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THE LOWER CARBONIFEROUS REEF LIMESTONES OF CRACOE, YORKSHIRE

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[PLATE VII]

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SUMMARY

The limestones forming the " reef-knolls " in the Cracoe district of Yorkshire lie at the eastern end of a belt of similar limestones which stretches westwards across the Central Province of the Carboniferous Limestone Series. This " reef belt " separates areas of contrasted sedimentation, the strata to the north being of massif (Great Scar) facies, while to the south lies the much thicker basin facies, of impure limestone with much interbedded shale. The Cracoe knolls have attracted much attention in the past, owing to their peculiar topography and the abundance of their fossils. Theories on their origin were based either upon supposed quaquaversal dips of original deposition or upon more normal deposition, followed by tectonic deformation and subsequent erosion.

It is now shown that the limestones in the Cracoe area are divisible into local faunal and lithological subdivisions, which can be mapped by the usual methods. These subdivisions are correlated with the coral–brachiopod zones and goniatite succession of the Viséan, and extend from S_2 to D_2. The peculiar facies is due to the beds having been laid down against a long narrow ridge which kept the basin and massif areas of sedimentation apart until it was finally submerged in D_2 times, when sedimentation became continuous across it.

The reef limestones are, in fact, the marginal facies of the Great Scar Limestone, and the lateral change of each member of the local subdivision is traced through the marginal facies into the normal Great Scar Limestone.

The structure consists of a series of anticlines and broader synclines, arranged in echelon, which pass obliquely across the facies belts and die out north-eastwards. They were formed by pressure from the south impinging obliquely on a ridge of older rocks. The folding took place under exceptionally light cover and was completed before the Bowland Shales were deposited. The knoll topography was blocked out by faults which cut across the fold axes. The knolls themselves were eroded to very much their present shapes before the Bowland Shales, which lie with strong unconformity on the limestones, were laid down. The removal of these shales is now proceeding, and is re-exposing the buried topography of the knolls.

I. INTRODUCTION

THE palaeogeography of the Middle Viséan times is becoming increasingly well known, and it has been shown that deposition took place in a series of " provinces ", each with its own area of sedimentation.   Conditions differed from province to province, and considerable variation of facies is found even within a single province.   The distribution of facies in the Central Province has been critically reviewed by Hudson and Cotton (1945). Their map, from which Fig. 1 has been taken, shows that there were two contrasted types of sedimentation, the " basin ", or shales and limestone facies and the familiar Great Scar (massif) facies, the former being considerably thicker than the latter over the same period of accumulation.
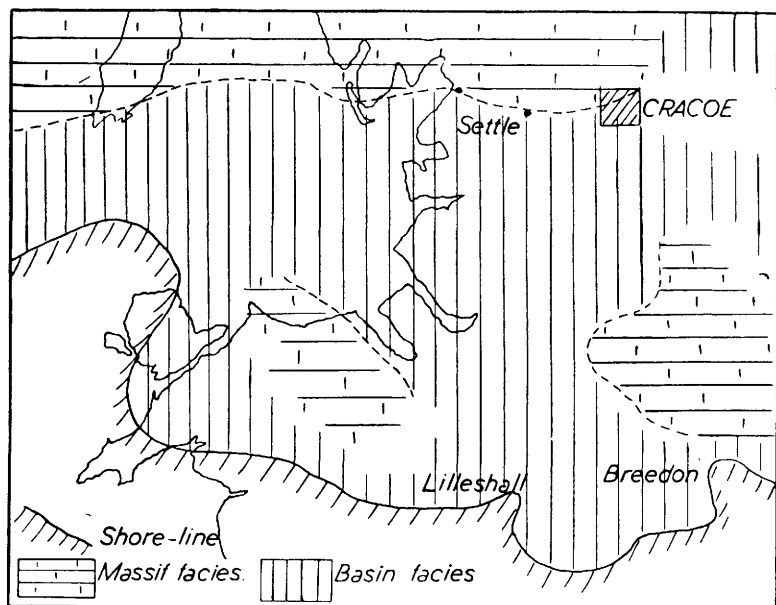

FIG. 1.—Sketch-map showing the position of Cracoe in relation to areas of basin and massif sedimentation during Middle Viséan times.   (After Hudson and Cotton.)

These two contrasted types of sediments, reflecting different conditions of deposition, are generally separated by a narrow belt of rocks unlike either facies, the marginal facies.   In the Central Province there are three such belts; one passes near Prestatyn, a second along the western side of the Derbyshire massif, and a third stretches eastwards from Ireland, through the southern end of the Isle of Man, Carnforth and Settle to Cracoe, and is finally lost under the Millstone Grit.

Cracoe lies at the eastern end of this belt.   It was the area in reference to which the term " reef-knoll " was first used.   The rocks are well exposed, mainly as a result of limestone quarrying on Swinden Knoll and extensive lead prospecting in earlier times.

To the north and north-east of the line of the reef belt, the lithology of the Lower Carboniferous is of " massif " facies.   The rocks rest upon a platform of Lower Palaeozoic sediments, termed the " rigid block " by

Marr (1899), and up to the base of D_2 shales are rare and pure limestones are dominant.

Conditions changed at the beginning of the D_2 subzone and there followed the rhythmic succession of shales, limestones and sandstones of the Yoredale Series. Limestones continue to be prominent members of the succession until the first beds of the Millstone Grit are reached, which have been shown by Chubb and Hudson (1925) to lie unconformably on the Yoredales.

The attitude of the beds is nearly horizontal throughout, except close to the North Craven Fault, where local disturbances have produced moderate dips. Faulting within the area of the Rigid Block is insignificant.

South of the knolls there is a striking contrast in lithology. The base of the Lower Carboniferous is nowhere exposed, though zones as low as Z have been shown to exist near Skipton (Hudson and Mitchell 1937). The lithological facies is different throughout the zones Z–D, which consist of a great thickness of shales and shaly limestones, with only occasional pure limestones. It is dominantly a muddy water facies, and has been aptly named the basin facies of sedimentation. A strong unconformity is present in the D zone, which is followed by Bowland Shales. This, in turn, is followed by the Millstone Grit.

Structurally, the contrast between basin and massif is marked. The rocks of the basin are violently disturbed, with much small-scale folding on the limbs of the main folds, which trend north-north-eastward. Faulting is powerful, mainly cutting the fold axes more or less at right angles.

The different lithological facies seen in these two areas is reflected in faunal contrasts. The basin facies (Z–D) has been correlated by Hudson and Mitchell (op. cit.) with the zones of Garwood and Goodyear on the massif. The faunal phase of the Bowland Shale facies is of goniatite–lamellibranch type throughout.

It is between these two contrasted areas that the limestone knolls of Cracoe lie.

Topographically, the area is unlike either the basin or the massif country, consisting of large, conical, almost isolated limestone hills (Tiddeman's reef-knolls) rising from the surrounding shales. The limestones are very pure and almost white, thus resembling the " massif " or Great Scar facies, but they are overlain by typical Bowland Shales. Much of the limestone is obscurely bedded, but where bedding can be made out dips are often steep, though not so steep as in the Craven Lowlands. Though much of the limestone is somewhat unfossiliferous, there are horizons where fossils are extraordinarily abundant, the rock being made up almost entirely of shells and shell fragments.

The fauna is, at first sight, entirely peculiar, the " standard " coral–brachiopod forms being very rare and swamped by a great number of individuals of species not often found outside the limits of the knolls. It combines a strong molluscan element with a brachiopod assemblage of forms uncommon in rocks of the basin or massif facies; corals are rather scarce.

The best exposures of the knoll limestones are found in the various workings of the Settle Lime Company's quarries on Swinden Knoll. The first part of the author's field-work consisted of collecting stratigraphically from these workings and attempting to make a local lithological and palaeontological subdivision of the succession exposed there. The succession is shown diagrammatically in Fig. 2.

The second part of the work consisted of mapping the remaining

limestone area on a scale of six inches to the mile, using the incomplete sequence found at Swinden as a standard, and completing the stratigraphy of the limestone series by adding the remaining members from their field relations. Fossils were recorded from each exposure, which was given a locality number. These numbers are given after species names in the faunal lists, and are shown on the map accompanying this paper.

Since previous workers have nearly always recorded their fossils under generalized localities such as " from the White Limestone of Stebden ", or simply " Elbolton ", or even " Cracoe ", it has been thought advisable to include in the faunal lists only forms collected and pin-pointed during the present work. Very rare exceptions have been made to this rule, and these are noted in the lists.
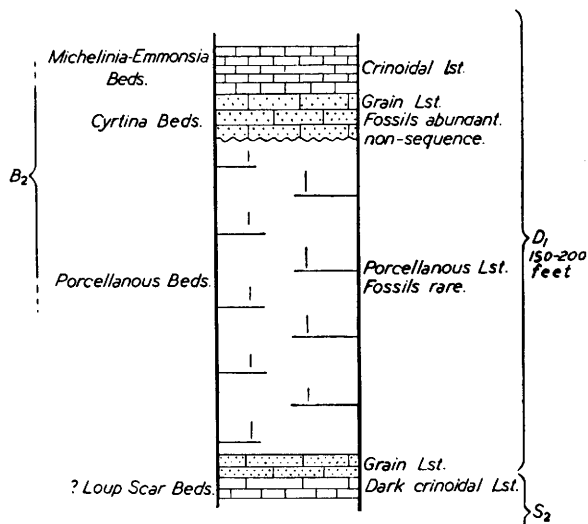

FIG. 2.—Diagrammatic section of the exposures in Swinden quarry, showing the correlation between coral–brachiopod and goniatite zones.

The structure of the limestone was deduced from the mapping, and from an analysis of joint, fault and fold directions in relation to the various ages of movement. By these means, a picture has been built up of the conditions of life, sedimentation and later history of this narrow belt of rocks. For most of the time, conditions did not favour invertebrate life, but towards the end of the period invertebrates such as molluscs, brachiopods and crinoids became established, and their remains constitute one of the most varied and extensive faunas of Lower Carboniferous times.

II. History of Previous Research

The area was mapped for the Geological Survey in 1890 by R. H. Tiddeman, W. H. Dalton and W. Gunn as parts of sheets 92 NW. and NE. of the old series one-inch Geological Survey map of Great Britain, but no memoir was published. Since that date, the limestone hills lying between the northern and southern outcrops of the Millstone Grit, and which were first named reef-knolls (or knoll-reefs) by R. H. Tiddeman, have formed the subject of many papers and much discussion.

Tiddeman (1900) advanced the view that they were of an original depositional nature, perhaps modified slightly by subsequent tectonics and erosion, but mainly resulting from the accumulation of organic debris as discrete mounds upon a sinking sea-floor, the tops of the mounds, or the " reef-knolls ", being probably subject to wave action.   This explanation was based upon the evidence of dips which seemed to be quaquaversal, together with the peculiar nature of the fauna associated with the knoll limestone.

Tiddeman's views were summarized in Marr's paper (1899), in which a very different explanation was given.   Marr sought to explain the phenomena observed by tectonics; brecciation, relief of pressure and recrystallization all playing their part, denudation subsequently moulding the present shapes.

A balance between palaeontology and tectonics was struck by Wilmore (1910) who, unfortunately, while recording faunas from individual knolls did not pin-point his records sufficiently accurately for use in the present work.   He correlated the limestones with the Pendleside Limestone.

The zonal position of the Cracoe knolls was also discussed by Garwood and Goodyear in 1924.   It is to Dr. R. G. S. Hudson, however, that we owe most of our knowledge of these rocks.   His views, expressed from time to time in various papers, are summarized in his paper (with Cotton, 1945) on the boring at Alport in Derbyshire, in which he gives a detailed account of the stratigraphy and conditions of deposition of the Lower Carboniferous rocks in the Central Province, paying particular attention to the correlation of the goniatite succession with coral–brachiopod zones. Hudson has shown that the peculiar facies at Cracoe and elsewhere is found where areas of Great Scar sedimentation adjoin the muddy water basin areas of deposition.   The present paper is an attempt to show in detail how these differences arose in one small part of a marginal belt, and how the peculiar knoll topography was evolved from the resulting sediments.

III. STRATIGRAPHY

The solid geology of the area is as follows :—

UPPER CARBONIFEROUS $\begin{cases} \text{Millstone Grit} \\ \text{Upper Bowland Shales.   } E_1 \end{cases}$

LOWER CARBONIFEROUS $\begin{cases} \text{Lower Bowland Shales.   } P_1–P_2 \\ \textit{Michelinia–Emmonsia} \text{ Beds.   Upper } D_1 \text{ and lower } D_2 \\ \text{Elbolton Limestone Series.   Upper } S_2 \text{ and lower } D_1 \\ \text{Threaplands Limestone Series.   } S_{1–2} \end{cases}$

With the exception of Elbolton Limestone and Threaplands Limestone Series, all the above terms have been previously published.   Although the best exposures of the Elbolton Limestones are in Swinden quarry, the term Swinden Series has been used by Hudson and Dunnington (1945) in another area, and to avoid confusion a different name is desirable.   Local names have been used in describing the succession, because it is an entirely local succession.   These subdivisions are not meant to be extended outside the district, but they serve as useful units of lithology and fauna for local mapping.

It is not proposed to discuss the rocks above the limestones.   The Bowland Shales were mapped in detail recently by Black (1940) whose work showed the importance of the sub-shale unconformity.

The description of the various members of the limestone series which follows is based on their best exposures, and is given in ascending stratigraphical order.

There is a considerable lateral variation of lithology and faunal content in some members of the succession, and this is discussed in a separate section.

(a) The Threaplands Limestone Series (S_{1-2}). Base not seen.

The oldest beds exposed in the area of the map are the Threaplands Limestone Series. They are found only in the south-west corner of the mapped area, and are exposed in Skelterton Beck and as a small inlier in Threaplands Gill, where a stream emerges from a cave. In this exposure they are followed by a thin limestone conglomerate of rounded pebbles, formed of limestone resembling the typical Skelterton Limestones. The series also forms the low ridge connecting Threaplands and Langerton, where it ends abruptly.

The rocks of the series are black, earthy and shaly limestones, with a certain amount of dark chert. Thin sections show that the limestone consists of organic material, such as broken crinoid ossicles and fragments of brachiopod shell, embedded in a fine-grained calcareous matrix. The larger organic fragments, though broken, are not rolled, and many of the fragile tests of foraminifera are unbroken. The matrix is patchily recrystallized into areas of clearer calcite.

The insoluble residue is bulky, with a large clay fraction. After removal of clay the inorganic detrital residue, of specific gravity above 2·9, is very scanty indeed. One almost perfectly rounded grain of water-clear zircon, and a few ragged flakes of biotite were the only recognizable minerals found. The organic detrital material is more interesting, and consists of some fragments of what seems to be bone, a fish tooth, coprolites, sponge spicules and a few casts of foraminifera. By far the greater part of the residue after removal of clay consists of authigenic minerals, including fluorite, pyrite (and limonite as an alteration product), blende, cryptocrystalline silica, crystalline silica loaded with pyrite, and euhedral quartz crystals.

Exposures in these beds are numbered 64, 66, 111.

The following fossils have been found in this series of limestones :—

Archaediscus sp., 64 [1]	*Michelinia* cf. *tenuisepta* (Phillips), 64
Endothyra sp., 64	*Martinia* cf. *glabra* (Martin), 64
Saccaminopsis sp., 64	*Productus* sp., 64
Calcisphaera sp., 64	*Hyalostelia smithii* Young & Young, 64
Caninia cf. *hettonensis* Wilmore, 111	Crinoid debris
Zaphrentis sp., 64	

The limestone is considered to have been formed in comparatively shallow water, sometimes subjected to wave action. Deposition was probably rapid, and the supply of terrigenous material considerable, suggesting deposition on a sinking floor, near a shore-line.

These beds farther to the south-west, along a continuously traceable outcrop, were discussed by Hudson and Mitchell (1937), who determined their age as S_2.

The exposures within the area of the map are rather poor, and the fauna recorded is scanty. The fossils were mainly collected from exposure 64, on the site of an old lime-kiln a little north-east of Threaplands House.

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[1] Numbers after species in this, and all succeeding lists, indicate localities from which a species was collected. For their position see map.

The occurrence of chert suggests a low horizon (Hudson 1930B) and *Caninia* cf. *hettonensis* is consistent with an age low down in S_2.

The facies of the fauna and lithology is unlike anything in the true " reef " limestones, being typical of the basin sedimentation to the south. Considered as part of that region, it falls naturally into place in the geological history of the Cracoe area.

(b) The Elbolton Limestone Series (S_2–D_1)

(i) *The Loup Scar Beds (base not seen).*—The rocks grouped under this name occur in the core of an anticline which crosses the River Wharfe at Loup Scar, just north of Burnsall, and are also brought up by a gentle fold which passes between Hartlington Kail and Langerton Hill, whence they can be traced north along the river to Wilfred Scar, above Burnsall. They are dark crinoidal limestones, with a fairly abundant fauna, and are easily distinguished from the porcellanous limestones which overlie them. When the base of the main quarry face at Swinden is clear, a few feet of dark crinoidal limestone, sometimes with a brecciated texture, may be seen below the Porcellanous Beds. These dark limestones may be on the same horizon as the Loup Scar Beds.

The limestone, in section, is a fragmental or grain-limestone, composed of partly rolled fragments of brachiopods and crinoids. No true oolites occur, and the tests of foraminifera are mostly intact. The matrix is fine-grained and dark, with a spotted texture and some clear recrystallized patches of calcite. The insoluble residue is bulky, but is composed largely of clay matter. After its removal the residue is found to consist principally of authigenic material.

These limestones are considered to have been deposited in comparatively shallow water, but under conditions of rather rapid accumulation. The abundant clay fraction suggests the proximity of a shore-line, which, since the equivalent horizons farther north on the massif are of much purer limestone, must have lain to the south, and at no great distance.

The following fauna has been collected from the Loup Scar exposures (115) :—

Saccaminopsis sp.	*Sinuatella sinuata* (de Koninck)
Dielasma sacculus (Martin)	*Zaphrentis* sp.
—— sp.	*Naticopsis ampliata* (Phillips)
Pugnax pleurodon (Phillips)	*Posidoniella vetusta* Sowerby
—— cf. *angulata* (Linnaeus)	*Pterinopecten* sp.
—— sp.	*Glauconoma* sp.
Pustula cf. *subelegans* Thomas	*Phillipsia* sp. and other trilobite frag-
Reticularia lineata (Martin)	ments
Schizophoria resupinata (Martin)	Crinoid debris
—— *connivens* (Phillips)	?*Koninckopora* sp.

To the east of the Wharfe, similar limestones are found underlying the Porcellanous Beds in the Dibb valley, where they were mapped by Anderson (1928), who referred them to S_2. In the Dibb valley, they contain a rather massive dolomite which is absent, or not reached, in the area covered by this paper. The Loup Scar Beds are discussed by Hudson and Cotton (1945, p. 300 *et sqq.*), who conclude that they are of lowest D_1 age. The fauna recorded here has no resemblance to S_2 faunas of basin or massif facies, having a distinctly " reefy " appearance. Practically all the forms found can be matched by specimens from the D_{1-2} limestones of the knolls themselves, and none is of diagnostic value. There is an absence of *Lithotrotion* and *Dibunophyllum*, and all that can be said for certain is

that the beds underlie a lower D_1 series apparently without break. They must, therefore, belong either to the top of S_2 or the lowest part of D_1. Their exact position is not important, but it is important that they are of a marginal type.

(ii) *The Porcellanous Beds. Lower D_1. 0–200 feet.*—These beds form the thickest member of the Elbolton Series. They are well developed at Swinden quarry, where they form the greater part of the main face. They are also seen in the lower parts of Elbolton, Thorpe Kail, and Hartlington Kail, and they occupy much of the lower-lying ground around Thorpe village.

They are massive, porcellanous or very fine-grained limestones, almost calcite mudstones, and are pale buff in colour. The bedding is often obscure, and it is probably this member of the succession which in the past has caused so much difficulty in the determination of dips. The beds are of widespread occurrence and are easily recognized by their obscure bedding, splintery, almost conchoidal fracture, colour and the rarity of fossils.

The lowest few feet at Swinden tend to be more fossiliferous grain-limestones. A coral of the genus *Dibunophyllum* can be seen, in situ, on the face of the prominent joint-plane which forms the eastern wall of the main quarry at Swinden, proving that the beds belong to the D zone.

These porcellanous limestones reach a maximum thickness of about 200 feet and do not appear to contain a single persistent fossil band or distinctive assemblage. Such forms as are found occur also in the succeeding beds, where fossils are extremely abundant. The top part of these beds contains a little penecontemporaneous tufa, so that their upper limit is ill-defined.

A micro-slide of a typical specimen shows occasional crinoid plates, set in a very fine-grained, calcite-mudstone matrix. The matrix is somewhat spotted or clotted, and is of the type figured by Wood (1941, pl.·ii, fig. 5).

It is considered that these porcellanous calcite mudstones represent an extensive development of lagoonal conditions, where precipitation, either by algae or chemical action, took place. Somewhat similar deposits have been described from South Wales by Dixon and Vaughan (1911). Macroscopic organisms certainly contributed very little to their formation and the fauna is very meagre in both species and individuals.

Exposures in these beds are numbered, 6, 8, 31, 32, 35, 36,[1] 38, 39, 50, 77, 79, 84, 88, 97, 117.

The following fauna has been collected :—

Brachythyris ovalis (Phillips), 79
Gigantella spp., 88
Productus triquetrus Muir-Wood, 84
—— sp., 36, 79
Pustula subelegans Thomas, 36
Reticularia lineata (Martin), 79

Spirifer striatus Martin, 79
Schellwienella cf. *crenistria* (Phillips), 36
Pinna sp., 84
Dibunophyllum cf. *bourtonense* Garwood, at Swinden
Zaphrentis sp. 79

The occurrence of breccia and oolite at the base of these beds at Swinden quarry may indicate a small break, possibly the equivalent of the break between S_2 and D_1 found by Hudson and Mitchell (1937) in the Skipton area. Neither oolite nor breccia has been seen between the Loup Scar Beds and the Porcellanous Beds, where the change in lithology, though abrupt, does not seem to indicate non-sequence.

[1] May be at the base of the succeeding Tufa Beds.

(iii) *The Tufa Beds.   Middle D_1.   0–50 feet.*—Although there is some development of tufa in the topmost part of the Porcellanous Beds, the limestone becomes very much more tufaceous at about the horizon where a marked increase in fauna occurs.   Thus, although it is hard to distinguish an unfossiliferous and unweathered hand-specimen of these beds from the underlying porcellanous limestone, the difficulty is considerably less in field exposures.   The greatest obstacle in the field is the rapid lateral variation of this member of the series.   The Tufa Beds are not found in the main face of Swinden quarry.   There seems to be a break in the succession on their horizon.   In the extreme south-west corner of the runway from the main quarry to the waste tip, a little tufaceous limestone can be seen, probably belonging to this horizon.   It is very fossiliferous, and has yielded goniatites.

These beds are absent on Skelterton, but they are well exposed on Butterhaw, where they are highly fossiliferous.   The tufa can be seen encrusting fossils in concentric layers of radiating fibrous calcite, particularly round the corallites of fasciculate *Lithostrotion*.

On Stebden the horizon is just reached in the quarry on the north side, half a mile south of Escoe House.   On Elbolton and Thorpe Kail these beds reach their best development and are richly fossiliferous.   The equivalent horizon must be present below the *Cyrtina septosa* limestones in the Wharfe valley, near Lythe House on the north bank, and along the edge of the gorge on the south bank, but it is entirely changed lithologically and faunally.   On Hartlington Kail, beds very like those on Elbolton are found, but have not yielded so rich a fauna.

In hand-specimens the typical Tufa Beds limestone is fine-grained and dark or medium grey in colour when fresh.   It weathers to a pale shade of grey.   The irregular layers of tufa do not show well on fresh specimens, but on surfaces long exposed to the weather the layers of tufaceous calcite are clearly etched out.

In section, the matrix is seen to be a very fine clotted limestone, rather like the porcellanous limestones below.   The tufa shows as areas of clearer crystalline fibrous calcite, with the fibres standing perpendicular to the edges of the clotted area and encrusting organic remains.

Apart from large and almost undamaged shells, micro-slides show that this limestone contains very little recognizable organic material.   The fine-grained matrix contains a few foraminifera and *Calcisphaerae*, but no pellets, rounded grains of shell fragments, or algal filaments.   The beds are often crowded with beautifully preserved fossils, but breakage and comminution before burial seem to have been reduced to a minimum.

The conditions of deposition of such a limestone are somewhat difficult to picture.   The fossils found are of types common in the succeeding *Davidsonina (Cyrtina) septosa* Beds, which were probably formed in turbulent shallow-water conditions, with many broken shells and rolled fragments.

Part of the fauna of the Tufa Beds could, therefore, exist under shallow and turbulent conditions, but the nature of the matrix points to quiet water.   The presence of tufa would seem to indicate very shallow, warm water.   The porcellanous texture of the matrix may possibly be accounted for by sheltered lagoonal conditions, in which chemical precipitation produced the layers of tufa.   The matrix has the appearance of an algal precipitate, though no traces of algae have been found.   The spotting or clotting of the fine-grained mud on recrystallization resembles that described by Wood (1941), who states (p. 198) that " Whenever the lime-

stone weathers china-white and appears fine-grained and structureless when broken, material similar to algal dust will be found in a thin section."

The following large fauna has been collected from these beds. Exposures in this series are numbered, 2, 5, 9, 10, 14, 15, 16, 28, 36a, 43, 46, 48, 56, 75, 80, 81, 85, 89, 90, 91, 92, 94, 96, 98, 99, 102, 107, 112, 113, 114, 118, 119, 120, 121, 122, 127.

Calcisphaera sp., 46
Endothyra sp., 46
Brachythyris ovalis (Phillips), 29, 14, 102
Chonetes cf. *papillionacea* (Phillips), 102
Productus (*Eomarginifera*) *derbiense* Muir-Wood, 2, 14, 91
—— *flexistrius* McCoy, 118
—— cf. *griffithianus* de Koninck, 91
—— (*Plicatifera*) *mesolobus* (Phillips), 14, 15
—— (*Plicatifera*) *plicatilis* (J. de C. Sowerby), 14, 15
—— *productus* Martin, 107, 113
—— (*Krotovia*) *spinulosus* J. de C. Sowerby, 96
—— *sulcatus* J. Sowerby, 2, 9, 14, 43, 81, 99
—— (*Avonia*) *youngianus* Davidson, 15
—— (*Gigantella*) sp., 5, 10, 43, 102
Pugnax acuminatus (Martin), 9, 15, 16
—— *pleurodon* (Phillips), 2, 9, 14, 91, 127
—— *pugnus* (Martin), 2, 80
—— *reniformis* (Davidson), 2, 9, 14, 91
—— *ovalis* (Phillips), 9
—— *pilosa* Thomas
—— cf. *punctata* (Martin), 96
—— *pustulosa* (Phillips), 91
—— *venusta* Thomas, 91
Pustula sp., 127
Reticularia lineata (Martin), 2, 15, 91
—— cf. *lobata* Muir-Wood, 14
—— sp., 14
Schellwienella crenistria (Phillips), 9, 14, 43
—— *sharpei* (Morris), 2, 15
Schizophoria resupinata (Martin), 2, 15, 91, 112, 118

Spirifer striatus Martin, 15
—— cf. *bisulcatus* J. de C. Sowerby, 2, 85, 91, 118
—— *crassus* de Koninck
Amplexus coralloides J. Sowerby, 15
Lithostrotion sp., 96
Bellerophon sp., 91
Mourlonia carinata (J. Sowerby), 81
Murchisonia sp., 81
Straparollus dionysii de Montfort, 91, 118
—— *fallax* de Koninck, 118
Gastropods (undetermined)
Conocardium alaeforme J. Sowerby, 15, 85
Edmondia cf. *primaeva* Portlock, 85, 114
Eumicrotis hemisphericus (Phillips), 85
Pterinopecten concavus McCoy, 91
—— *radiatus* Phillips, 99
Beyrichoceras castletonense (Bisat), 15
—— cf. *micronotum* (Phillips), 15, 94
—— cf. *phillipsi* Bisat, 94, 102
—— cf. *vesiculiferum* (de Koninck), 102
Goniatites hudsoni Bisat, at Swinden (*fide* G. B. Alexander)
—— *maximus* Bisat, 51, 56, 81, 85, 107
Nomismoceras vittigerum (Phillips), 15
Fenestella spp., 2, 14, 16, 85
Hemitrypa hibernica McCoy, 85
Millepora spicularis Phillips, 99
Polypora sp., 14, 85, 118
Griffithides carringtonense Etheridge MS. (in Woodward), 14
Phillipsia cf. *cracoensis* Cowper Reed, 14
—— sp., 14, 15, 43, 102
Chaenocaris cf. *tenuistriata* (McCoy), 118
Entomoconchus globosus Jones, Kirkby & Brady
Platycrinites sp., 15
Cravenechinus uniserialis Hawkins, 14

It is very largely a brachiopod fauna, with a notable admixture of rare goniatites. The brachiopods make up the vast majority of individuals preserved. The commoner individuals are of species found also in the succeeding *Cyrtina* Beds.

In terms of the coral-brachiopod zones, the age of this division cannot be obtained at all accurately from the fauna. This contains many long-range forms of brachiopods, but, in addition, rare goniatites which give the age in terms of the goniatite zonal scheme. The occurrence of *Goniatites maximus* (s.l.) immediately places the beds in the B_2 zone. The occurrence of *Beyrichoceras castletonense*, *B.* cf. *micronotum*, *B.* cf. *phillipsi*, *B.* cf. *rectangularum* and *B.* cf. *vesiculiferum* is consistent with such a zonal position.

(iv) *The* Davidsonina (Cyrtina) septosa *Beds. Middle D_1. 0–50 feet approx.*—These form the highest subdivision of the Elbolton Series. Except at Swinden quarry, they are not clearly defined from the beds below.

Where typically developed they are easily recognized by their fauna and lithology. They are referred to below as the *Cyrtina* Beds.

They are absent at Skelterton Hill and are not seen (going north-eastwards) until Threaplands Gill is reached. Their local base is visible in the cave entrance just behind Threaplands House, and is marked by a thin pebble-bed. They are well developed on Butterhaw, Stebden, Elbolton, Thorpe Kail, Byra Bank, in the quarry (" Q12 ") containing the telephone exchange on the Burnsall road, and across the Wharfe on Hartlington Kail and Langerton Hill. Beds of equivalent horizon but different fauna and lithology occur on both sides of the Wharfe near Lythe House.

In most exposures the bedding is well developed, though it tends to be rather massive. In the larger exposures little difficulty is met with in determining the dips.

The following description of the lithology is based upon material from the upper quarry at Swinden (exposure A). Much of the limestone is composed of grains, sometimes with graded bedding. Several units may recur in a section of six inches. There are some layers of calcite mud-stone, and possibly some tufaceous material near the base of the series which is occasionally brecciated.

In slide, the limestone is a typical grain-limestone as defined by Wood (1941) and strongly resembles his illustration. Few true oolites are present, the grains being rounded fragments of brachiopods and crinoids. Foraminifera are abundant and many of their tests are broken. There are also fragments of the calcareous alga *Koninckopora*. The groundmass is completely recrystallized to clear crystalline calcite in large, optically continuous plates. There is a surprising amount of this material in the slides, the grains often being separated from all contact with each other by the matrix, when seen in two dimensions. The insoluble residue is extremely scanty and consists almost entirely of pyrite-loaded quartz crystals and irregular mosaics of silicified limestone. No detrital grains or casts of foraminifera have been found, and the clay fraction is very small.

Fossils are abundant, the fauna recorded here being composed of over 130 species collected in the course of the present work. Individuals of many species are extremely numerous. Preservation is less perfect than in the underlying Tufa Beds, but the greater abundance of individuals makes the collection of good specimens so easy that there is danger of overlooking the frequent occurrence of shells broken before burial. This type of grain-limestone, with a clear crystalline matrix and an abundance of rolled and broken fragments, suggests accumulation under shallow-water, turbulent conditions. The packing of the grains suggests that the clear calcite was introduced into the shell-sand in solution, probably soon after the accumulation of the grains, around which it was precipitated until the pore spaces were sealed up.

The following fauna has been collected from these beds. The list is made up largely from the collection made by the author from the upper quarry (A) at Swinden, but the main elements of the fauna are widespread throughout the knolls region. The list could probably be extended considerably by further collecting.

Exposures in this series are numbered, 1, 7, 13, 17, 18, 19, 21, 29, 30, 37, 41, 42, 44, 45, 49, 51, 54, 55, 60, 63, 64a, 68, 78, 83, 93, 95, 103, and quarry A (Swinden).

Archaediscus sp., A   *Textularia* sp., A
Cribristoma sp., A   *Athyris expansa* (Phillips), A
Endothyra sp., A   —— cf. *globularis* (Phillips), A, 19

Gonatites near *wedberensis* Bisat, 83
—— *maximum-wedberensis* group, A
—— *striatus* Sowerby, 29 (*fide* R. G. S. Hudson)
Sagittoceras discus (Roemer), 29 (*fide* R. G. S. Hudson)
Orthoceras sp., A, 13, 63
Subclymenia evoluta Phillips, 95
Fenestella spp., A, 1, 18, 19, 41, 51, 63, 68, 95
Millepora spicularis Phillips, 95
Pinneretopora sp., A
Fistulipora incrustans (Phillips), A, 1, 29, 60

Entomoconchus globosus Jones, Kirkby & Brady, 41
Brachymetopus sp., A, 13
Griffithides acanthiceps H. Woodward, 29
—— *carringtonense* Etheridge in H. Woodward, A
—— *globiceps* Phillips, A
—— *longiceps* Portlock, A
Phillipsia cf. *cracoensis* Cowper Reed, A
—— *derbiense* (Martin), A, 63
—— *eichwaldi* Fischer, A
—— *gemmulifera* Phillips, 41
—— sp., A, 1, 19, 29, 51, 60, 64a
Koninckopora inflata (de Koninck), A

This fauna has many species, particularly of *Productus*, in common with the fauna of the Tufa Beds below. In addition, it contains many more species of lamellibranche, more corals, many more brachiopods, particularly of the genera *Dielasma*, *Athyris*, *Martinia* and *Brachythyris*. Together, the fauna of the Tufa Beds and the *Cyrtina* Beds make up the typical knoll fauna.

This varied fauna, confined to a relatively restricted vertical thickness of limestone, contrasts strongly with the very scanty list of forms in the much thicker limestone of the Porcellanous Beds. Its position can be given in terms of the normal coral–brachiopod zones and of the goniatite succession, since forms diagnostic of each occur.

The presence of *Davidsonina (Cyrtina) septosa*, as noted by Hudson (1938), definitely places these beds in relation to the standard coral–brachiopod zones of the Rigid Block. where this fossil occurs in a narrow but widespread band of middle D_1 age. *Chonetes comoides* has also been found in exposures assigned to these beds.

Goniatites maximus (s.l.) shows that the position in the goniatite time-scale is in the B_2 zone, and the associated goniatites, *Beyrichoceras micronotum*, *Goniatites hudsoni* and *G.* near *wedberensis*, fix the position within the B_2 zone.

The relations of the goniatite assemblages to the coral–brachiopod zones is further discussed in a separate section on correlation.

(c) The *Michelinia–Emmonsia* Beds.   Upper D_{1-2}

This series of well-bedded limestones is divisible into two parts. The lower part is characterized by a fauna containing *Michelinia* cf. *tenuisepta* and *Emmonsia parasitica*, and is referred to below as the *Michelinia–Emmonsia* Beds. The upper series contains much chert and a fauna of *Lithostrotion* spp. These beds are referred to as the *Lithostrotion* Cherts.

Michelinia–Emmonsia *Beds.   Upper* D_1 *and lowest* D_2. *50–75 feet.*— These beds contain the lowest horizon which can be traced from the Craven Lowlands (basin facies) across the area of the Cracoe knolls, and into the limestones of Great Scar type, though the horizon in question changes in facies laterally.

These limestones are well exposed in Clints quarry just south-west of the area under discussion, whence they can be followed to Skelterton Beck and thence round the face of Skelterton Knoll. They are also seen in Threaplands Gill and in the hollow between Butterhaw and Stebden knolls. On Swinden Knoll the beds cap much of the knoll but are not fully exposed in the main quarry. They are seen again near Catchall, at the north-western end of this long knoll. They are present around Escoe House, and on the

south-western face of Elbolton.   Beds referred to this division occur in the valley of the Wharfe near Lythe House, and just below the suspension foot-bridge leading to Hebden from the Burnsall road.

The limestones are well bedded in all exposures, and are coarsely crinoidal in texture.   Tiddeman's Breccia, a thin limestone with a brecciated appearance on weathered surfaces, occurs near the base of these beds.   It is a useful horizon in correlation, since it is well known in the Craven Lowlands, where its horizon was determined by Hudson and Mitchell (1937), who placed it high up in the D_1 subzone.   In the Skipton anticline of the Craven Lowlands two breccias are present, separated by some feet of limestone.   The upper breccia is the one which has been named after R. H. Tiddeman, and it is this which is present at Clints quarry and in the knolls area.

In hand-specimen, the crinoidal limestones of the typical *Michelinia–Emmonsia* Beds is medium to dark grey when fresh, weathering to a rather paler grey.   It is composed almost entirely of crinoid debris of a rather coarse grade.

In section, it is seen to be composed of large crinoidal fragments, averaging a quarter of an inch in diameter, set in a small amount of matrix of grain-limestone type.   The grains themselves are embedded in the usual clear crystalline calcite.   The larger crinoid fragments are rather uniform in size and there is a distinct break in grade between them and the grains of the finer part.   There are rolled fragments of brachiopods, spines and shell fragments both occurring.   There are many foraminifera, often broken, in the matrix.   There are, in one slide, a few small nodules full of algal filaments or borings.   They are not *Girvanella*, though the horizon from which the specimen was collected is near that of the *Girvanella* Band.

The fauna is recorded below.   Though *Michelinia* and *Emmonsia* are common in the southernmost part of the area, the beds are not generally very fossiliferous.   Exposures are numbered, 4, 5, 12, 47, 58, 59, 61, 62, 67, 67a, 78, 82, 86, 87, 90, 91, 100, 104, 105, 106, 110.

Endothyra sp.
Athyris planosulcata (Phillips), 82
Aulacophoria aff. *keyserlingiana* (de Koninck), 104
Buxtonia scabricula (Martin), 12
Chonetes sp., 12
Productus (*Plicatifera*) *plicatilis* (J. de C. Sowerby), 12, 82
—— (*Striatifera*) *striatus* Fischer, 91
Pustula cf. *subelegans* Thomas, 12
—— cf. *rugata* Thomas, 12
—— sp., 91
—— *pyxidiniformis* (de Koninck), 87
Pugnax pleurodon (Phillips), 91
—— sp., 91
Schizophoria resupinata (Martin), 12
Spirifer trigonalis Martin, 90
Amplexus coralloides J. Sowerby, 82
Caninia cf. *juddi* Thomson, 12
Clisiophyllum sp., 12
Emmonsia parasitica (Phillips), 82, 86, 106

Lithostrotion cf. *irregulare* (Phillips), 12
—— *junceum* (Fleming), 58, 78
Michelinia cf. *tenuisepta* (Phillips), 86, 90, 106
Palaeosmilia cf. *murchisoni* Edwards & Haime (very large form), 12
Syringopora sp., 87
Zaphrentis sp., 12, 90
Pinna flabelliformis (Martin), 82
Naticopsis sp., 59, 104
Beyrichoceratoides truncatum (Phillips), 90, 105
Goniatites crenistria (Phillips), 90
—— *maximus* Bisat (s. l.), 104
—— sp., 82
Griffithides obsoletus H. Woodward, 91
Phillipsia derbiensis (Martin), 90
Trilobites indet., 90
Girvanella sp., 78, 100
Coelosporella sp. (fragments)
Crinoid debris
Ostracods, 90

The facies suggested by this assemblage is of " reef " type.   The productids include typical reef forms, *Buxtonia*, *Plicatifera*, *Pustula*, *Striatifera*;   the orthids include *Schizophoria* and the rare *Aulacophoria*

aff. *keyserlingiana*.   *Pugnax* is also found.   None of the above is of direct zonal significance.

Among the corals, *Amplexus coralloides* gives no indication of horizon, and though locally useful in mapping, *Michelinia* cf. *tenuisepta* and *Emmonsia parasitica* are both phasal and long range.

The fauna provides an age determination independent of its field relations, since *Palaeosmilia* cf. *murchisoni* (a very large form) is characteristic of the upper D_1 subzone while the *Beyrichoceratoides truncatum–Goniatites crenistria* band indicates a lower P_{1a} age in terms of the goniatite succession.   The presence of the *Girvanella* Band near Catchall, noted by Hudson (1938), and just south of the Hebden suspension bridge, shows that the beds lie right at the top of the D_1 subzone, and as they can be shown to overlie the *Cyrtina* horizon they must represent the top beds of the D_1 subzone of the Rigid Block facies.

Their zonal position has been dealt with rather fully since their distribution right across the knolls area, from the Craven Lowlands to the massif, renders them of great importance in the interpretation of the conditions of deposition of the limestone series.

The fauna is similar to that recorded by Parkinson (1935) from his *Emmonsia parasitica* subzone at Pendle.

Lithostrotion *Cherts*.   *Lower D_2*.   (*Top not seen.*)—These beds are only found in a small infaulted area on Swinden Knoll, near Catchall Corner, and their relationship to the *Michelinia–Emmonsia* Beds is by no means clear.

The limestone is dark and crinoidal, well bedded, and contains tabular chert conforming to the bedding of the limestone, and probably an " orthochert " as defined by Jessop (1931).   Fossils are scarce, except for masses of *Lithostrotion* spp. forming large sops in the limestones.   These include *L. junceum* and *L.* cf. *maccoyanum* Edwards and Haime.

The only exposure of these beds is numbered 57 on the map.   They are placed in the D_2 subzone since they apparently overlie the *Girvanella* Band.

(d) Evidence of the Order of Superposition

The stratigraphy has been described above in what is believed to be the correct ascending order, but no evidence was adduced to support it.   It is desirable to give this evidence, and to indicate sections where the succession is uncomplicated by tectonics, for, in spite of the beautiful exposures in the quarries on Swinden Knoll, there is no single section where the complete limestone sequence can be seen.

Clints quarry.—The *Michelinia–Emmonsia* Beds with Tiddeman's Breccia, of upper D_1 age, are separated by a considerable stratigraphical break from the Rylstone Limestone, of S age and basin facies.   The whole of the lower D_1 subzone, and perhaps some of the top of S_2, are thus missing in this section, but there is no angular discordance visible.

Skelterton Beck.—This section agrees with Clints, except that the thickness of *Michelinia–Emmonsia* Beds is greater.

Swinden quarries.—This long knoll has an anticlinal structure with a north-easterly pitch.

The main quarry at the south-western end exposes the full thickness of the porcellanous limestone.   This is abruptly followed by the *Cyrtina* Beds, seen in the upper quarry (A), the sharp junction and absence of certain goniatite assemblages suggesting a non-sequence.   The north-easterly pitch brings in a few feet of the lower part of the *Michelinia–Emmonsia* limestones, above the *Cyrtina* Beds at the top of the face, at the Catchall

end.   Only the fossils found in quarry A (upper quarry), which was entirely in *Cyrtina* Beds while this work was in progress, have been included in the faunal list.   It is impossible to be certain of the horizon of specimens from the other workings, although the nature of the matrix gives a good indication.

Threaplands Gill.—The section exposed in a small quarry above the road shows a grain-limestone overlain by a strongly crinoidal, well-bedded limestone.   The fossils and lithology of the former link it with the *Cyrtina* Beds at Swinden, while a thin breccia in the latter, exposed in a small anticline upstream from the quarry, is correlated with Tiddeman's Breccia.   This section confirms the succession seen in Swinden quarries.
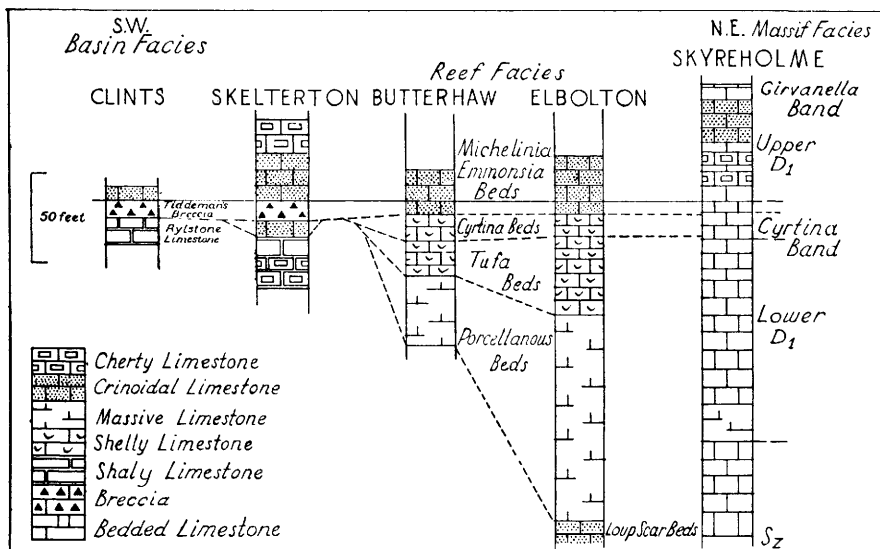
Fig. 3.—Vertical sections on a line north-east and south-west across the knolls area.

Butterhaw.—The south side of the knoll shows a clear succession, dipping uniformly with the slope of the hill.   The highest exposures show typical *Michelinia–Emmonsia* Beds overlying *Cyrtina* Beds.   Below these are the deposits referred to as Tufa Beds, the base of which is not exposed, but at the south-western end of the knoll they can be seen dipping off massive porcellanous limestones, like those of Swinden quarry.   The exposures on Elbolton and Thorpe Kail give a similar succession.   Hence, the Tufa Beds occupy the horizon of the suspected non-sequence below the *Cyrtina* Beds at Swinden quarries.

The stratigraphical order is, therefore, as given above, and it can be seen that the gap in the succession at Clints quarry corresponds to the position of the Elbolton Series which make up the greater part of the knolls.   This series appears fairly suddenly north-east of a line through Skelterton Hill, and rapidly attains its greatest development at Swinden, Elbolton and Thorpe Kail.   Conditions of deposition which could lead to this peculiar distribution are discussed below.

Vertical sections lying on a line north-east and south-west across the knolls area are given in Fig. 3.

V. LATERAL VARIATIONS OF FACIES, AND CONDITIONS OF DEPOSITION
OF THE LIMESTONE SERIES

The local subdivisions of the limestone series, used in mapping, have been found to hold their character laterally only when traced in an east-south-east to west-north-west direction, and to change rapidly when traced in the direction at right angles. As the lithology changes so does the fauna. These east-south-east to west-north-west facies belts cut diagonally across the tectonic axes, and it is unlikely that such changes can be the result of movements along them taking place during the accumulation of the sediments. Since the North Craven Fault is post-Namurian in age, it cannot have influenced the depositional facies of the pre-Namurian limestones. The fault system, which may be the mid-Craven, lies within the belt termed " reef facies " and is pre-Namurian in age. Since it cuts the limestones, its main movement must post-date their deposition, but its position within the reef belt is probably not entirely coincidental. The position of the fault and the position of the belt of " reef " limestone facies are both related to the underlying basement and are, therefore, indirectly connected.

Turning to the individual members of the limestone series, their variations will be described as seen in the traverse across the strike of the reef facies belt, from south-west to north-east.

Threaplands Limestones are limited to a small area in the south-west corner of the map. These limestones have not been seen north-east of Threaplands Gill. When beds of approximately the same age are seen again (the S_2 beds of the Dibb valley described by Anderson 1928) they are completely changed in facies. Instead of the earthy impure limestones of " basin " type, they are pure fragmental limestones of massif facies. Such a change has been held in other areas to be due to deposition on opposite sides of a low barrier of Lower Palaeozoic rocks whose surface sloped steeply towards the basin and very gently towards the massif.

The Loup Scar Beds of the Elbolton Series are next in stratigraphical order. Their dark colour seems to be due to the relatively large amount of clay matter, which is found in the insoluble residue. It has been suggested that they originated in comparatively shallow water, and the high content of clay suggests that the ridge of Lower Palaeozoic rocks may still have been undergoing denudation during their deposition. Their fauna contains such typical knoll-facies forms as *Dielasma, Pugnax, Reticularia, Sinuatella, Schizophoria* spp., trilobites, lamellibranchs and gastropods, lending support to the view that they are of " abnormal " facies, when compared with their equivalents on the Rigid Block proper. Since these beds are not found south-west of Elbolton, and do not seem to have been deposited south-west of a line passing through Elbolton and the eastern end of Swinden Knoll, they must be regarded as the marginal facies of the equivalent horizon on the Rigid Block. Shallow-water conditions allowed some of the typical reef fauna to become established. The beds are strongly crinoidal, which is not typical of the reef facies proper, and this probably accounts for the presence of only a part of the reef fauna.

Conditions changed slightly after the deposition of the Loup Scar Beds and remained almost constant throughout the formation of the thick Porcellanous Beds. These appear quite suddenly north-east of a line which passes through Swinden Knoll and Carden Hill and rapidly attain a thickness of nearly 200 feet. They occur farther south-west than the beds stratigraphically below them and probably overstep them in this

direction. They are noteworthy for their very small clay fraction and fine grain, and are considered to have been formed in still-water, lagoonal conditions. Their shore-line may have lain within the area of the map, and perhaps coincided with the line of their present sudden disappearance. The Lower Palaeozoic rocks were probably completely submerged by the time of their deposition, and it is suggested that their southern shore-line was formed by a low ridge of the Threaplands Limestone Series, raised during the Cravenian earth-movements by compression of the basin facies against the south-western face of the Lower Palaeozoic Rigid Block. The low relief and small area of this ridge, its calcareous nature, and the quiet lagoonal conditions, would account for the remarkable purity of this member of the Elbolton Series. The Porcellanous Beds maintain their lithological facies within the limits of the map, but the equivalent lime-stones in the Great Scar Series on the massif are finely fragmental lime-stones with a meagre fauna. The fauna of the Porcellanous Beds is scanty, but contains the following typical reef forms : *Brachythyris ovalis*, *Pustula subelegans*, *Schellwienella crenistria*, *Pinna mutica* and *Reticularia lineata*. The area of deposition must have formed a comparatively wide lagoon, the sediments passing gradually north-eastwards into the normal fragmental limestones of the massif facies. They must have terminated south-westwards rather abruptly against a low slope of Threaplands Limestone.

The Tufa Beds have a distribution very like that of the Porcellanous Beds, but they are missing at Swinden quarry. This non-sequence may be due to a gentle movement of uplift along the Swinden anticlinal axis. A similar minor break is known in the Craven Lowlands in the middle of the D_1 subzone. The lithology indicates a persistence of lagoonal conditions, but a greater part of the reef fauna was able to establish itself. This takes place quite suddenly, at the horizon at which tufa becomes noticeable, and must indicate a change of some kind in the environment. The lithology indicates quiet, clear water, saturated with calcium salts, but the fauna contains many species which flourished even more success-fully in the rougher waters of the overlying *Cyrtina* Beds.

Goniatites occur in both these horizons, though somewhat rarely. It is difficult to account for their restricted distribution. Presumably they resembled the modern *Nautilus* in their mode of life, floating near the surface of the sea. In that case, it is hard to see why they are not found in the limestone of the massif facies, which is the lateral con-tinuation of the Cracoe reef limestone. They are found in the quiet lagoonal deposits of the Tufa Beds, in the grain-limestones, indicating rougher water, of the *Cyrtina* Beds, and in the crinoidal limestones of the *Michelinia–Emmonsia* Beds, and yet they have never been found beyond the limits of the reef belt. If they were bottom-living creatures this would be easily understood, but it is difficult to see why they were not occasionally drifted off-shore and preserved in the non-reef facies. The currents must have set perpetually along-shore or on-shore, although this seems improbable. Perhaps the shallow water was subjected to consider-able evaporation by hot sun, giving rise to a steady surface drift of water from the more open and deeper parts of the sea.

The gradual failure of the whole reef fauna takes place in the same north-easterly direction as the disappearance of tufa, and these beds pass laterally into unfossiliferous limestones of typical Rigid Block facies. The change takes place within the limits of the map. On the south side of Elbolton the Tufa Beds are typically developed, yet on the north bank of

the Wharfe at Lythe House they can no longer be recognized, either by their lithology or fauna.

The distribution of the *Cyrtina* Beds is practically the same as that of the underlying tufa and porcellanous limestones, but they overstep these for a short distance to the south-west. They are seen resting on the Threaplands Limestone Series in the entrance to Threaplands Cave, where their local base is pebbly. The change from lagoonal conditions (Tufa Beds) to the turbulent-water grain-limestones of the *Cyrtina* Beds is very marked, and allowed the full development of the reef fauna.

The lateral change from the grain-limestone with the abundant reef-facies fauna to the much less fossiliferous, buff, fragmental limestone with platy structure characteristic of the *Cyrtina* Beds of massif facies, takes place within the limits of the map. The exposures on the summit of Elbolton show a somewhat intermediate lithology. The fauna still includes B_2 goniatites and *Cyrtina septosa* has been collected with them. Going north-eastwards to the exposures on the southern bank of the Wharfe opposite Lythe House, the beds have lost the reef fauna, and the lithology is typical of the *Cyrtina* Beds. *Cyrtina* itself has not been found but *Chonetes comoides* has been collected from these exposures. Completely typical *Cyrtina* Beds, with *Chonetes comoides* and *Palaeosmilia murchisoni*, occur on the north bank of the Wharfe at Linton Tin Bridge, just on the upthrow side of the North Craven Fault. The band was recognized at this point by Garwood and Goodyear (1924).

The reef limestones belonging to the division mapped as *Cyrtina* Beds thus form a continuation of this well-known and widespread horizon, but are modified by reason of their marginal position. This modification was probably due to shallowing of the water, which allowed the abundant reef fauna to thrive, and numerically to swamp the normal fauna of the band. That this was able to survive is shown by the occurrence of *Cyrtina septosa*, *Chonetes comoides*, *Productus maximus* and *Palaeosmilia murchisoni* var. in association with the reef forms, though the abundance of the latter tends to cause them to be overlooked. Nevertheless, *Cyrtina septosa* has been found as far south-west as exposure 64a, which is almost on the south-western limit of the area in which the beds are found.

The distribution of the *Michelinia–Emmonsia* Beds shows a very significant change when compared with that of the underlying limestones. A horizon low down in these beds is the first that can be traced from the Craven Lowlands in the basin area of deposition, across the Cracoe reef belt, and into the massif area of sedimentation. Combined with the evidence of the depositional limits of the underlying limestones (given above), this shows that direct connexion between basin and massif was established at the horizon of the lower part of the *Michelinia–Emmonsia* Beds. Tiddeman's Breccia forms a valuable local marker in establishing this conclusion. It is seen in Clints quarry and, in a much thinner but otherwise typical development, as far to the north-west as Threaplands Gill, where it can be seen in several exposures. It is accompanied by strongly crinoidal, rather dark, well-bedded limestones, carrying *Emmonsia* and *Michelinia*. It was in these exposures that its position in relation to the *Cyrtina* Beds was determined. Farther to the north-east, the beds are seen between Stebden and Butterhaw, where they lie in a syncline. Tiddeman's Breccia has not been found, having probably thinned out and disappeared. *Michelinia* survives, but *Emmonsia* has gone. The same condition is found in these beds where they occur on Swinden Knoll to the north-west (i.e. along the strike of the reef belt). The beds are again seen

on Elbolton, where *Michelinia* is very rare, but the lithology is typical. Here they contain the well-known *Goniatites crenistria–Beyrichoceratoides truncatum* band of P_{1a} age.   *Beyrichoceratoides truncatum* has also been found on the north slope of Langerton Hill (near Far Langerton House). The beds are not seen again, in a north-easterly traverse, until the River Wharfe is reached near Hebden suspension bridge (just north of the quarry containing the telephone exchange on the Burnsall road), where they are less crinoidal and darker in colour.   They contain the *Girvanella* Band, which crosses the Wharfe at this point.   Thus, although the horizon of the *Michelinia–Emmonsia* Beds can be traced right across the area, it passes laterally into the Lower *Lonsdaleia* Beds of the Rigid Block type of sedimentation.   In doing so, various features characteristic of the basin facies gradually fail (Tiddeman's Breccia, *Michelinia–Emmonsia* fauna), being replaced by a facies typical of the reef belt (*crenistria-truncatum* band) which in turn gives way to a facies typical of the massif area (*Girvanella* Band), the belts being parallel, and striking with the remainder of the reef belt north-west and south-east.   These three well-known bands are not quite on the same horizon, but they all occur within the limits of these beds, which are only some 50 feet thick.

The whole of the Cracoe reef belt can, therefore, be considered as the direct continuation and marginal modification of the Great Scar Limestone of the same age, as developed on the Rigid Block.

These facies changes are indicated in Fig. 3 in a series of vertical sections taken across the reef belt.

V. CORRELATION BETWEEN THE CORAL–BRACHIOPOD ZONES AND THE GONIATITE SUCCESSION

The correlation value of the majority of the fossils from the Cracoe reef belt is very low indeed.   The fauna is phasal, and liable to occur at almost any horizon in the Lower Carboniferous where suitable bathymetric conditions prevailed.   Thus, many species found by Parkinson (1926) in the Clitheroe knolls of C age are found with little or no modification in the D_1 reef limestones of Cracoe.   In addition, however, to these facies forms, rare examples of fossils of diagnostic value occur, by means of which correlation of the Cracoe limestones with the standard coral–brachiopod succession is established.   The age of each fauna recorded has already been discussed in describing the stratigraphy.

The band characterized by *Cyrtina septosa* has been shown by Garwood and Goodyear (1924) to have a wide distribution on the Rigid Block.   It forms a well-marked and easily mapped horizon in the middle D_1 subzone. It is some 30 feet thick, and has the following characteristics fossils : *Davidsonina (Cyrtina) septosa, Chonetes comoides, Productus maximus* and *Palaeosmilia murchisoni*.   All these forms are found sparingly in the Cracoe reef belt, associated with the fauna from quarry A at Swinden. Quite apart from field evidence, therefore, it is possible to correlate this horizon and its fauna of phasal reef forms with the *Cyrtina* Beds of the massif.

This conclusion can be checked by reference to the *Girvanella* Band, used by Garwood and Goodyear to define the junction of D_1 and D_2 subzones on the massif.   This band occurs at two places in the area under discussion. It crosses the Wharfe at Hebden suspension bridge, where it can be shown to overlie the beds mapped as *Cyrtina* Beds in a quarry on the Burnsall road.   The *Girvanella* Band also occurs near Catchall Corner on Swinden

Knoll, in beds referred to the lower part of the Skelterton Series. This confirms the position of the reef fauna of Swinden quarry as middle D_1 and therefore equivalent to the *Cyrtina* Beds of the massif.

The correlation of goniatite and coral–brachiopod zones has been dealt with outside the Cracoe area by Shirley and Horsfield (1940) in Derbyshire and by Parkinson (1935, 1943) in Derbyshire and other areas; these authors reached conflicting conclusions. The Cracoe goniatite assemblages have been discussed by Hudson (1930A, 1938) and Hudson and Cotton (1945), whose results support Parkinson's correlation. A note was contributed to the discussion of Shirley and Horsfield's paper by the present author (Bond 1942) stating his own main conclusion on this point.

The following succession of faunas is given by Hudson and Cotton (1945, p. 301).

F.   *Bt.*[1] *truncatum, G. crenistria, Nm. germanicum*
E.   *B. micronotum, B. rectangularum, G.* aff. *crenistria, G. maximus* var.
D.   *B. castletonense, B. delicatum, G. crenistria* group early form, *G. maximus* var. *b*
C.   *B.* aff. *delicatum, B. phillipsi, G. maximus* var. *b, Sg. discus*
B.   *B. micronotoides, B.* aff. *vesiculiferum, G. hudsoni, Pr.* aff. *discoides*
A.   *B.* aff. *phillipsi, B. submicronotum, B. vesiculiferum, G. maximus, Pr. discoides, Sg. discus*

[1] Abbreviations: *Bt., Beyrichoceratoides; G., Goniatites; Sg., Sagittoceras; B., Beyrichoceras; Pr., Prolecanites; Nm., Nomismoceras.*

These faunas are given in stratigraphical order, "though it is not possible . . . to confirm such a succession by demonstrating its occurrence in a number of more or less continuous sections" (op. cit. p. 301). They are grouped as follows :—

F,   lower pert of P_{1a}
CDE, upper B_2 (*B. delicatum*) $\{$ Zone of *G.*
AB,   lower B_2 (*B. vesiculiferum*) $\{$ *maximus* (s.1.)

From the data given by Hudson and Cotton it is possible to pin-point their goniatite localities on the author's six-inch maps. By this means their relative stratigraphical positions, and hence the positions of these goniatite assemblages in the coral–brachiopod zonal succession, have been determined.

In the following table the goniatite assemblages of Hudson and Cotton are given, with the present author's locality numbers and their stratigraphical position in the local subzones.

LOCALITY	ASSEMBLAGE	FAUNA	STRATIGRAPHICAL POSITION IN LOCAL SUBDIVISIONS
29	*B.* aff. *delicatum* *B. phillipsi* *G. maximus* var. *b* *Sg. discus*	C	Base of *Cyrtina* Beds
91, 92	*B.* aff. *delicatum* *B.* cf. *phillipsi* *Pr. discoides*	C	Top of Tufa Beds
94	*G. hudsoni* *G. antiquatus*	Allied to B	Lower part of Tufa Beds
32 or 38	*B. vesiculiferum* *B.* cf. *micronotoides* *G. maximus* *Pr. discoides* *Sg. discus*	A	Base of Tufa Beds or at the top of Porcellanous Beds

LOCALITY	ASSEMBLAGE	FAUNA	STRATIGRAPHICAL POSITION IN LOCAL SUBDIVISIONS
103	B. micronotum B. rectangularum G. maximus	E	Cyrtina Beds
51	B. castletonense	D	Base of Cyrtina Beds
	B. micronotum B. rectangularum G. aff. crenistria G. maximus	E	Well above base of Cyrtina Beds
South quarry Swinden	G. maximus B. vesiculiferum	A	Position discussed below
	B. micronotoides B. aff. vesiculiferum G. hudsoni	B	

Goniatites have been collected from the following additional localities by the author. Their full determinations are not yet to hand, but preliminary determinations are given.

90, 105	Bt. truncatum		
90	G. crenistria	Michelinia – Emmonsia Beds; includes fauna F	Zone of G. crenistria (P₁ₐ)
104	G. maximus		
82	G. sp.		

90, 105   Bt. truncatum
90   G. crenistria   } Michelinia – Emmonsia Beds; includes fauna F } Zone of G. crenistria (P$_{1a}$)
104   G. maximus
82   G. sp.

95   B. rectangularum
95   B. castletonense (group)
83   *B. cf. micronotum
95   B. phillipsi
41, 29   G. sp.   } Cyrtina Beds; includes faunas E, D, C
1, 64a   G. maximus
A   *G. maximus-wedberensis (group)
83   *G. cf. wedberensis   } Zone of G. maximus (s. l.) (B$_2$)

15   B. castletonense
15, 94   B. cf. micronotum
94, 102   B. cf. phillipsi
102   B. cf. vesiculiferum   } Tufa Beds; includes fauna A
56, ? 81,
85, 106 } G. maximus

*Nm. vittigerum

* Indentified by W. S. Bisat

The position of faunas A and B as recorded by Hudson and Cotton from Swinden south quarry cannot be ascertained directly; the main face is made up largely of Porcellanous Beds, with a thin capping of the Cyrtina Beds. The Tufa Beds are missing, but there are indications that they occur in the cutting leading from the working floor to the rubble tip at the extreme end. The matrix containing the specimens of fauna B was stated to be " very tufaceous "; they probably came from the horizon of the Tufa Beds. The specimens referred to fauna A cannot be placed accurately. Possibly they came from near the summit of the main face : that is, near the top of the Porcellanous Beds.

The evidence collected above shows that the stratigraphical position and order of occurrences of these goniatite faunas are substantially as given by Hudson and Cotton, except that possibly C and D occur on

practically the same horizon. Furthermore, it shows that faunas A–E occur within a narrow vertical range, and well below fauna F.

The rarity of goniatites in the exposures in Swinden quarries appears to be due to the absence of the Tufa Beds over most of Swinden Knoll, and it is possible that the lowest few feet of the *Cyrtina* Beds, containing faunas C and D, are also absent.

The following table summarizes the correlation of the goniatite assemblages with the local subdivisions, and with the zonal succession of the Lower Carboniferous rocks of the Rigid Block area.

GONIATITE ZONES	GONIATITE FAUNAS	LOCAL ZONES	CORAL–BRACHIOPOD ZONES
Lower P_{1a}	F	Upper part of the *Michelinia– Emmonsia* Beds	Upper D_1
Lower B_2	B A	Tufa Beds Tufa Beds or top of Porcellanous Beds	Top of lower D_1
Upper B_2	E D C	*Cyrtina* Beds	*Cyrtina* Beds

VI. THE TECTONIC STRUCTURE OF THE CRACOE REEF-KNOLLS

The present structures in the area are mainly due to the post-D_2–pre-Bowland Shale movements : that is, to the Sudetian 1 period of folding. Before giving a description of the structures three points must be mentioned.

(1) The limestones of the knolls (Elbolton Series and *Michelinia–Emmonsia* Beds) are remarkably free from interbedded shale, not even a thin parting being seen in the face of Swinden quarry. There was, therefore, an absence of any lubricating material between the bedding-planes.

(2) The folding must have taken place under very light cover. It is shown below that the chief period of folding occurred in the interval between D_2 and the lowest Bowland Shale horizon to be deposited (P_{1b}). Assuming that a maximum thickness of 200 feet of D_2 limestone was deposited, it follows that the *Cyrtina* Beds were only buried to a depth of some 300 feet when folding took place, and lower beds proportionately deeper.

(3) Movements acted upon a wedge-shaped series of rocks, which were thick on the north-east and thinned quickly south-westwards.

The combination of the first two of these factors has resulted in rather severe shattering of the rocks and the partial obliteration of bedding-planes, since there were no shale partings which could lubricate them, and low superincumbent load allowed upward relief of pressure. Shattering is thus more severe than would normally have resulted from movements of this intensity.

Digressing for a moment to discuss the Skipton anticline, it may be said that if the Cracoe rocks had contained as much argillaceous material as the limestones forming the anticline of Haw Bank, there would probably have been no controversy over the tectonics of the knolls region. Conversely, if Haw Bank had been of the extremely pure limestone found at Swinden quarry in the knolls, it would have resembled the typical Cracoe reef-knolls in structure.

The third factor, the rapid lateral change in thickness of the knoll limestones, has produced a marked effect upon the degree of folding. Where the series is thick, as at Elbolton and Thorpe Kail, the folding is quite gentle, without violent crumpling; where it is thicker still, as in Dibb Beck, the pre-Namurian folding is even less intense, and is difficult to prove.   On the other hand, where the series is thin, as in Threaplands Gill, the folding is steepest, and subsidiary crumples on the southern limb are plainly visible.

The above evidence shows that the folding was not of a deep-seated origin ; that it was rather in the nature of sliding of surface layers (the knoll series of limestone) over a rigid basement (the Lower Palaeozoic rocks).   The pressure acted from the south, and crushed the rocks against a northern horst.   The acute anticlines separated by broad synclines, as between Langerton and Swinden, would be typical of such a *décollement*.

The structure is essentially a continuation of the Hetton anticline, which breaks up, on entering the area of the knolls, into a series of anticlines and synclines in echelon, trending approximately east-north-east and west-south-west.

The axis of one of these anticlines runs north-east through Swinden Knoll and another passes east-north-east through a line joining Skelterton Hill and Butterhaw Knoll.   This knoll forms the core of the anticline, and owes its shape in part to this structure.

The anticline forming the long knoll of Swinden is of a simple, nearly symmetrical form, pitching north-east.   It is broken by a fault smash between the north-eastern end of the quarry and Catchall Corner.   This results in the preservation of a down-faulted wedge of *Michelinia–Emmonsia* Beds.   The limestone disappears north-east of Catchall railway-cutting, where it pitches under Bowland Shales.

The fold passing through Butterhaw Knoll is a more complex structure and has a number of subsidiary folds on its flanks.   The ridge on which Langerton House stands is one of them, being a comparatively gentle symmetrical anticline separated from Butterhaw by a shallow syncline.

In Threaplands Gill (south of the road to Thorpe) two anticlines with steep limbs can be seen, separated by a steep-limbed syncline.   These structures were noted by Wilmore (1910), and appear to branch off the anticlinal axis which passes just north of the face of Skelterton Hill. They have not been traced farther than the fault east of Carden Hill.

An anticlinal axis passes between Elbolton and Thorpe Kail.   This is a gentle flexure, pitching north-east, and it can be traced to the Wharfe near Hebden suspension bridge.   A similar fold can be picked up on the other side of the Wharfe (which here follows the line of the North Craven Fault), passing just south-east of Lythe House and disappearing north-eastwards under Bowland Shales.

South of Thorpe Kail, Byra Bank exposes another gentle anticline, which crosses the Wharfe between Loup Scar and Wilfred Scar, and swings eastward to cross the River Dibb, where it brings up an inlier of S_2 limestone. Another gentle fold breaks off this, and swings east-south-east through Hartlington Hall and passes just north of Hartlington Kail.

Thus none of these anticlines can be traced very far.   The fold pattern (Fig. 4) shows a series of axes arranged in echelon, all trending north-east or east-north-east and tending to swing round to the east as they approach the Rigid Block, their intensity decreasing very markedly in this direction, which is also the direction in which the limestone series thickens.   The folds are cut by cross-faults approximately at right angles to the fold axis,

and it is noticeable that a fold often fails to cross a fault.   The majority of
these faults, including the complex ones which cut Elbolton and Thorpe
Kail, are of pre-Bowland Shale age, as may be seen from the map.

The faults probably have a marked lateral component, but can only be
shown to displace one axis.   This can be seen where the anticline lying
between Elbolton and Thorpe Kail crosses the River Wharfe.   It is cut
by a branch of the North Craven Fault (a post-Millstone Grit fracture),
and appears to be displaced to the north-west, appearing on the other side
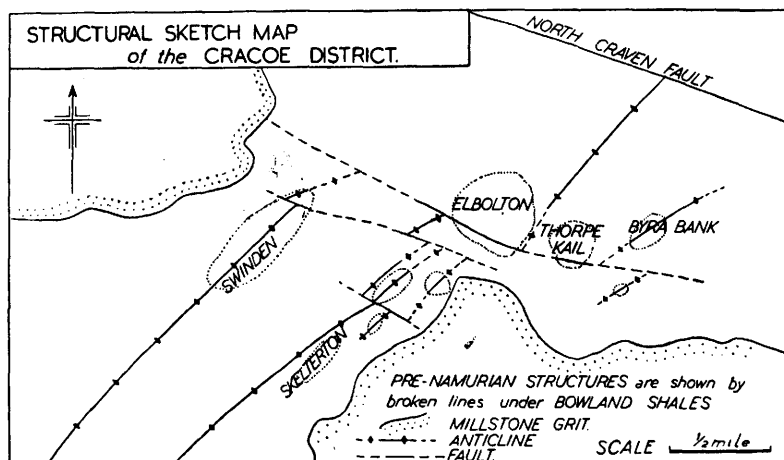as the axis passing near Lythe House.

Fɪɢ. 4.—The pre-Namurian fold and fault pattern in the Cracoe knolls area,
showing the principal reef-knolls and the North Craven Fault, a post-Namurian
fracture.   The structures are shown as though the cover of Bowland Shales had been
removed.

A peculiar structure affects the limestone of Stebden Knoll and Carden
Hill.   The strata on the north face of Stebden belongs to the *Michelinia–
Emmonsia* Beds, overlying the *Cyrtina septosa* Beds and dipping 45°–50°
NW., that is, more steeply than the slope of the hill.   They can be seen
round the base of the knoll.   The higher parts of the knoll are poorly
exposed, but show dips to the south, and the limestone appears to belong
to the lower part of D_1.   It seems that these lower limestones have reached
their present position by a reversed fault, developed from the fracture of a
limb of one of the smaller anticlines.   The limestone near the line of this
supposed dislocation has been greatly altered.   A small thickness has
been converted into a rock composed of quartz and fluorite.   In origin
and appearance this rock resembles that described by Arnold-Bemrose
(1898) from Derbyshire.   Such rocks are, however, rare in Yorkshire.

The same kind of structure is held to account for the occurrence of
southerly dipping beds, apparently of upper D_1 age and including Tidde-
man's Breccia, on the summit of Carden Hill, where they seem to overlie a
sharp fold in *Michelinia–Emmonsia* Beds.

This dislocation, like many of the faults in the limestone series, is of
pre-Bowland Shale age, since the shales are entirely unaffected.

VII. THE PRE-NAMURIAN UNCONFORMITY AND TOPOGRAPHY

The relationship between the limestone series and the Bowland Shales has been shown by Hudson (1932) to be an unconformity. The detailed zonal mapping of the shales by Black (1940) and of the limestone series presented here, allows the extent and nature of the unconformity to be more clearly defined. This shows that the Bowland Shales overstep various members of the limestone series, begin at different horizon themselves, and are unaffected by folds and faults found in the limestones.

The following examples will make the extent of the break apparent.

In the hollow between Elbolton and Thorpe Kail, which forms the course of Thorpe Beck, Bowland Shales of lower E_1 age extend downstream to the village. They are horizontally bedded and undisturbed by the faults that cut the south-west corner of Elbolton and reappear from under the shales to cut the southern face of Thorpe Kail. Since these faults do not cut the shales they must be pre-Namurian in age. The shales rest on a low horizon in D_1 in this stream section, and pass on to successively higher D_1 horizons south of Elbolton Knoll.

At Stebden, E_1 shales completely encircle the knoll and are entirely unaffected by the structures which can be made out in the limestone of the knoll. In Waterspout Beck, P_2 horizons are present between the limestones and E_1 shales, showing that the shales do not commence everywhere at the same horizon. The limestone–shale junction, though sinuous, is quite unaffected by the numerous faults that cut the limestone, none of which can be found in Millstone Grit or Bowland Shales. The fold axes traceable in the limestones do not appear in the Bowland Shales, in which the dips are largely due to compaction on their uneven floor.

An appearance of conformity can be seen in the section exposed in Skelterton Beck, where the upper part of the limestone series seems to underlie the calcareous lower Bowland Shales conformably. But in all other sections, though the actual contact is seldom exposed, the overlap of different shale horizons on to different limestone horizons shows that there is strong unconformity, due to pre-Namurian folding, faulting and erosion.

The knolls themselves were moulded to much their present shape by pre-Namurian erosion. Thus, Stebden stands up almost to the heights of the basal Millstone Grit and must have formed a considerable elevation in the floor of the Bowland Shale sea. Butterhaw, Elbolton, Thorpe Kail, and all the smaller knolls must have formed hills in much the same way. The depression between Swinden and Butterhaw is now floored mainly by drift, but Bowland Shales are exposed in several places on the slopes leading down from Langerton and Threaplands, showing that they are probably present below the drift. Wherever the slope of the limestone surface covered by shale is gentle, the shales form a feather edge, yet in the hollows the shales bank up steeply against the limestone surface. The steep southern face of Elbolton must have formed an imposing cliff, against which the Bowland Shales were deposited.

In Badger Beck (loc. 85), south-west of Thorpe village, there is a small, dome-shaped inlier of white limestone. The dips show that it is the crest of an anticline. Some 20–30 feet of limestone is exposed. The fauna and lithology is that of the Tufa Beds. Goniatites of the *Beyrichoceras* zone have been found in it, and it cannot belong to the Bowland Shales, which completely encircle it. It appears to show an early stage in the excavation of a buried knoll. An even earlier stage of the process was suspected as

long ago as 1899 by Dakyns, who found swallow-holes in Millstone Grit on the summit of Simonseat, a few miles to the south-east, but lying on the general line of the reef belt.   This can best be explained by the nearness to the surface of a large mass of limestone, presumably a buried knoll.   A much smaller mass of limestone, in Waterspout Gill, seems to be completely enveloped in shale and to be no more than a large boulder of reef limestone, derived by erosion and incorporated in the shales.   The limestone conglomerates found in the Bowland Shales near upstanding masses of limestone, as in Starton Beck at the foot of Thorpe Kail, are to be similarly explained.   The boulders are stained black by the shales, but yield a typical " reef-knoll " fauna.

In terms of the zonal scheme, there is little time between the deposition of the topmost limestones of the knolls, which are referred to P_{1a}, and the lowest horizon of the Bowland Shales, which is referred by Black (1940) to P_{1b}.   In this interval, folding and faulting occurred.   Erosion, which took place along the faults crossing the fold axes, blocked out the ground-plan of the knolls.   Their conical shapes were accentuated as the shales were deposited, the bases being protected by shale from further attack while the summits were still subject to erosion.   The topography of the knolls is young in aspect, many of the ridges owing their shape to their anticlinal structure, the hollows between being the sites of synclines.   Finally, the deposition of muddy sediment drowned the entire topography, which was preserved with little disturbance by later earth-movements until the removal of the shales began.   This is now proceeding, and re-exposing the buried pre-Namurian topography.

VIII. List of Works to which Reference is made

ANDERSON, F. W.   1928.   The Lower Carboniferous of the Skyreholme anticline, Yorkshire.   *Geol. Mag.* 1928, p. 518.

ARNOLD-BEMROSE, H. H.   1898.   On a quartz-rock in the Carboniferous Limestone of Derbyshire.   *Q.J.G.S.* liv, p. 169.

BISAT, W. S.   1928.   The Carboniferous goniatite zones of England and their Continental equivalents.   *Congrés de Stratigraphie Carbonifère, Heerlen,* 1927, p. 117.

BLACK, W. W.   1940.   The Bowland Shales from Thorlby to Burnsall, Yorkshire.   *Trans. Leeds Geol. Assoc.* v, p. 308.

BOND, G.   1942.   Discussion on Shirley & Horsfield's paper on the Castleton–Bradwell area.   *Q.J.G.S.* xcvii (for 1941), p. 180.

BOOKER, K. M., & R. G. S. HUDSON.   1926.   The Carboniferous sequence of the Craven Lowlands south of the reef limestones of Cracoe.   *Proc. Yorks. Geol. Soc.* xx, p. 411.

CHUBB, L. J., & R. G. S. HUDSON.   1925.   The nature of the junction between the Lower Carboniferous and the Millstone Grit of North-West Yorkshire.   *Proc. Yorks. Geol. Soc.* xx, p. 257.

DAKYNS, J. R.   1899.   The limestone-knolls below Skipton and Grassington in Craven.   *Q.J.G.S.* lv, p. 359.

DIXON, E. E. L., & A. VAUGHAN.   1911.   The Carboniferous succession in Gower (Glamorganshire), with notes on its fauna and conditions of deposition.   *Q.J.G.S.* lxvii, p. 477.
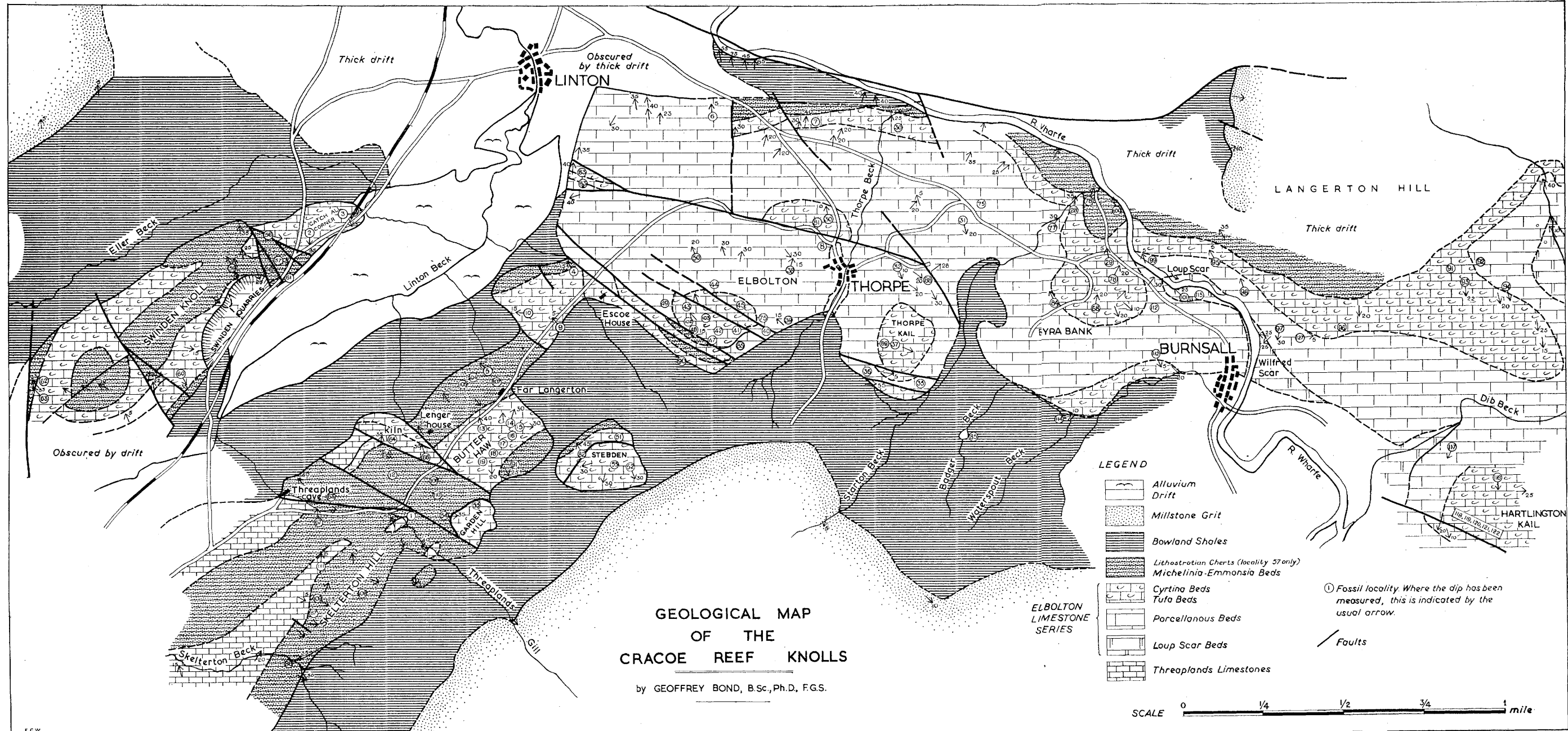
GARWOOD, E. J., & E. GOODYEAR. 1924. The Lower Carboniferous succession of the Settle district and along the line of the Craven Faults. *Q.J.G.S.* lxxx, p. 184.

HUDSON, R. G. S. 1927. The Cracoe knolls. *Brit. Assoc. Excursion Handbook, Leeds*, p. 15.

——. 1930A. The Carboniferous of the Craven Reef Belt : the Namurian unconformity at Scaleber, near Settle. *Proc. Geol. Assoc.* xli, p. 290.

——. 1930B. The age of the " *Lithostrotion arachnoideum* " fauna of the Craven Lowlands. *Proc. Leeds Phil. & Lit. Soc. Sci. Sect.* ii, p. 95.

——. 1932. The pre-Namurian knoll topography of Derbyshire and Yorkshire. *Trans. Leeds Geol. Assoc.* v, pp. 49–64.

—— & G. COTTON. 1945. The Lower Carboniferous in a boring at Alport, Derbyshire. *Proc. Yorks. Geol. Soc.* xxv, p. 254.

—— & H. V. DUNNINGTON. 1945. The Carboniferous rocks of the Swinden anticline, Yorkshire. *Proc. Geol. Assoc.* lv, p. 195.

—— & G. H. MITCHELL. 1937. The Carboniferous geology of the Skipton anticline. *Summ. Progr. Geol. Surv. for* 1935, pt. 2, p. 1.

—— & J. S. TURNER. 1933. Early and mid-Carboniferous earth movements in Great Britain. *Proc. Leeds Phil. & Lit. Soc. Sci. Sect.* ii, p. 455.

—— & OTHERS. 1938. The geology of the country around Harrogate. *Proc. Geol. Assoc.* xlix, p. 293.

JESSOP, P. 1931. Agate, and the cherts of Derbyshire. *Proc. Geol. Assoc.* xlii, p. 29.

MARR, J. E. 1899. On limestone-knolls in the Craven district of Yorkshire and elsewhere. *Q.J.G.S.* lv, p. 327.

PARKINSON, D. 1926. The faunal succession in the Carboniferous Limestone and Bowland Shales at Clitheroe and Pendle Hill (Lancashire). *Q.J.G.S.* lxxxii, p. 188.

——. 1935. The upper limit of the *Beyrichoceras* zone in the Pendle Hill area. *Proc. Yorks. Geol. Soc.* xxiii, p. 25.

——. 1943. The age of the reef-limestones in the Lower Carboniferous of North Derbyshire. *Geol. Mag.* lxxx, p. 121.

——. 1947. The Lower Carboniferous of the Castleton district, Derbyshire. *Proc. Yorks. Geol. Soc.* xxvii, p. 99.

SHIRLEY, J., & E. L. HORSFIELD. 1940. The Carboniferous Limestone of the Castleton–Bradwell area, North Derbyshire. *Q.J.G.S.* xcvi, p. 271.

TIDDEMAN, R. H. 1900. On the formation of reef knolls. *Rep. Brit. Assoc. Bradford,* p. 740; republished in *Geol. Mag.* 1901, p. 20.

VAUGHAN, A. 1916. The knoll region of Clitheroe, Bowland and Craven. *Proc. Yorks. Geol. Soc.* xix, p. 41.

WAGER, L. R. 1931. Jointing in the Great Scar Limestone of Craven and its relation to the tectonics of the area. *Q.J.G.S.* lxxxvii, p. 392.

WILMORE, A. 1910. On the Carboniferous Limestone south of the Craven Fault (Grassington-Hellifield district). *Q.J.G.S.* lxvi, p. 539.

WOOD, A. 1941. " Algal Dust " and the finer-grained varieties of Carboniferous Limestone. *Geol. Mag.* lxxviii, p. 192.

EXPLANATION OF PLATE VII

Geological map of the Cracoe area of Yorkshire.   Scale : 3 inches to 1 mile.

DISCUSSION

Dr. R. G. S. HUDSON congratulated the author on the completion of a first-class piece of work, especially valuable since the lithological and faunal succession which he had erected for the marginal facies of the Middle Viséan could now be used to elucidate the structure of other areas of the Craven reef belt. He agreed with the author's demonstration of the equivalence of the upper *Beyrichoceras* (B_2) and lower *Dibunophyllum* (D_1) zones and suggested that the goniatite zonal indices (B_1 and B_2) might now be abandoned and the coral–brachiopod indices used instead. Mr. Bond's confirmation of the speaker's theory of the pre-Namurian origin of the knoll topography was pleasing, as was his factual

LINTON

Obscured by thick drift

Thick drift

Thick drift

LANGERTON HILL

Thick drift

R. Wharfe

ELBOLTON

THORPE

Thorpe Beck

THORPE KAIL

Loup Scar

EYRA BANK

BURNSALL

Wilfred Scar

Eller Beck

CATCH ALL CORNER

SWINDEN KNOLL

SWINDEN QUARRIES

Linton Beck

Escoe House

Far Langerton

Langer house

Kiln

BUTTER HAW

Threaplands Cave

GARDEN HILL

STEBDEN

Threaplands Gill

SKELTERTON HILL

Skelterton Beck

Obscured by drift

Station Beck

Badger Beck

Waterspout Beck

R. Wharfe

Dib Beck

HARTLINGTON KAIL

ELBOLTON LIMESTONE SERIES

LEGEND

Alluvium
Drift

Millstone Grit

Bowland Shales

Lithostrotian Cherts (locality 57 only)
Michelinia-Emmonsia Beds

Cyrtina Beds
Tufa Beds

Porcellanous Beds

Loup Scar Beds

Threaplands Limestones

① Fossil locality. Where the dip has been measured, this is indicated by the usual arrow.

Faults

GEOLOGICAL MAP
OF THE
CRACOE REEF KNOLLS

by GEOFFREY BOND, B.Sc., Ph.D., F.G.S.

SCALE

0   ¼   ½   ¾   1 mile

E.C.W.

demonstration of the pre-Namurian faulting and folding in the area. He thought, however, that the origin of these folds was much more complex than the explanation given by the author.

Dr. Hudson could not agree with Mr. Bond's suggestion that the shell-reef facies of the Middle Viséan was deposited in an area divided from the main Craven basin by a " low ridge ". He regretted that he might have contributed to such a suggestion by postulating a condensed succession in the Middle Viséan at Rylstone immediately south of the shell-reef sedimentation, since recent work in that area had shown that that suggestion of a mid-Viséan uplift was an error. The shell-reef sedimentation was surely one of open sea on the upper part of a submarine slope between basin and massif, though it was possible that contemporaneous uplift had contributed towards the formation of that slope.

Dr. Hudson also disagreed with the author's tentative suggestion that the complex of faults passing through Elbolton represented the continuation of the mid-Craven Fault of the Malham area. The throw of these faults, their mineralization, the lack of a fault-scarp and their discontinuity were at variance with the comparable features of the mid-Craven Fault. He rather thought, as he had suggested elsewhere, that in the Grassington–Greenhow area the fault complex known as the North Craven Fault was the expression not only of post-Namurian movement but also of an earlier pre-Namurian movement continuing that of the mid-Craven Fault of Settle and Malham.

Dr. K. C. DUNHAM congratulated the author upon his demonstration that lithological units could be mapped within the Cracoe " reef-knolls ". The abandonment of Tiddeman's interpretation and the return to that of Marr, that the form of the knolls was, at least in part, of tectonic origin, brought these features into line with the domes along the crest of the nearby Greenhow anticline, which were comparable in scale with the " reef-knolls ", but composed of rocks belonging definitely to the massif facies. If quaquaversal dips and knoll form were no longer to be regarded as characteristics of reef limestone, how did the author define this type of limestone? Could it be regarded as having distinctive petrographical characters? Was tufa a necessary ingredient? Did the definition require the presence of some abundant, distinctive fauna?

At Greenhow Hill folding of both pre-Namurian and post-Namurian age had occurred, but Mr. Bond had made a good case for restricting the Cracoe movements to pre-Namurian age. Mineralization was present in both areas; did the mineral veins in the Cracoe knolls follow the fault-lines mapped by Mr. Bond?

Dr. J. SHIRLEY was interested in the correlation between the goniatite and the coral–brachiopod zones since he and Mr. Horsfield had suggested a different correlation in North Derbyshire. He noted with interest the approach to a compromise in equating B_2 with upper D_1 and asked if the author was convinced that *Cyrtina septosa* really occurred with B_2 goniatites, having regard to the difficulty of separating contemporaneous fossils from those contained in derived blocks when the whole consisted of limestone.

Dr. E. E. L. DIXON drew attention to the occurrence at Linney Head, in the southernmost outcrop of the Carboniferous Limestone of Pembrokeshire, of a mass of white limestone, near calcite-mudstone, with traces of bryozoa in position of growth, which, though wholly enclosed in dark, evenly bedded, highly fossiliferous zaphrentid-phase limestones, had a

pronounced lenticular form and evidently rose as a distinct elevation on the floor of the Avonian sea. In this respect it confirmed the essential part of Tiddeman's view of the Cracoe knolls, though their form had evidently, from the author's observations, been emphasized by earth-movement. In being also essentially a bryozoan reef the Pembrokeshire mass accorded with Delépine's conception of some at least of the Waulsortian reefs.

Mr. J. E. PRENTICE sent the following written contribution :—

"The structural features of the area described by Mr. Bond bear a remarkable resemblance to those of the Manifold valley in North Stafford-shire, which lies on the western margin of the 'Rigid Block' of the Derby-shire massif. Here, the folding is mainly post-Namurian in age; the effects are similar, however—the thin-bedded limestones are highly folded, whilst the reef limestones are hardly folded at all. There is intense faulting between the reef limestones and their bedded equivalents; and it can be demonstrated that the faulting is nearly always associated with the zone of passage—i.e. in an area where highly competent beds give place to those which possess a lesser resistance. Might this not be the case at Cracoe? In other words, is it not possible that the fault pattern has been superimposed upon an original knoll-reef structure? Mr. Bond has supplied a timely caution against invoking 'original deposition' as the explanation of all the many problems of the reefs; but more evidence will be needed before Tiddeman's theory can be completely discarded."

Dr. G. MITCHELL also spoke.

The AUTHOR, in reply to Dr. Dunham, said that it was impossible to define reef limestone concisely. There were many ways in which lime-stones which had been called "reef" had accumulated. He was trying to work out a system of nomenclature which would keep the lithological and structural aspects separate.

In the Cracoe district the mineral veins followed the pre-Namurian faults in general, but mineralization also occurred in branches of the North Craven Fault complex.

In his contribution to the discussion on the paper by Dr. Shirley and Mr. Horsfield he had suggested a possible reason for the discrepancy between the goniatite–coral-brachiopod correlations in Derbyshire and Yorkshire. In the Cracoe district it seemed beyond dispute that B_2 goniatites did occur in limestones which also contained rare examples of *Cyrtina septosa*, and there seemed no possibility that the latter were derived fossils, or that the goniatites occurred in the matrix and *Cyrtina* in derived blocks.

He welcomed Dr. Dixon's contribution as it showed how very complex the problems of reef limestone were. The scale of Dr. Dixon's example was much smaller than the knolls at Cracoe, and seemed much more like structures found recently by Dr. Black in the Middle Limestone of Grassing-ton. Bryozoa were apparently absent or very rare in the porcellanous limestone at Cracoe, and the speaker could not agree that the example cited by Dr. Dixon confirmed Tiddeman's view of the Cracoe knolls, but it certainly showed that the true Tiddeman reef-knolls did occur in the Lower Carboniferous.

In reply to Mr. Prentice, the author said that marginal zones such as Cracoe and the Manifold valley must be particularly sensitive to tectonic disturbance of this kind since the sedimentation was dependent to some extent upon the underlying floor, these limestones occurring only in the zone between a basin and a rigid block. This being so, it was impossible

to generalize at this stage, before the details of each area had been fully worked out.

Dr. Hudson had raised two important points. The suggested low ridge against which the reef sediments seemed to have been deposited was only a suggestion which the mapping of the local subdivisions brought out. Even if an actual emergence did not take place, shallowing certainly did.

The second point, the position of the mid-Craven Fault, was by no means settled. The only faults which could represent this within the area were those cutting Elbolton and Thorpe Kail. The suggestion that the North Craven Fault was here a renewal of movement along the mid-Craven Fault line would go far to clearing up the point, and the author welcomed it.

He thanked Dr. Mitchell for his encouraging remarks. The map he had made and the details of the distribution of fauna and lithology shown on it could not be regarded as a final answer to all the problems of this complex area, but would, he hoped, serve as a basis on which further work could be carried out. Without detailed mapping no theories of the origin of these knolls could be regarded as finally proved.

The following contribution was received from Dr. D. PARKINSON after the meeting :—

" I wish to extend my congratulations to Mr. Bond on his work in the Cracoe area. I am in general agreement with his main conclusions.

" On reading the account of the discussion on Mr. Bond's paper I felt rather disturbed at the scant recognition which seemed to have been given by some of the speakers to the value of Tiddeman's pioneer work on the problem of the origin of reef-knolls. To judge from the general trend of the discussion one would imagine we are now well on the way to discarding Tiddeman's original deposition theory in favour of the alternative tectonic hypothesis of Marr. I was glad to note, however, that Mr. Bond accepted Dr. Dixon's example from Pembroke as a true reef-knoll in Tiddeman's sense.

" After 27 years of work in the Lower Carboniferous of Lancashire, Yorkshire, Derbyshire and Staffordshire I still feel convinced of the essential truth of Tiddeman's explanation as forming a basis for a satisfactory theory of the origin of many of the larger as well as the smaller masses of reef limestone. There are different types of reef-knoll, and it is true that the Cracoe reefs, in common with others of mid-Viséan age elsewhere, are not discrete accumulations as envisaged by Tiddeman; but surely an important, if not the most important, aspect of Tiddeman's work was his recognition of these structures as *reefs*, of whatever kind. That fact is not now in dispute, and it is therefore unfortunate, and likely to give a wrong impression to those unfamiliar with the problem, that Marr's views should be brought forward as having more significance than those of Tiddeman, presumably because the reef limestones are associated with fault and fold movements. It would indeed be surprising if it were otherwise.

" Tiddeman's views were based not only on the Cracoe reefs but also on those of Clitheroe and Bowland, and I have at various times submitted evidence attempting to show that the latter structures conform in their essentials to his explanation of their origin. Recent work in the Dovedale area has shown that the reefs of the C zone resemble those of similar age at Clitheroe, while those of D_1 age are in general, though not invariably, of Cracoe type.

" I can confirm Mr. Prentice's observations that the reef limestones on

the western margin of the Derbyshire massif are much less folded than their bedded equivalents, but in Dovedale the passage from one type to the other is not usually accompanied by faulting.

" Finally, I must express my satisfaction that Mr. Bond has correlated the B_2 zone with upper D_1. I agree with him and with Dr. Hudson that there is no possibility that the D_1 brachiopods and corals in the B_2 reef limestones are derived. In the Dovedale area a similar association of B_2 goniatites and D_1 corals is occasionally found in the rocks of basin facies as well as in the reef limestones."

The Author replies as follows :—

" I agree that an important aspect of Tiddeman's work was his recognition of the Cracoe and other structures as ' reefs ', although the choice of the term was not altogether happy. I share Dr. Parkinson's admiration for his pioneer work, which I should not like to appear to belittle. Although Marr recognized various tectonic features in the Cracoe district he seems to have ignored the faunal and lithological peculiarities of these limestones. In the brief introduction to the paper I have endeavoured to hold the balance between their conflicting views. It is gratifying to find that the correlation of B_2 and D_1 is confirmed by Dr. Parkinson's researches in the Dovedale area, and particularly interesting to hear that B_2 goniatites are sometimes found with D_1 corals in rocks of the basin facies."