studied the underground drainage over much of the area by pouring various chemicals into the streams where they disappeared and noting where the chemicals reappeared.

They found that the direction of the joints controlled underground drainage, so that the Smelt Mill stream, sinking at 882660, must follow a major joint direction south-eastwards, and reappears at the foot of Malham Cove. The Tarn outflow stream, however, reappears at Aire Head Springs (90156215) and it was suggested that it might follow first one major joint direction south-east to Grey Gill and then another in a south-westerly direction to Aire Head. In both instances the underground drainage and the surface drainage are quite unrelated.

Most of the area described is in Lower Carboniferous rocks, in which limestone predominates. However, at Malham Tarn the Pre-Carboniferous basement is exposed. The older rocks exposed here form the southern margin of the Askrigg Block, which together with the Alston Block are the stable, structural units of the northern Pennines. The oldest rocks are the Ingletonian "grits" and "slates", best exposed at Ingleton, and presumed to be of late Pre-Cambrian age, since they appear to have been folded by a Pre-Cambrian orogeny. The sediments themselves contain fragments of igneous and metamorphic rocks, derived from an archaean land mass, which itself may form a part of the Askrigg Block.

Cambrian strata are not seen in the Craven district and therefore their relationship with the Ingletonian is unknown. The nearest outcrop of Cambrian age occurs on the Isle of Man, but Cambrian seas may well have invaded the Craven district and rocks of this age may lie unexposed beneath the Ordovician rocks.

Upper Ordovician and Silurian rocks, exposed in the small inliers to the north of the North Craven fault, are characteristic of shallow water conditions and there are a number of breaks in sedimentation. It has been suggested, therefore, that the Ordovician and Silurian seas lapped around the fringes of the proto-Askrigg Block, which acted as a positive element whilst the main Caledonian geosyncline lay to the west of it. A comparison of the lithology and thickness of the strata in Craven with those of the Lake District would seem to support this.

The main movements of the Caledonian orogeny took place at the end of the Silurian, and in this region the Lower Palaeozoics were gently folded in concentric folds running approximately east/west. This is not the normal south-west/north-east Caledonian trend, but may be due to basement control by the proto-Askrigg Block. During the Devonian the area probably formed the foot-hills of the Caledonian mountain chain through Wales, the Lake District and Scotland, thus forming an area of erosion rather than deposition, so that Devonian sediments are not found.

At the close of the Devonian, the Carboniferous seas began a widespread transgression over the land. The lowest zones of the Carboniferous are not found on the Askrigg Block, though lower zones may be present in the Craven lowlands. Eventually, however, Lower Carboniferous seas did sweep across both the Alston and Askrigg Blocks and sediments were derived from a land mass to the north, which gradually graded southwards into clear, limestone-forming seas. At the same time, in the so-called "basin facies" to the south of the Askrigg Block, the sediments were thicker and quite different from those to the north. The two successions do not seem to intermingle, but around Black Hill and Daw Haw the "Yoredale series" of the northern succession are represented by thin, dark limestones and shales which closely resemble those of the basin facies; this may represent a transition between the two types of sedimentation. A much fuller account of Carboniferous history is given by Rayner (1953).

Mid-Carboniferous earth movements caused some slight breaks in sedimentation of the unstable "basin" area and it is thought that the Mid-Craven fault was active then. During the Upper Carboniferous quieter conditions prevailed and deltas from the north-east extended southwards over the whole of the Craven area. The coarse grits, shale bands and thin coal seams form the Millstone Grit series, known here as the Grassington Grit. Coal Measures are preserved on the eastern flank of the Pennines, but around Malham Tarn the Grassington Grit is the youngest rock seen, apart from Pleistocene deposits. At the end of the Carboniferous further major earth movements, the Variscan orogeny, took place, but their effects in the north of England are slight. Nevertheless they caused the folding of the Carboniferous in the Craven lowlands and the North Craven fault became active at this time.

There is no direct evidence about the geological history of the area during Mesozoic or Tertiary times, since the strata, if they were laid down, have been eroded away. Pleistocene deposits show quite clearly that the area was glaciated within the last million years and ice action, glacial deposits and periglacial conditions have had a considerable effect on present-day topography. With the gradual amelioration of the climate the area was colonized by Mesolithic man, and their flint implements are found, especially near the Tarn, close to Tarn House and at Hilary's mound. Since then there has been more or less continuous occupation by man in this area and remains dating from bronze age and iron age are found together with evidence of Norse and Saxon occupation (Raistrick and Holmes, 1962).

Table 1. *The Geological Succession.*

PLEISTOCENE	Glacial and Recent deposits		
			Variscan earth movements
CARBONIFEROUS	Upper Carboniferous—Namurian		
	Lower Carboniferous—Dinantian (Avonian)	Viséan Tournaisian	
Major unconformity			Caledonian earth movements
SILURIAN	Lower Ludlow	Studfold Sandstone Horton Flags	
	Wenlock	Austwick Grits and Flags	
SILURIAN (*contd.*)	Llandovery	Skelgill beds	
Unconformity			
ORDOVICIAN	Ashgillian	Coniston Limestone series (upper part Ashgillian in age)	
Major unconformity			
INGLETONIAN	? Pre-Cambrian		

I. THE PRE-CARBONIFEROUS BASEMENT

The Pre-Carboniferous rocks, Ingletonian, Ordovician and Silurian, are exposed in small inliers to the north of the North Craven fault. The folding in these rocks contrasts strongly with the horizontally bedded Carboniferous rocks which lie unconformably above them. The relationship between the Ingletonian and Ordovician/Silurian strata is not seen since both at Ingleton and Ribblesdale the junction is faulted.

(1) *The Ingletonian* (?Older than 600 million years ±20*)

This series outcrops in Chapel-le-Dale to the north of Ingleton and also at the northern end of Ribblesdale at Horton-in-Ribblesdale. The rocks are best exposed in the narrow gorges known as the Ingleton Glens. Here the beds strike north-west/south-east with steep dips of over 75° to the south-west. At Horton the strike runs in a more east-west direction.

The composition of these "grits" and "slates" was studied by Rastall (1906). He found that the characteristic greenish colour is due to a widespread diffusion of chlorite through the cement which binds together the larger particles of quartz and feldspar with fragments of both igneous and metamorphic rocks. This type of rock is known as a greywacke, the unsorted nature of the rock and the freshness of the feldspars indicating rapid deposition. The difference between the "grits" and "slates" is due to particle size rather than composition.

Particular attention to sedimentary structures was paid by Leedal and Walker (1950), who thereby proved quite conclusively that the Ingletonian is an isoclinally folded series, with the southern limbs of the synclines overturned, and not, as previously thought, a vast series of tilted strata some 2¼ miles thick. By examining current bedding and slump directions, they concluded that the material was washed in by currents from the south-east and deposited on a slope dipping north-west. After its deposition, the series was subjected to intense folding, the principal pressure coming from the south-west and causing cleavage in the slates and a certain amount of jointing and tension fractures in the coarser grained rocks, but very little metamorphism.

The rocks are unfossiliferous and only one "trace fossil" has been recorded from it (Rayner, 1957). Its junction with the Carboniferous is a striking unconformity, and it is faulted against Ordovician rocks both at Horton-in-Ribblesdale and in the Ingleton Glens (Wood, 1948). Hence the age of these rocks is still uncertain. Both a Pre-Cambrian and a Lower Palaeozoic, pre-Coniston Limestone (Ordovician), age have been postulated. Nowadays they are generally regarded as Pre-Cambrian but the arguments on which this conclusion is based are not sufficient to rule out the other possibility.

The main argument in favour of a Pre-Cambrian age is based on the different intensity of folding in the Ingletonian and the Lower Palaeozoics. The isoclinal folding in the Ingletonian would seem to have been folded by different earth movements from those, the Caledonian, which caused the gentle folds in the Ordovician and Silurian strata. There are no known earth movements during the Cambrian and Ordovician which could account for the isoclinal folding, but if the series is considered as Pre-Cambrian the difference in folding and

* Approximate ages as given by A. Holmes, 1959.

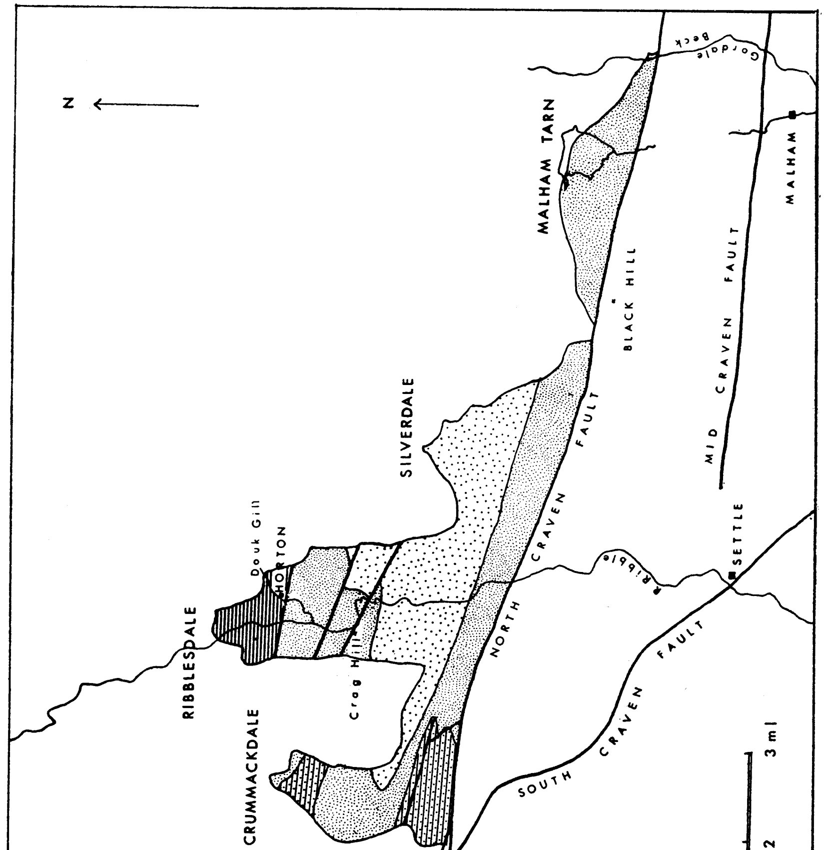

FIG. 1.
Pre-Carboniferous rocks along the North Craven Fault.

metamorphism can be attributed to a Pre-Cambrian orogeny. Also supporting a Pre-Ordovician age is the neptunean dyke described by King (1932) from a railway cutting at Horton-in-Ribblesdale. He found a band of fossiliferous rock, of Ordovician age, in the Ingletonian rocks and concluded that this represented a crack in the already folded and consolidated Ingletonian, which was subsequently filled by material swept in by the Ordovician seas. Thus, the weight of evidence certainly favours a Pre-Cambrian age.

(2) *The Ordovician and Silurian*

The rocks are found as inliers bounded to the south by the North Craven fault.

1. The Ingleton inlier: Coniston Limestone series faulted against the Ingletonian to the north.
2. The Jenkin Beck and Clapham inliers: both small, exposing Ordovician rocks.
3. The Ribblesdale/Crummackdale/Silverdale inlier: probably the most important and exposing both the Ordovician and Silurian.
4. The Malham Tarn inlier: Silurian.

The largest of these inliers, described by King and Wilcockson (1934), occupies the lower parts of Ribblesdale, Crummackdale and Silverdale. Here, the Ordovician and Silurian rocks form a synclinorium pitching east-south-east, within which numerous anticlines and synclines are developed and pitch eastwards at an angle of anything from 0° to 20°. Due to this structure, the lower (Ordovician) rocks are best exposed to the west in Crummackdale, with two isolated exposures in Ribblesdale, at Crag Hill and Douk Gill, where they have been up-faulted. The Silurian occupies the central portion of the synclinorium with the topmost beds, the Studfold Sandstone, confined to the east where they are preserved owing to the pitch of the fold.

Ordovician (500 ± 15—440 ± 10 million years)

The Coniston Limestone series at Ingleton is a highly cleaved, grey, calcareous slate which contains a few fossils, on the evidence of which these beds have been correlated with the Coniston Limestone series of the Lake District, probably of Low Ashgillian age. The Ordovician beds at Crag Hill and Douk Gill have yielded numerous fossil trilobites and brachiopods which weather out very well in the "gingerbread limestones". The main outcrop, however, is in the southern part of Crummackdale. Here, evidence of contemporaneous volcanic activity is found in the form of ash bands interbedded with the calcareous mudstones. Towards the top of the series is the Wharfe conglomerate, indicating a nearby shoreline and shallow seas. An unconformity above this is taken as the base of the Silurian on the fossil evidence.

Silurian (440 ± 10—400 ± 10 million years)

After a short gap in sedimentation, the Llandovery or lowest Silurian was laid down. They are thinner and more sandy than their Lake District equivalents, but bands of dark shales containing *Monograptus* spp. allow an accurate correlation.

Above these lie the Austwick Grits and Flags composed of fine-grained greywackes, 700–800 feet thick in the Ribblesdale inlier, compared with 1,000 feet of flags in the Lake District. These greywackes pass upwards into a more quartzose formation, the Horton Flags, and above, preserved in the easterly pitch of the Ribblesdale synclinorium, is the Studfold Sandstone, which has been correlated with the Coniston Grits of the Lake District.

Both Ordovician and Silurian successions are most complete in the Ribblesdale inlier where the thickness and structure of the rocks can be studied. The lower Palaeozoics are not well exposed in the other inliers. A few outcrops of Silurian occur around Malham Tarn, but the area is largely drift covered. Nevertheless at the head of Gordale, Horton Flags of the *Monograptus nilssoni* zone occur as highly cleaved slates, grey in colour, in which the original bedding is all but obscured by the cleavage but appears to dip southwards (Williamson, 1959). A few specimens of *Monograptus* sp. have been collected from this exposure.

Another outcrop of Silurian is found on the northern slope of Black Hill (865665) where the rock is coarser-grained than at Gordale but appears to dip in the same direction. No fossils have been recorded from this locality so far. Outcrops of these Silurian slates also occur in Cowside Beck (Stainforth); one quite large exposure occurs where the beck has cut deeply into it near Cowside Farm.

Exposures are few but the junction of Silurian and Carboniferous is marked by a line of springs, since the Silurian is impervious and lies below the well-jointed Carboniferous limestone. A prominent scarp running behind Capon Hall towards Highfolds Scar also marks the junction and cold springs have been recorded some way out in the Tarn itself. At Great Close Mire, and along the east shore of the Tarn, blocks of a basal conglomerate containing pebbles of Silurian slate in a limestone matrix are found; and at Gordale, up a small tributary on the left bank, the Silurian and Carboniferous outcrop within a few yards of each other, but nowhere is the actual junction visible in this inlier.

The proximity of the Lower Palaeozoic floor is inferred from a line of springs at the foot of Malham Cove and Gordale, where there was reputed to be a small outcrop of Lower Palaeozoic rock (Davis and Lees, 1878). This is not visible now, but may well be buried under scree. The permanent springs of Cowside Beck (Skirfare) may also be associated with the Lower Palaeozoic floor, since they are about the same height as the Silurian rocks at Malham Tarn (1,200 feet).

The Ordovician and Silurian rocks of the Craven area are thinner and tend to be more sandy with frequent breaks in the succession than those of the nearby Lake District. They appear to have been laid down in a shallow sea, close to a shoreline, whereas the Lake District succession indicates deeper water conditions.

II. The Carboniferous (350 ± 10—270 ± 5 million years)

Apart from the relatively small inlier of Silurian at Malham Tarn, the area shown on the folded Map is made up of Carboniferous rocks, partly obscured by Pleistocene deposits. At the very beginning of the Carboniferous the seas were restricted and there is some doubt as to whether the lowest zones of the Carboniferous exist in the Craven area at all (George, 1958). They may be present in the core of the Skipton anticline (Hudson and Mitchell, 1937) but certainly do not occur in the area covered by the map. At the beginning of the Viséan a great marine transgression took place and the seas finally inundated the Askrigg Block. Only the lowest members of the Upper Carboniferous are found in this area. The Coal Measures and higher zones of the Namurian were presumably deposited but subsequent erosion has removed them.

The stable, tectonic unit known as the Askrigg Block had a great effect on Carboniferous sedimentation. On the Block itself the sediments are mainly calcareous, but south of a belt containing reef limestones near the Mid-Craven fault, a basin facies is developed. The sediments here are largely shale although argillaceous limestones and sandstones also occur. In both areas the seas were shallow and the term "basin" does not imply deep water; but, in contrast to those on the Block, the sediments of the basin were deposited in an unstable, frequently subsiding region, which received a larger proportion of clastic material.

This change in facies between the sediments of the Block and those of the basin makes correlation difficult. Limestones and calcareous sediments contain a coral/brachiopod fauna, whilst goniatites and lamellibranchs predominate in the non-calcareous sediments of the basin facies. Fortunately a few goniatites have been found in the sediments of the Block and it is on these that the correlation is based.

The Coral/Brachipod Zones

A zonal system for the Lower Carboniferous was worked out by Vaughan (1905) using the corals and brachiopods which occur in the limestone succession near Bristol. The zones are generally known by the initial letter of the zonal index fossil. However, these fossils are scarce in the north of England, which was separated from the south-west region by St. George's land, and Garwood (1912) therefore found it necessary to modify the system for northern England, using the fossils which were common there. A zone may thus be named in three ways, e.g. the *Linoproductus corrugato-hemisphericus* zone, the *Seminula* zone, or more simply the "S" zone.

Zone	Bristol Succession	Northern Province
D_2	*Dibunophyllum*	*Dibunophyllum bipartitum*
D_1		*Dibunophyllum bourtonense*
S	*Seminula* (*Composita*)	*Linoproductus corrugato-hemisphericus*
C	*Caninia*	*Michelinia grandis*
Z	*Zaphrentis*	—
K	*Cleistopora* (*Vaughanis*)	—

The Goniatite/Lamellibranch Zones

Goniatites are excellent zonal fossils since they were a rapidly evolving group and widespread geographically. Since Bisat (1924) first published his work on the zoning of the Carboniferous by means of the goniatites, numerous subzones have been recognized, using them. Again the zones are known by the initial letter of the zonal index fossil, as follows:

		Zone name
Upper Carboniferous	E	*Eumorphoceras* (a goniatite)
Lower Carboniferous	P	*Posidonia* (a lamellibranch)
	B	*Beyrichoceras* (a goniatite)

Table 2. *Correlation of the two systems.*

	NORTH OF THE MID-CRAVEN FAULT		Coral/ Brachiopod zones	Goniatite/ Lamellibranch zones		SOUTH OF THE MID-CRAVEN FAULT
Upper Carboniferous	Grassington Grit					Grassington Grit Pendle Top Grit
				•–•–•	*Cr. malhamense*	
	Main Limestone and shales above (Yoredale)			E_1	*Cr. leion*	Upper Bowland Shales
Lower Carboniferous	Yoredale facies			P_2		Lower Bowland Shales
			- - - - -	P_1		
		"*Girvanella*" band	D_2			
	Great Scar Limestone	*Davidsonina septosa* band	–•–•–•	B_2		Impure limestones and shales with reef limestone developed in places
		Porcellanous band	D_1	– – –		
			S_1 & 2	B_1		
	Lower Palaeozoic basement		C	base not seen		

D = *Dibunophyllum*
S = *Seminula* (*Composita*)
C = *Caninia*
Cr = *Cravenoceras*
E = *Eumorphoceras*
P = *Posidonia*
B = *Beyrichoceras*

There is no correlation between the vertical scale of this diagram and the thickness of the strata.

(1) *Lower Carboniferous north of the Mid-Craven Fault*

During the Lower Carboniferous the Mid-Craven fault appears to have marked the southern limit of the Askrigg Block in this area, and for this reason it is convenient to describe the Lower Carboniferous under two main headings; north of the Mid-Craven fault and south of the Mid-Craven fault.

To the north of the North Craven fault, a very pure limestone, the Great Scar Limestone, rests directly on the Lower Palaeozoic floor. Above this lies the Yoredale Series, which is capped by the Grassington Grit on Fountains Fell. A good section through the Lower Carboniferous can be seen in Darnbrook Beck, from limestone of "S" age to the base of the Namurian.

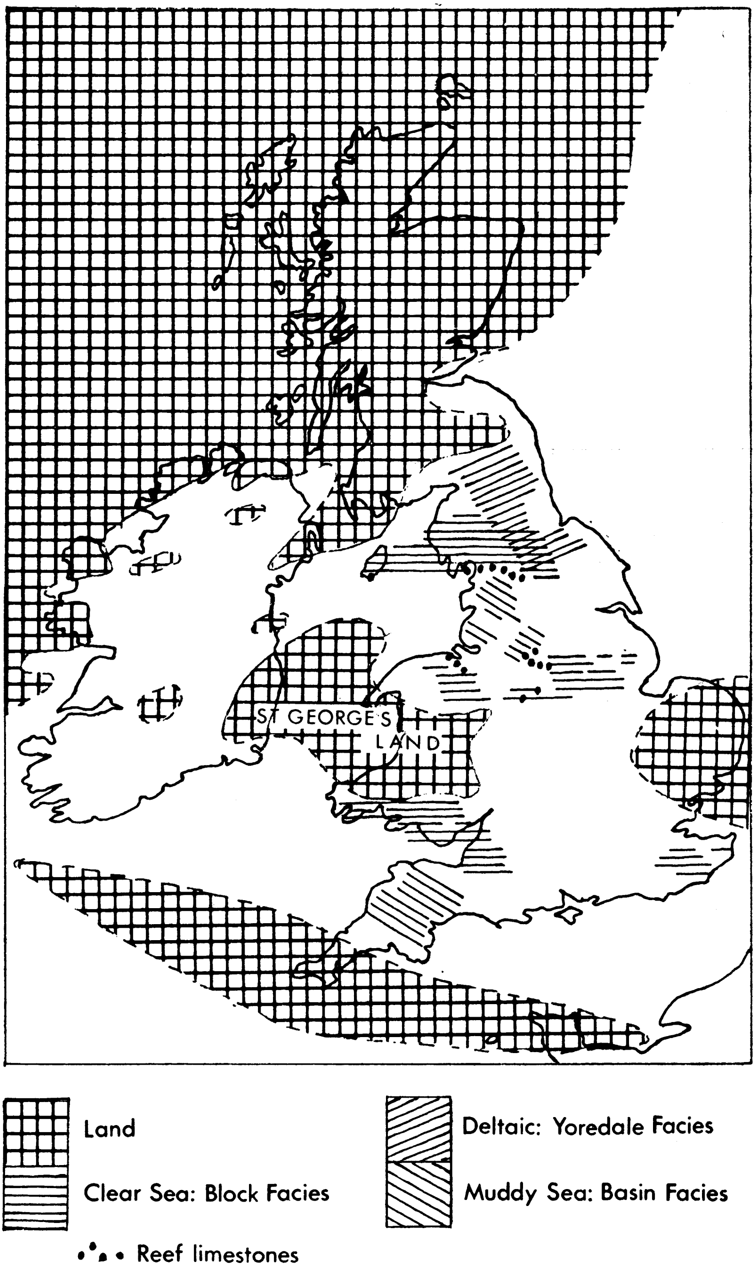

FIG. 2.

Palaeogeography during the Lower Caıboniferous (Viséan). After L. J. Wills (1950).

The Great Scar Limestone

This is the name given to a particularly pure limestone facies found in the Yorkshire dales. If it is traced northwards, the limestone is partly replaced by shales and sandstones and on the Alston Block its attenuated northern equivalent is known as the Melmerby Scar Limestone.

The Great Scar Limestone is well exposed in the area, especially at Malham Cove, Goredale and in the High Mark area. It is light grey to buff in colour when fresh and weathers even lighter. It is remarkably pure; the insoluble residue after treatment with hydrochloric acid averages around 0·5 per cent, and in thin section it has been estimated that about 50 per cent is made up of recognizable organic debris, crinoid ossicles, shell fragments and foraminifera in a matrix of recrystallized calcite mud with very little impurity (Schwarzacher, 1958).

Analysis of a sample from Beecroft Quarry, Horton-in-Ribblesdale:

	Percentage
Silica	0·12
Iron oxide	0·13
Aluminium oxide	0·02
Manganese dioxide	trace
Calcium oxide	55·5
Magnesium oxide	0·1
Phosphoric anhydride	0·19
Sulphuric anhydride	0·01
Carbonic anhydride	43·8
Organic matter	trace
Water	0·04

Calcium carbonate = 98·5%

The most common impurity is silica either in the form of crystals scattered in the matrix (Schwarzacher, 1958) or in the form of chert nodules which occur along certain bedding planes. The chert is usually dark and generally rather porous in texture. Its superior resistance to weathering makes it stand out from the surrounding limestone in irregular masses. Stylolites are commonly found in limestones and are pressure-solution phenomena formed in the consolidated rock. A thin line of impurities is left behind where a considerable amount of limestone has been forced into solution by pressure. They are often found parallel to bedding planes and generally have an amplitude of about 1 cm.

The formation is mainly composed of bioclastic limestones, sometimes oolitic and current-bedded. Current bedding is found just below the *Davidsonina* band in this area, and is well developed at Langscar (884654). Such evidence of shallow water conditions with current action playing an important role is common throughout the Great Scar Limestone, but there are very fine grained "porcellanous limestones" which denote rather quieter conditions. Evidence of particularly strong current action both above and below major bedding planes was found by Schwarzacher (1958). By tracing nine of these major bedding planes over a wide area, he divided the Great Scar Limestone into nine cyclic units each of which shows a rhythmic variation in the conditions of deposition.

The bedding is particularly well developed in the D_1 limestones, and has a regional dip of approximately 5° to the north-west, but locally the dips vary in magnitude and direction. The bedding is cut at right angles by vertical jointing; generally two sets of joints are developed at right angles to one another but subsidiary sets of joints may also occur. The limestone itself is crystalline and almost impervious to water, which drains away down the joints and bedding planes. The gradual dissolution of the limestone by percolating ground waters gives rise to features typical of limestone country: limestone pavements, pot-holes, underground drainage of streams and large depressions, all of which can be seen near Malham Tarn.

Fossils are not very numerous in the Great Scar Limestone but it contains a coral/brachiopod fauna typical of what is sometimes known as "standard phase" limestone. The lowest zone present, the C zone, is represented by a few scattered outcrops in Chapel-le-Dale and Ribblesdale. Only in S times was the marine transgression general over the area and in many places S_2 limestone, containing *Lithostrotion minus*, lies directly on the lower Palaeozoics.

The upper limit of the D_1 zone and the top of the Great Scar Limestone facies is taken at the *Girvanella* band, a bed of very dark, bituminous limestone containing *Girvanella* nodules (*Osagia*). These nodules represent a symbiotic intergrowth between three species of lowly plants and animals, including the alga *Girvanella*, which forms concentric rings around a shell fragment. In the Malham area this band is a good marker horizon, but if it is traced northwards the band splits into a number of horizons and loses its stratigraphic value. It is well exposed down Cow Gill Cote in two places, 932647 and further down-stream at 938642. In the High Mark area, to the north-east of Middle House Farm, it follows the 1,675 ft. contour whilst up Darnbrook Beck it occurs at about 1,425 feet and is particularly well developed in a tributary valley at 893716.

The junction between the S and D limestones of this area is marked by a conspicuous band of porcellanous limestone, which weathers very much lighter than the surrounding limestone. This band can be seen in a disused quarry on the Settle/Arncliffe road (859673). It is fortunate that such an easily mappable band occurs at this junction, since it would be difficult to map otherwise. It is not developed in the area between the North and Mid-Craven faults.

Within the upper 50 to 80 feet of the D_1 limestone in the Malham area there are bands of *Davidsonina* (*Cyrtina*) *septosa*. The *Davidsonina* band is well developed throughout the area, but is perhaps best seen at the following localities: along the 1,600 ft. contour to the north-east of Middle House Farm (marked on O.S. maps as Ing End Brow), and at Langscar (884654). It can also be found up Darnbrook Beck valley at about 1,250-1,300 feet, and on the roadside at 835660.

The Yoredales

The Yoredale series is the name given by John Phillips (1836) to a particular facies which is well developed in Wensleydale. It is the product of rhythmic or cyclic sedimentation and is divided into units or cyclothems each consisting of:

Coal Sandstone Shale Limestone	Yoredale cyclothem

Thus the sediments vary from marine to terrestrial. Typically a cyclothem begins with a limestone, generally dark and argillaceous, but containing a coral/brachiopod fauna. Above the limestone lie marine shales often calcareous and fossiliferous, followed by a less fossiliferous, ferruginous shale which in turn gives way to a sandstone. At the top of the sandstone may be a thin coal seam resting on a ganister, or leached zone, containing the carbonized remains of roots, evidence that terrestrial conditions prevailed at that time. In some cases more than one coal seam occurs, but in others it appears to have been eroded away altogether by the incoming limestone or sandstone, leaving only the ganister as evidence of terrestrial conditions.

Table 3. *Types and approximate ages on both goniatite and coral/brachipod time scales.*

Coral/Brachiopod zones	*Limestone horizons*	*Goniatite/Lamellibranch zones*
	Main Limestone	E1
	Undersett Limestone Three Yard Limestone Five Yard Limestone Middle Limestone Simonstone Limestone	P2
D2	Hardraw Limestone } Gayle Limestone } Lower Lonsdaleia Series	P1

The conditions which gave rise to the Yoredale facies have been described by Dunham (1950), Hudson (1924), Johnson (1959 and 1960), and Moore (1958). Very simply and diagrammatically these can be summarized as follows but it should be noted that the vertical scale of Fig. 3 represents a period of time rather than the actual thickness of sediments, since during the three cycles shown the thickness of strata in the north would be very much greater than that in the south.

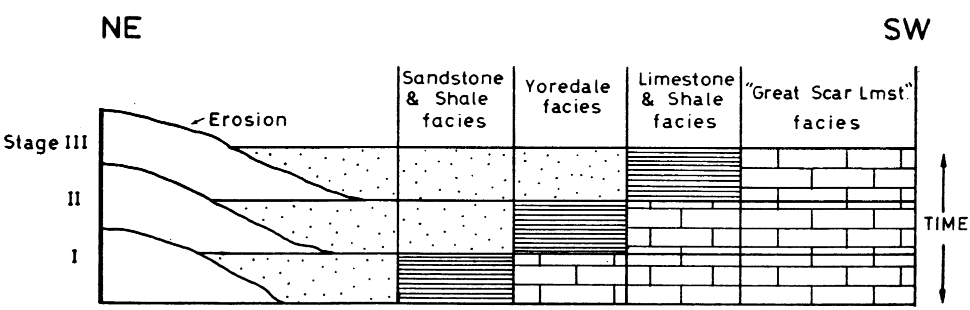

Fig. 3.
Diagram to show variation in facies from NE to SW in Lower Carboniferous.

During the Lower Carboniferous a shallow sea stretched over the Alston and Askrigg Blocks with a land mass to the north. Even a slight fluctuation in sea level on such a shelf would cause the shoreline to advance or recede considerably. Fig. 3, stage 1 shows the normal type of sedimentation expected in a shallow, shelf sea, where sandstones and coarse detritus build out from the land as deltas. These gradually grade into finer sediments, silts and shales, becoming progressively marine in character until, finally, there is little or no sediment coming in and limestones are formed in clear shallow water. Stages 2 and 3 show a shift in the different types of sedimentation, due to a seaward extension of the shore line. Following stage 3 there is a rise in sea level relative to the land and another cycle begins at Stage 1. The consequent change in facies from north to south can be seen from the diagram. Close to the land mass the series will be mainly terrestrial with sandstones, coal and a few shales; to the south of this the mixed facies is termed Yoredale. Continuing southwards, first the sandstones die out, leaving a limestone/shale series, and finally little to no sediment is brought in and a pure limestone like that of the Great Scar Limestone can develop.

During D_2 times (or, using the goniatite time scale, from the uppermost part of P_1 to low in E_1) a Yoredale facies was developed in Wensleydale. This facies extended into the area around the field centre and is best seen in Darnbrook Beck on Fountains Fell. Since it is more or less on the southern fringe of the Yoredale facies, limestone tends to be developed at the expense of the shales and sandstones. This is particularly true of the lower part of the section; the Gayle cyclothem and Hardraw limestone cannot be separated from one another and are sometimes termed the Lower *Lonsdaleia* series. Over to the east on High Mark most of the Yoredales have been eroded off, but the Lower *Lonsdaleia* series occurs there, and at Parson's Pulpit about 5 feet of sandstone, the Dirt Pot Grit, is found.

Further south, between the North and Mid-Craven faults, there are several areas in which the Lower *Lonsdaleia* and Simonstone Limestones are present. But no sandstones are found and even the persistent Dirt Pot Grit has died out. Following down Cow Gill Cote, for instance, the *Girvanella* band is found (932647); above it occur limestones and shales of the Lower *Lonsdaleia* series, and further south on the right hand bank is a cherty limestone, containing silicified colonies of the corals *Lithostrotion junceum* and *Orionastraea spp.* This has been identified as the Simonstone Limestone. The *Orionastraea* band, which is found in the Simonstone Limestone, has been mapped in the Grizedale area, south-south-west of the Tarn, by Garwood and Goodyear (1924), and can also be traced in the area south of the Mid-Craven fault (Hudson, 1930a). However, no limestones equivalent to the higher Yoredale limestones are known in this area between the faults, so that at Cow Gill and Grizedales, Bowland shale of E_1 age lies unconformably on the Simonstone Limestone and Lower *Lonsdaleia* series respectively.

In these two areas the Bowland Shale, a basin facies, is said to overlap. Pre-Bowland Shale erosion and/or non-deposition may account for the absence of the upper Yoredale limestones, and evidence for Pre-Bowland Shale faulting is found in the small rift valley close to Lee Gate Farm. The faults here affect the *Girvanella* band and D_2 limestones and can be traced right up to the Bowland

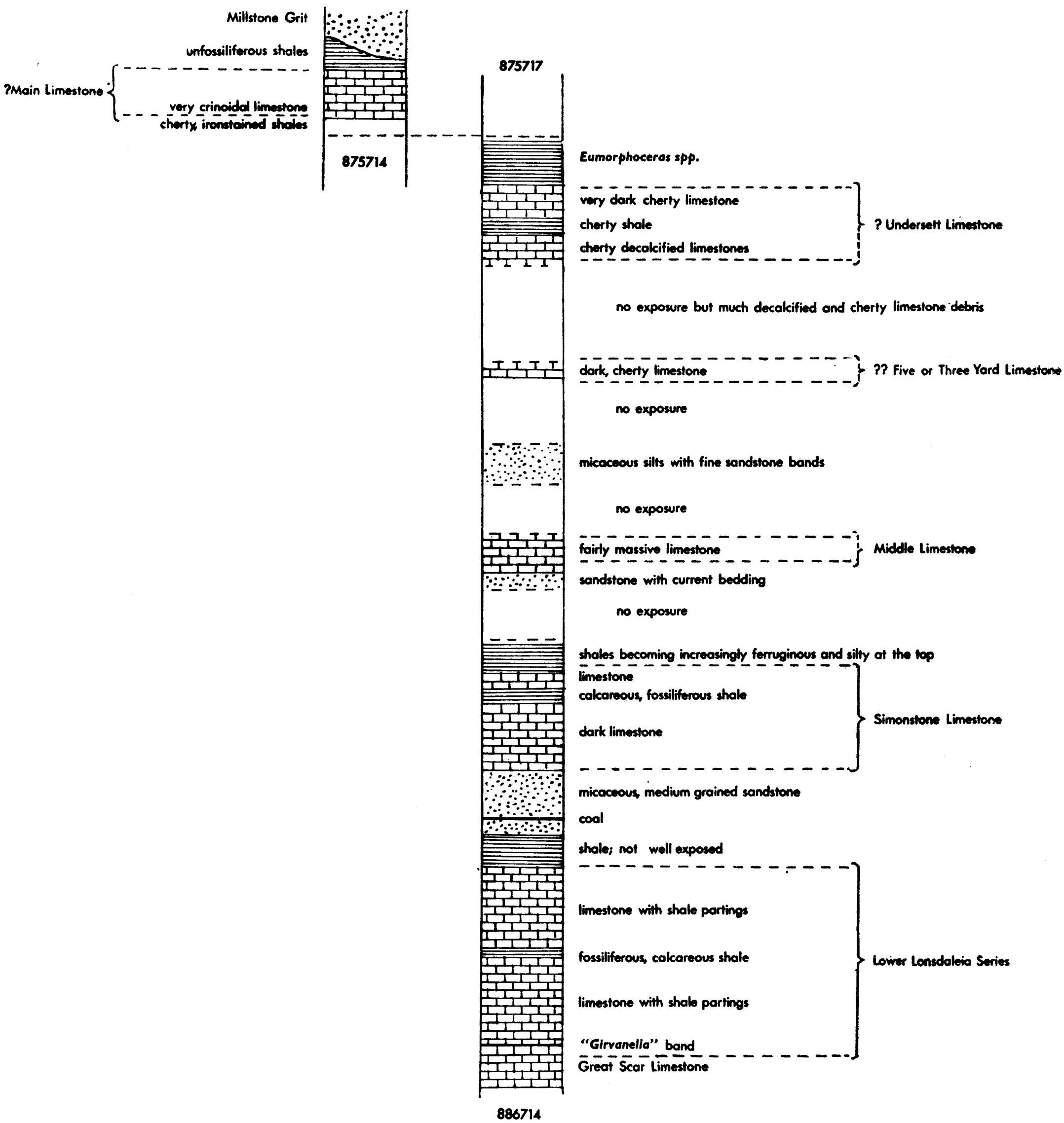

FIG. 4.

Section up Darnbrook Beck, Fountain's Fell. Vertical scale: 1 cm. = 40 ft.

The new specimens of *Eumorphoceras*, mentioned in the text, were found in the shales lying approximately 2 feet above the Undersett Limestone.

Shale overlap, but the shales, of upper E_1 age, are not affected. In the Grassington area, to the east, the Namurian overlap rests on the Middle Limestone of upper P_2 age; erosion and faulting therefore most probably took place between upper P_2 and upper E_1.

To the south-west of Black Hill is a slightly different facies of dark, well-laminated shales, and dark, horizontally bedded, thin limestones. The best exposures are seen in Cowside Beck (Stainforth), where the shales very much resemble the Bowland Shales, and it has been suggested (Rayner, 1953) that that area represents the intermingling of the Bowland and Yoredale seas. Where a fault crosses the stream, the shales contain nodules which have formed round fish remains, coprolites and some goniatites. Goniatites are preserved "in the round" in these nodules and have been identified as *Dimorphoceras* (*Metadimorphoceras*) *lunula* Knopp. Crushed specimens of dimorphoceratids and *Caneyella membranacea* also occur in the shales. Further downstream, below a thin dark limestone, the shales have yielded *Sudeticeras* sp. These goniatites are of late P_2 age, so that shales here are approximately equivalent in age to the Middle Limestone on Fountains Fell. Goniatites have also been found further downstream at Daw Haw (Hudson and Jackson, 1929; Hudson and Cotton, 1945): *Goniatites spiralis* s.l., *Cravenoceras malhamense*, *C. leion*, and *Eumorphoceras* cf. *tornquisti*.

Apart from the goniatites mentioned above, the Yoredale facies contains a predominantly coral/brachiopod fauna. Unfortunately these fossils though abundant are not very suitable as zonal fossils above D_1, and it is therefore desirable that the goniatite/lamellibranch system should be used as far as possible. To the south the boundary between the Upper and Lower Carboniferous is marked by a distinctive faunal change at the base of E_1 with the appearance of two important goniatite genera, *Cravenoceras* and *Eumorphoceras*. Goniatites, however, are rare in the Yoredale facies and so the boundary between the Upper and Lower Carboniferous was until recently uncertain; the evidence now indicates that it should be drawn just below the Main Limestone (Johnson, Hodge and Fairbairn, 1962). On Fountains Fell, goniatites of the genus *Eumorphoceras* have recently been found just above a thin cherty limestone some 50 feet below the Main Limestone, which outcrops to the north and south of it, and one of these specimens has been identified as *Eumorphoceras tornquisti* (Wolterstorff). Another species, *Eumorphoceras pseudobilingue* (Bisat), has previously been collected from this area (Hudson, 1941; Black, 1950a).

(2) *Lower Carboniferous South of the Mid-Craven Fault*

UPPER CARBONIFEROUS		Grassington Grit Pendle top Grit Upper Bowland Shale	E_1
		Unconformity	
			Lower Bowland Shale P_2*
LOWER CARBONIFEROUS	Limestones	D_2 D_1 S_2	

*At School Share only

During the Lower Carboniferous the line of the Mid-Craven fault appears to have formed the southern margin of the Askrigg Block, so that immediately to the south of it the Lower Carboniferous may be considered as a transition facies between the limestones of the Block and the more argillaceous succession of the "basin". As might be expected the limestone succession, in the area shown on the map, bears more affinity to the Great Scar Limestone facies to the north than to the basin facies; very little shale is present and much of the limestone is very like that of the northern facies.

The succession is well exposed in the Scaleber and High Hills area, east of Settle (Hudson, 1930a). S_2 limestones are exposed in the beck below Scaleber Force, where they are dark, well-bedded with shaley partings and not very fossiliferous. Above these, and also exposed to the east around Malham village, lie D_1 limestones, less argillaceous and therefore lighter in colour. They differ from the D_1 limestones of the Block in the development of dolomitic and "reef" limestones. Around Scaleber the beds dip northwards at an angle of 10°-15°; D_2 limestones are therefore found on the northern slopes of the hills in that area. Both the *Girvanella* band and *Orionastrea* band (from the Simonstone Limestone) have been traced there.

One of the most important characteristics of this transition facies is the occurrence of reef limestone. This forms the greater part of Cawdon, the south side of Wedber and Burns Hill, rounded hills near Malham, and is also found to a lesser extent on the southern part of High Hill and up Scaleber Beck. The dominant rock type in reef limestone is a calcite mudstone, either poorly bedded or unbedded and containing a specialized, locally abundant fauna. Although each of these three properties may occur separately outside a reef environment, when all three conditions of rock type, bedding and fauna exist together, it forms the distinctive reef facies (Black, 1950b, and 1954). The form in which reef limestone was deposited and the processes involved are still matters of controversy.

Lower Bowland Shales

These belong to the P_2 zone and are therefore Lower Carboniferous in age. They are well developed in the "basin" facies and not well represented in the Malham area, in fact they are only known to occur beneath an impressive boulder bed at School Share (845624) (Dixon and Hudson, 1931). About 8 feet of Lower Bowland Shale can be seen; a closely jointed shale, containing *Goniatites newsomi* and *Sagittoceras* cf. *meslerianum*, which denote an age high in P_2. A distinct break separates them from the overlying Upper Bowland Shale. This probably represents a non-sequence since on the goniatite time scale the topmost part of P_2 appears to be missing.

Carboniferous Reef Facies

Reef limestones form a distinctive facies and are found in this region along the southern margin of the Askrigg Block. They also occur in a somewhat similar position with respect to the Derbyshire massif at Clitheroe. Tiddeman (1892) was the first to describe the rounded hills at Malham and Cracoe as "reef knolls". He saw them as discrete mounds accumulating on the sea floor and built up of living organisms. These mounds would have been covered eventually by Bowland Shale and re-exposed by present-day erosion of these shales. However, Tiddeman's theory was challenged by Marr (1899), who ascribed a purely tectonic origin to the rounded hills, which Tiddeman regarded as original knolls. Thus there are two problems implicit in any discussion of the reef facies:

(*a*) The origin of the distinctive reef limestone and how it was deposited.
(*b*) The origin of the rounded, knoll-like hills of Malham, Cracoe and Clitheroe.

A purely tectonic theory might explain (*b*) but attempts no explanation for (*a*). On the other hand, although reef limestone is often associated with knoll-like hills such as Cawdon and many of those around Cracoe, a knoll-like topography is not necessarily related to reef limestones; Low High Hill and Sugar Loaf Hill near Scaleber are knoll-like hills, but are largely made up of standard, bedded limestones. Their shape is mainly due to the combination of bedding and a series of north-west/south-east faults.

Tiddeman's theory implied that the Carboniferous reefs were built by living organisms, and comparable in this respect with modern reefs. The chief drawback to this theory is the apparent absence of the reef builder. Modern reefs are wave resistant structures, built up of a strong framework of coral. In contrast, the Carboniferous reefs mainly consist of calcite mudstone, corals are few in numbers and species, and brachiopods and molluscs, which form the chief part of the macro-fauna, do not provide a suitable reef builder. Calcareous algae and bryozoa have been postulated as fulfilling this function, the lack of evidence on this point being attributed to the disintegration of the algae to become part of the limestone matrix (Black, 1954). An organic origin for *Stromatactis*, or the irregular bands of coarser grained calcite sometimes known as "reef tufa", has been suggested as a suitable sediment binder (Bathurst, 1959). Owing to the absence of a demonstrable reef builder and to the lack of breccias associated with wave action on a resistant structure, Earp *et alia* (1961) have assigned the origin of the Clitheroe knolls to a limebank deposition, whose original mound-like structure has been accentuated by subsequent tectonic forces and glacial erosion. Such a limebank would provide a specialized environment on which certain species and groups might flourish from time to time. If this is the case the term "reef" is very misleading.

On the other hand Parkinson (1957) and others believe the Clitheroe knolls and the Carboniferous reefs in general to have been built with the aid of living organisms, though the problem of a reef binder has not been solved. Bond (1950a and c) divides the Carboniferous reefs into two classes; marginal and basinal. He contends that there are several different types of reef each originating in a different way. Using his terminology, marginal reefs include apron reefs and flat reefs, and his interpretation of the Cracoe knolls (1950b) is of a continuous belt of marginal reef material, subsequently broken up by a combination of faulting, folding and erosion to form the knoll-like hills typical of that region. In the same way Hudson (1932) has suggested that a continuous reef belt existed parallel to the Mid-Craven fault between Malham and Settle, and this was dissected by pre-Namurian erosion to form the rounded hills which are only now being re-exposed from beneath the shales.

Few would deny the existence of discrete mounds of reef material, rising above the general level of the sea floor, and showing quaquaversal dips parallel to their flanks. Bond terms these basinal knolls, implying that they occur farther out to sea than his other category, marginal reefs. Black (1950, 1954, 1958) supports the view that all the Carboniferous reefs were built up as discrete mounds and terms them "knoll-reefs". He has described one from Grassington and argues that since they are all of the same composition it is reasonable to suppose that they were formed in the same manner. In his opinion, although subsequent erosion and tectonic features have played the greater part in forming the knoll-like topography round Malham and Stockdale, the reef limestones were originally laid down as knoll-reefs.

Since they hold that all Carboniferous reefs originally built up as mounds on the sea floor, both Black and Parkinson differ from Bond over the terms "marginal" and "basinal" when applied to knoll-reefs. In their view a basinal knoll would be symmetrical, since the rate of sedimentation on all sides would be equal, whilst an asymmetric knoll-reef would be classified as a marginal knoll, since its asymmetry can be explained by a greater rate of sedimentation on the landward side.

Thus the conditions of deposition of reef limestone are still a matter of controversy. The main points at issue are how far its formation was due to organic or inorganic processes and whether it was originally laid down as a continuous belt of reef material or accumulated in discrete mounds or knoll-reefs. So far no one solution has been universally accepted.

(3) *The Upper Carboniferous*

In the basin facies the Upper Carboniferous is represented by the Upper Bowland Shales, Pendle Top Grits and Grassington Grit. To the north, as previously discussed, the junction of Upper and Lower Carboniferous is somewhat uncertain but probably occurs slightly below the Main Limestone, so that on the Block the Upper Carboniferous is represented by the upper part of the Yoredale facies and the Grassington Grit.

Succession	
Grassington Grit	E_1
Pendle Top Grit	E_1
Upper Bowland Shale	*Cravenoceras malhamense* E_{1c} *Eumorphoceras pseudobilingue* E_{1b} *Cravenoceras leion* E_{1a}
Lower Bowland Shale	P_1 and P_2

Upper Bowland Shales

The Upper Bowland Shales are mainly confined to the south of the Mid-Craven fault but in two areas, Kirkby Fell and around Moor Close Gill, the E_{1c} zone extends a short distance over it on to the "block" sediments to the north.

The shales themselves are dark, impervious, fine-grained, highly fissile, "paper" shales. The shale partings are frequently stained rust coloured and yellow with iron oxides and other weathering products of iron pyrites, which is dispersed throughout the shale. These properties give rise to the scenery typical of the Upper Bowland Shales. The landslips, slumping, steep gullies with surface drainage and a vegetation typical of acid waterlogged soils, contrast strongly with the topography, drainage and vegetation of limestone country.

The series is non-calcareous except at a few horizons where thin bands of argillaceous limestone, known as limestone bullions, are developed. The fauna is therefore very different from the predominantly coral/brachiopod assemblage of a calcareous environment. Goniatites and lamellibranchs are most commonly found, with brachiopods playing a very minor part. Crushed specimens of goniatites, and the lamellibranchs *Caneyella* and *Posidonia*, are found in the shale, but in the limestone bullions uncrushed goniatites are quite common.

The base of the Upper Bowland Shale is quite clearly defined by a widespread faunal change at that horizon, with the incoming of *Cravenoceras leion*. The top of the series is determined by two factors: the lithological change to the more arenaceous Pendle Top Grits, and by a marker band of *Cravenoceras malhamense*, which occurs just below the Grit (Earp *et alia*, 1961). Around Kirkby Fell the Pendle Top Grits tend to thin and are eventually replaced by shales as the Mid-Craven fault is approached (Hudson, 1944). The top of the Bowland Shales must therefore be determined by the *Cravenoceras malhamense* band.

Pendle Top Grits

These and the overlying Grassington Grit form the topmost part of the E_{1c} zone. The base of the Pendle Top Grit is taken at the *Cravenoceras malhamense* band. The series occurs on Weets Top, where it forms a distinct break in slope, and to the south of Kirkby Fell, where it is 500 feet thick, but thins rapidly northwards with the grits tending to be replaced by shale. They are not well developed around Malham, but can be seen in the upper part of Black Gill Beck (Hudson, 1930a). At High Halsteads and Low South bank, to the north of this, the whole succession has thinned and become shale.

Grassington Grit

The grits capping Fountains Fell, Black Hill, Kirkby Fell and Weets Top have all been grouped under this heading. Unfossiliferous strata such as these are difficult to correlate, but they are probably of the same age, at the top of E_1. The Grassington Grit lies unconformably on the Main limestone of Fountains Fell, since further north higher Yoredale limestones appear from below the grit, which itself passes laterally into the Mirk Fell ganister (Rowell and Scanlon, 1957).

Correlation of the grits on the isolated fells around Malham Tarn has been attempted by heavy mineral analysis (Appendix of Hudson, 1930a, by Versey). Samples from Black Hill, Fountains Fell and Rye Loaf (close to Kirkby Fell) were taken and compared with a sample from a Yoredale sandstone and with each other. Versey concluded from the mineral assemblages that the grits capping each of these could be correlated with each other and with the Grassington Grit, but were substantially different from the Yoredale sandstones. The heavy mineral fraction common to all contained a dominantly brownishpurple variety of tourmaline, with individual crystals of zircon showing a strong purple colour, rutile and—less commonly—garnet.

The lower part of the Grassington Grit is conglomeratic and erosive; quartz pebbles of 1 inch in diameter are found. But the lithology of the series varies considerably from coarse to fine-grained sandstones, made up of sub-angular quartz with much haematite/limonite in the cement. Thin bands of shale and coal also occur. Two coal seams have been worked on Fountains Fell and the workings can still be seen on the fell top, but the coal was not of a very high quality.

The Millstone Grit is generally considered to be of deltaic origin. Structures such as channels, washouts, current bedding, torrent bedding and load casts have been found, suggesting a shallow water origin with strong current action. Fossil remains, apart from plants, animal tracks and worm burrows are few, but these would also support a shallow water environment not far from land.

The Grassington Grit is one of the lowest members of the Millstone Grit Series, which, due to the Pennine anticlinal structure, is not well preserved in the region. In the area around the Tarn, erosion has removed the greater part of it as well as the succeeding grits and coal measures, which are better preserved to the east.

III. Pleistocene and recent

As in so much of Northern Britain the Pennine area was under thick cover of ice for a long period during the Pleistocene, and the detailed topography has been considerably modified by glacial action. Varied deposits of glacial or periglacial origin (drift) cover much of the area, though being unconsolidated these are easily and quickly eroded, so that great quantities must have been removed in the 10,000 years since Late Glacial time. No erratics derived from outside the immediate area are known and all the drift appears to be of very local origin. This applies to most of the Yorkshire Dales and a local ice cap has been postulated for this part of the Pennines, which was bypassed by the great streams of ice which moved southwards along its western margin, eastwards through the Stainmore and Aire gaps, and southwards down the Vale of York (Raistrick, 1926). The effects of one major glaciation only can be seen in the Dales (Raistrick, 1951), and if there were earlier glaciations the remnants of their deposits have been incorporated in those of the latest one to such an extent that they are no longer distinguishable.

Many of the drift deposits near the Tarn, as in the quarry at 882672, are derived predominantly from local limestone and consist of unsorted stones and pebbles embedded in a matrix of limestone rock flour, which may be of clay particle-size. Some of these deposits originated as a till, or ground moraine, left when the ice sheet melted; others are more probably solifluxion deposits (head) dating to the long period of periglacial conditions which followed the disappearance of ice. It is difficult to distinguish between these two types when the materials are the same. An undoubted limestone-rich till underlies the Tarn and Tarn Moss, which can be seen in a few places on the west shore of the Tarn, while a sandstone-rich till is well exposed in meander scars up Darnbrook Beck at about 1,200 feet. Solifluxion deposits of sandstone, grit and clay

Table 4. *Glacial and Post Glacial Chronology.*

Major divisions		*Malham Area* *Sequence*	*Pollen zones*	*Dates in years (not to scale)*
Post-glacial		Peat Erosion	VIII	A.D. B.C. 500
		Ombrogenous peat Formation	VII	5,500
		Birch Forest Period Solifluxion	IV-VI	8,300
Late-glacial		Valley glaciation	III	8,800
		Solifluxion	I-II	13,000
ICE AGE GLACIATION	Wurm	Ice Cover Glaciation		
	Last inter-glacial	Exact date and		
	Riss			
	Second inter-glacial	duration unknown		
	Mindel			

After Charlesworth (1957), Godwin (1956) and Johnson and Dunham (1963).

underly the peat of the blanket bog on the flanks of Darnbrook and Fountains Fell and these probably rest on high-level till of the same materials.

Well-sorted fluvioglacial deposits occur immediately south of the Tarn and in the quarry at 893660 the waterlain gravels and sands are again almost entirely composed of limestone, which makes it unlikely that these low ridges around Low Trenhouse have been responsible for damming up the water of the Tarn. Ice wedges have been demonstrated in this quarry. To the east of it there is an extensive flat area of acid grassland above which rise a number of limestone-rich mounds and these also may represent remnants of a more extensive fluvioglacial terrace.

Perched blocks comparable to the famous ones at Norber occur on the limestone pavement at Winskill, 8366; these are blocks of Silurian rock which have been lifted a considerable height from their outcrop in Ribblesdale and deposited on Great Scar limestone. The height of the pedestals under such erratics has been used as an indication of the amount of limestone removed by solution since glaciation, perhaps 1½-2 feet. Glacial striations are thus not likely to be preserved on exposed limestone but can sometimes be seen under the protection of the blocks and on large boulders which have recently fallen from drift.

Several glacial overflow channels, associated with meltwater during recession of the ice and bearing no relation to the present drainage, can be seen in the area. A dry channel on the high ground north of Tarn House breaches the watershed between Cowside beck and Gordale, another connects the Tarn basin with Gordale, and at Black Hill an impressive channel has been cut across the spur which forms the watershed between the Tarn basin and Ribblesdale. Other overflow channels are visible just east of Settle at Warrendale Knotts.

The glacial period of ice cover, ending about 13,000 B.C., was followed by a gradual climatic amelioration in the Late Glacial when periglacial conditions prevailed with widespread solifluxion (Table 4). Towards the end of the Late Glacial there was a temporary return to colder conditions when small corrie glaciers existed in the northern Pennines, and it is possible that some of the very fresh-looking till up Darnbrook Beck at 1,200 feet was deposited at this time. An account of the subsequent local Post Glacial changes of climate and vegetation has been given by C. D. and M. E. Pigott (1959), who studied the stratigraphy and pollen of the deposits laid down on the Tarn Moss and in the Tarn.

IV. Mineralization

Mining in the region of the Yorkshire Dales goes back at least to Roman times. In the area around Malham Tarn, especially around Pikedaw, the small veins were worked quite extensively during the late 18th/early 19th centuries, before a drop in the price of lead made these mines, always poor, uneconomic. Most of the veins were worked either by open cast methods or by a chain of bell-pits (Raistrick, 1938 and 1953). An exception to this is the big "calamine" mine on Pikedaw. Here a deep shaft was sunk into the cavern containing the deposit, and addits driven into it through the hillside (Raistrick, 1954).

The mineralization of the Askrigg Block (Dunham, 1959) is fairly extensive and the veins appear to occupy fault fissures of small throw. Although the veins are best developed and richest at about the horizon of the Main Limestone, they extend downwards through the Middle Limestone to the top of the Great Scar Limestone, but at this horizon the lower limit of the mineralized zone is reached. Around Malham Tarn the veins occur in the D_2 limestone of the High Mark area, and in the Pikedaw/Grizedale area. Since they are approaching the lower limit of mineralization, they are not very productive.

In each of the two main areas of mineralization near the field centre, the mineral veins follow the major joint directions, although in general only one set is mineralized (Raistrick, 1938). On High Mark the veins follow the north-east/south-west set of joints. Short and economically poor, the veins contain only a thin string of the galena (PbS) for which they were worked, and a gangue largely composed of barytes ($BaSO_4$) and calcite ($CaCO_3$). On the spoil heaps of this area various secondary minerals can be found: zinc minerals such as smithsonite (=calamine, $ZnCO_3$) and hydrozincite ($2ZnCO_3.3Zn(OH)_2$); an

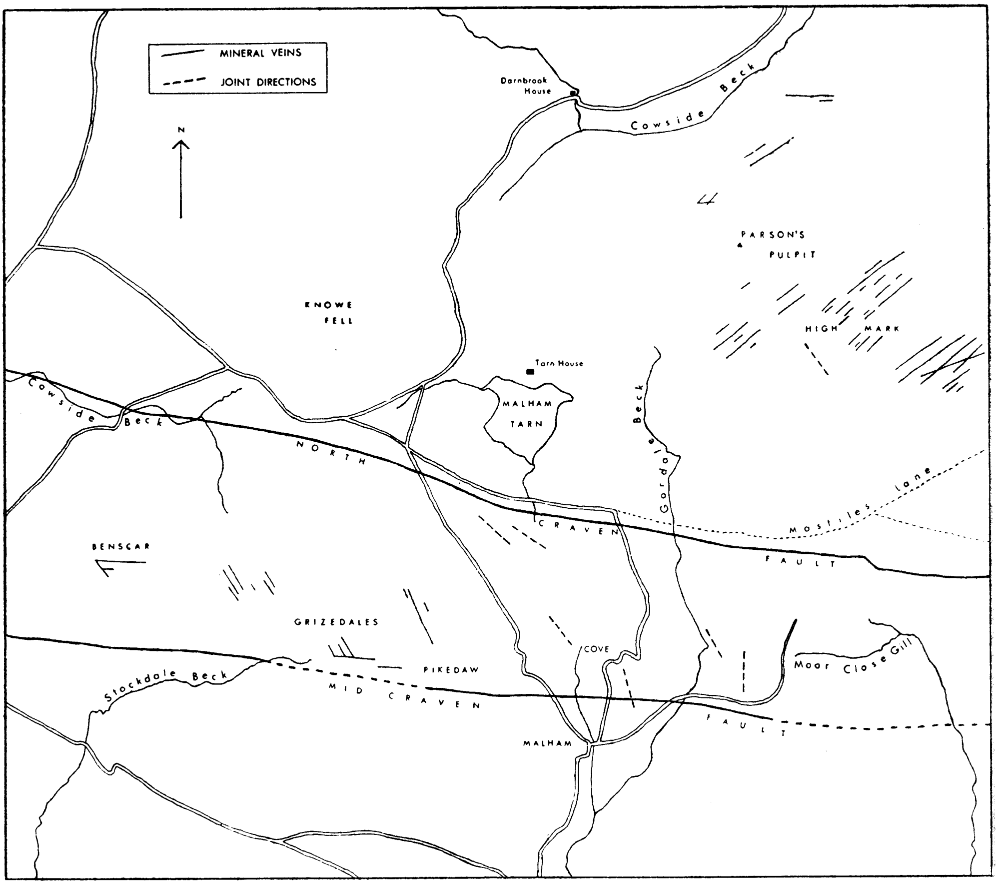

FIG. 5.
Mineral Veins and Joint Directions. After Raistrick, (1938) and Wager, (1931).

oxidation product from the galena, anglesite ($PbSO_4$) and a very little malachite ($Cu_2CO_3(OH)_2$), showing that traces of copper ore must have been present.

The veins at Pikedaw are, by comparison, richer in quartz and copper minerals. The veins again follow the major joints; mineralization is mainly in the north-north-west/south-south-east set but a few long veins occur in the other set, running approximately east/west, parallel to the Mid-Craven fault. Many veins have weathered deeply and leaching of the minerals has occurred, leaving an insoluble residue of quartz, limonite ($2Fe_2O_5.3H_2O$) and dolomitized limestone, known as gossan. Both galena (PbS) and smithsonite (=calamine) were worked in this area, and these are associated with a number of other minerals such as barytes and quartz, both fairly common with much lesser quantities of malachite, azurite ($2CuCO_3.Cu(OH)_2$), chalcopyrite ($CuFeS_2$), anglesite ($PbSO_4$) and cerussite ($PbCO_3$). A considerable proportion of iron pyrites occurs in the veins slightly to the east of Pikedaw, and there are veins at Benscar, above Attermire, which are not rich, but have been worked for the little galena they contain in a gangue mainly composed of calcite and barytes.

The large "Calamine" mine (smithsonite), formerly worked on Pikedaw, differs from the mineral veins described above, in that it forms an infilling to a cavern system in the limestone (Raistrick, 1954). The mineral itself is mostly silty and relatively little of the stalagmitic variety occurs, but the high purity of the deposit made it economic for use in paint and bronze manufacture during the 18th and early 19th centuries.

The mineralization of the Askrigg Block is not associated with any high temperature metamorphism. Only mild dolomitization or silicification of the surrounding limestone has occurred, and an origin from a combination of freely circulating ground waters and juvenile water forced up during the Variscan orogeny, at the end of the Carboniferous, has been suggested by Dunham (1959).

V. Structure

The stable Alston and Askrigg structural blocks underlie the northern Pennines. Malham Tarn lies on the southern margin of the Askrigg Block, which is the more southerly of the two and separated from the Alston Block by the Stainmore syncline. It is bounded to the west and south by faults but the eastern margin is obscured by younger rocks.

The Askrigg Block had a profound effect on sedimentation during the Carboniferous and probably even earlier. The Carboniferous sediments on it were not folded during the Variscan earth movements, in contrast to those sediments to the south of it.

The southern margin of the Askrigg Block is exposed in the small inliers to the north of the North Craven fault and the Ingletonian, Ordovician and Silurian rocks seen here probably form a fringe to an even older resistant core. This core is thought to have influenced the direction of folding in both the Ingletonian and Ordovician/Silurian rocks. Apart from these inliers, the block is covered by Carboniferous and younger sediments, so that its probable structure has been deduced by geophysical methods.

A gravity survey of the Craven district from Ribblesdale to Pateley Bridge was carried out by J. H. Whetton *et alia* (1956). They found a small positive gravity anomaly over the whole area, compatible with denser rocks, such as Lower Palaeozoics and Pre-Cambrian, lying beneath the Carboniferous. These anomalies followed the dominant geological structures of the area in an approximately west-north-west/east-south-east direction. To the north, however, in a traverse from Aysgarth in Wensleydale to Wharfedale, they discovered a large negative anomaly, which they interpreted as an acid Pre-Cambrian core to the block. This conception of a variable but dominantly acid core fringed with denser rocks to the south was supported by the findings of a magnetic survey of the Askrigg Block (Bott, 1961) and by Rastall's petrological work on the Ingletonian (1906).

To the south the Askrigg block is bounded by the Craven faults, which are the three main faults in the area: the North Craven fault, the Mid-Craven fault and the South Craven fault. North of the North Craven fault, faulting is not very common and no fractures of any major significance have been recognized. Contrasted with this, the faulting between the North Craven and Mid-Craven faults is considerable. None of the faults is very large but they are numerous. South of the Mid-Craven fault, small faults are quite common and the South Craven fault itself breaks up into several smaller faults south of Settle.

Both Anderson and Wager consider that the Craven faults are primarily wrench faults of Variscan age, caused by a maximum pressure from a south-easterly direction. Anderson, however, considers them to be dextral faults (1951), whilst Wager (1931) concluded from a study of the jointing that the North Craven fault was sinistral. He argues that the faulting and jointing probably took place simultaneously, so that the faults, by modifying the direction of maximum compression, caused the joints in their proximity to be deflected.

Away from the faults the joints are only affected by regional compression; that is well north of the North Craven fault and mid-way between the North Craven and Mid-Craven faults. The joint directions here are north-east/south-west and north-west/south-east. On approaching the North Craven fault from the north the joints in the north-west quarter tend to swing anti-clockwise to a more westerly position. Similarly, on approaching it from the south, there is some anti-clockwise deflection of the joints but less marked. On the other hand, close to the Mid-Craven fault the joints in the north-west quarter tend to swing clockwise to a more northerly position. From this Wager deduced that the North Craven fault was a sinistral fault and that there was some dextral movement along the Mid-Craven fault. The North Craven fault is a large fault, well exposed at Mastiles bridge and likely to have acted in different ways both along its length and during its history. It is closely related to the structure of the Askrigg Block (Whetton, J. T., *et alia*, 1956; and Bott, 1961), so that what is known as the North Craven fault may lie above some very ancient line of weakness which has been in operation for a very long time.

The Mid-Craven fault is interesting in that it appears to have acted as a normal fault in the Lower Carboniferous (Hudson, 1930a). Then it seems to have acted as a wrench fault associated with the Variscan earth movements (Williamson, personal communication; Anderson, 1951). During the Lower Carboniferous, it must have formed a prominent fault scarp along the margin of the block, with a downthrow of some 400 feet to the south (Hudson, 1944). At Kirkby Fell and on the Weets the Mid-Craven fault is overlapped by Namurian sediments, which appear undisturbed, but some movement along this fault is thought to have taken place in post-Namurian times.

Many of the faults between the North and Mid-Craven faults were mapped by Garwood and Goodyear (1924), but there are several others not shown on their map. Most of them have a north-west/south-east trend and their throw is small, sometimes almost negligible. It is possible therefore that these are also wrench faults, formed as a direct result of the stresses and strains set up by the lateral movement of the North and Mid-Craven faults. At Kealcup Hill, to the east of the area shown on the map, and close to Cowside Farm (846667), there are sharp kinks in the North Craven fault. Near to Cowside Farm there is a good exposure of slickenslided fault breccia, first mentioned by Kendal and Wroot (1924). These kinks have been regarded as abnormalities within the North Craven fault, but they might well be caused by north-west/south-east wrench faults cutting and displacing the main fault at these points (Williamson, personal communication).

The third large fault in the region, the South Craven fault, forms a magnificent fault scarp at Giggleswick Scar. At Ingleton it affects Permian strata and must therefore have moved in post-Permian times. Wager (1931) has suggested that this and other post-Permian faults represent a settling down of the strata after the compressive forces of the Variscan orogeny had ceased, resulting in the further sinking of the Craven lowlands relative to the Askrigg Block. Horizontal slickensliding has been recorded from one of its subsidiary branches just south of Scaleber force (840625), and Anderson considers it to be a dextral wrench fault similar to the others. Its comparatively recent movement is born out by the well-developed fault scarp. The epicentre of earth movements which were felt around Settle in 1947 was found to be situated on the South Craven fault (Versey, 1948).

It is clear that much of the geological history of the area is dominated by the stable qualities of the Askrigg Block and the Craven faults which form its southern limit. In this respect whilst the North and Mid-Craven faults seem to be closely associated with the general structure of the Askrigg Block, the South Craven fault appears to be much less important (Whetton *et alia*, 1956).

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