THE

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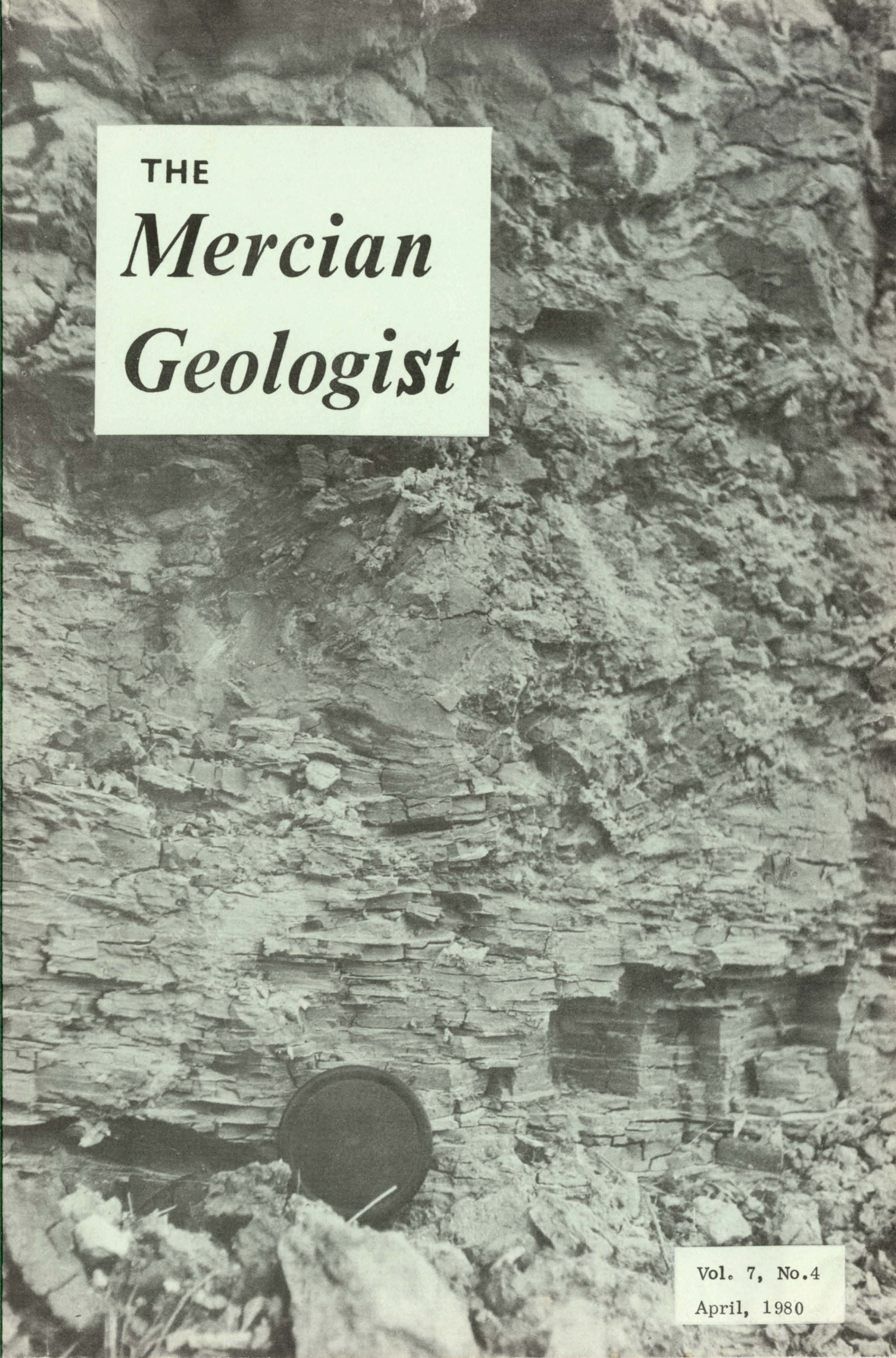

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EAST MIDLANDS GEOLOGICAL SOCIETY

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Address for Correspondence,

General information, membership details:

The Secretary,
East Midlands Geological Society,
311 Mansfield Road,
Redhill,
Arnold,
Nottingham

Tel. No. (0602) 267442

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Front Cover: Sequence of siltstones, Chilcompton Railway Cutting. See Plate 24, fig. B.

THE UPPER TRIASSIC SECTION AT CHILCOMPTON, SOMERSET, WITH NOTES ON THE RHAETIC OF THE MENDIPS IN GENERAL

by

Christopher J. Duffin

Summary

The temporary section at Chilcompton, Somerset, exposing rocks of Norian and Rhaetic age, is described and interpreted in terms of cyclic sedimentation. The Westbury Beds vertebrate fauna, which is dominated by hybodont selachians, appears to be replaced by a dominantly palaeoniscid fauna in the Cotham Beds. It is possible to correlate the cycles of sedimentation described for Chilcompton with those in sections in other parts of the Mendip area, and even further afield. In the Mendip Hills, the Westbury Beds typically contain two cycles, as do the Cotham Beds and succeeding Langport Beds. The bone-beds at the base of cycles Wb 1 and Cb 1, the mudcrack horizon at the base of Cb 2 and the contorted bed at the top of Cb 1 are particularly useful in regional correlation.

Introduction

The Chilcompton railway cutting was situated 300 m. to the east of Chilcompton village, in Somerset (ST 653523). The rocks exposed in the cutting were briefly mentioned by Woodward (1876, p.79) and Savage (1962, p.278); the former author examined the section shortly after its opening. Richardson (1911, p.66) later examined the section in more detail. The cutting quickly became overgrown, and after closure of the line, permission was granted to Clutton Rural District Council to utilise the site as a rubbish tip. It is now completely filled in.

The section comprises Triassic deposits from the Keuper to the White Lias and was one of the few exposures of these beds in the Mendip area. It was therefore decided to examine the section, prior to infill, by means of digging trenches down the cutting sides at regular intervals. More recently, the cutting sides were mechanically scraped to provide topsoil for covering successive layers of rubbish and a clean section was temporarily available for study. Sykes (1977) also examined this section, but his measurements differ considerably in certain cases to those given here (see table 1). Sykes' (pers. comm.) measurements were based on a single visit to the section made during the early stages of the mechanical scraping. The measurements given here were made over a period of time and result from the collation of data from trenches, scraped sections, and general observation of the cutting as a whole. This series of measurements revealed some degree of variability of individual units when traced along the length of the cutting.

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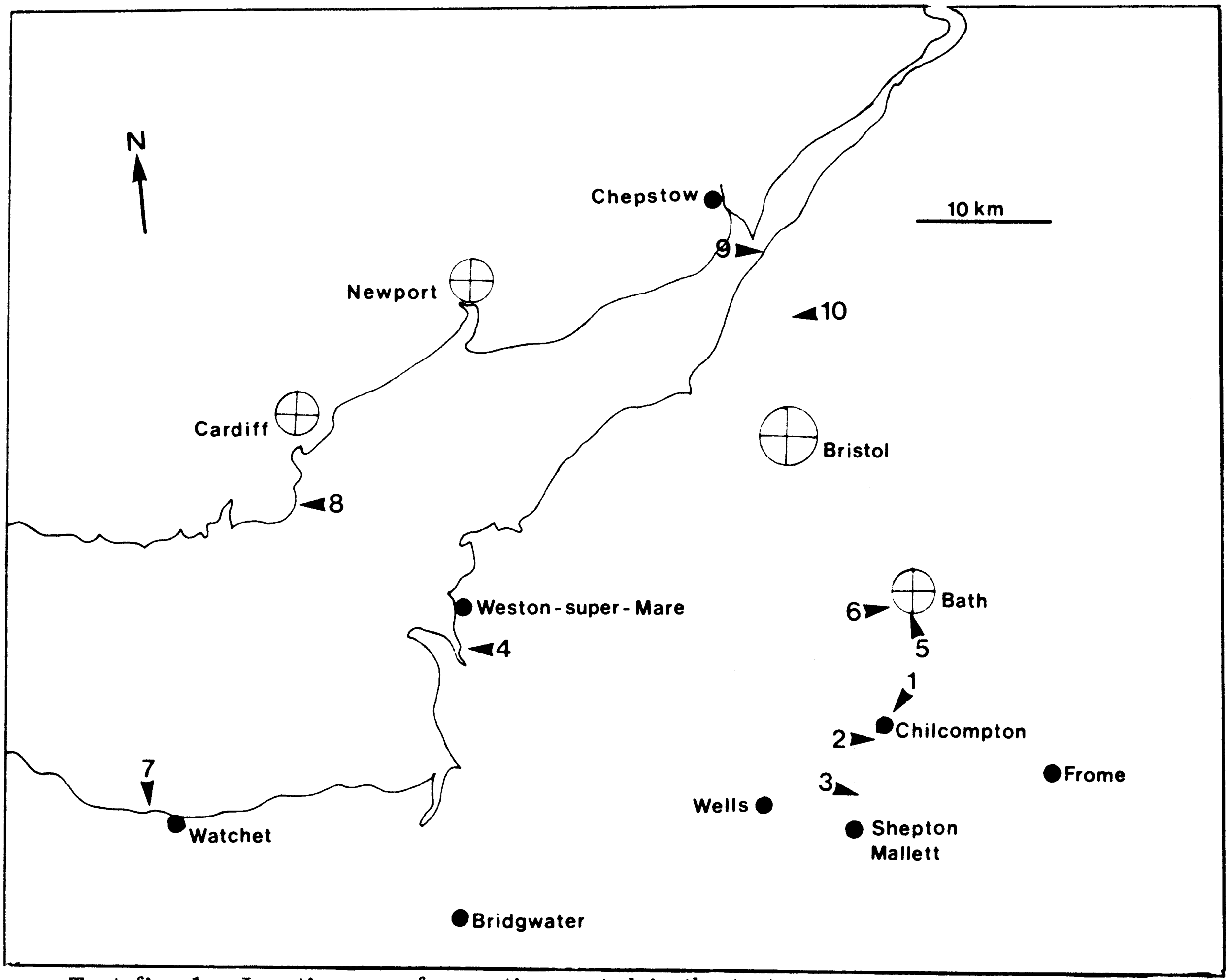
pp.251-268, 2 text-figs., plate 24.

Table 1. Comparison of data and correlation of lithological units of various measured sections at Chilcompton.
a - convention used in this paper;
b - data from Richardson 1911, p.66;
c - data from Sykes 1977, p.221.

a.			b.		c.	
Cycle	Unit	Thickness	Bed No.	Thickness	Bed	Thickness
Lb 2.	d	0.13 m.	Beds recorded as present, but out of correct sequence.		not recorded	
	c	0.13				
	b	0.19				
	a	0.14-0.36				
Lb 1.	b	0.12-0.25		Total 0.94 m	not recorded	
	a	0.1 -0.19				
Cb 2.	d	0.1 -0.13	present	0.125	not recorded	
	c	0 -0.2	1	0.175		
	b	0.4 -0.9				
	a	0.19-0.38	2(?)	0.76		
Cb 1.	b	0.62			light grey marl	0.12 m
	a	0.1 -0.16	3	0.1	grey marls + limestones	0.5
Wb 2.	b	1.4 -2.0	4-6	1.22	black shales	2.075
	a	0.2 -0.24	7	0.075	limestones + mudstone	0.125
Wb 1.	b	1.1 -1.17	?8-14	0.915	shale	0.7
	a	0 -0.025	15	0.025	Bone-bed	0.025
Tea Green Marl		3.6		3.66	not recorded	

The floor of the cutting was about 20 m wide, and the sides 7 m high at the point of greatest depth during the early stages of rubbish accumulation. The exposure was oriented north east - south west, and measured vertical sections were taken along some 200 metres, on both sides of the cutting. The strata displayed a northerly dip of 3° and less.

The geographical location of the section and its relation to other Rhaetic sections in the West Country is given in text-fig. 1. Text-fig. 2 is the tabulated sequence.



Text-fig. 1: Location map for sections noted in the text.
1, Chilcompton railway cutting; 2, Old Down; 3, Three Arch Bridge; 4, Uphill; 5, Newbridge Hill; 6, Kelston Station; 7, Blue Anchor Point; 8, Penarth; 9, Aust Cliff; 10, Filton By-Pass.

Stratigraphy

Keuper Marls

The red Keuper Marls which were just visible in the floor of the south side of the cutting gave way upwards to at least 3.5 m of Tea Green Marls. The unfossiliferous Tea Green Marls comprised hard, sandy limestones alternating with shaley marls. The topmost bed of this unit was a grey/green stiff clay, 0.13 to 0.15 m thick. The Keuper Marls showed no evidence of trace fossils or evaporites.

Rhaetic : Westbury Beds

The base of the Westbury Beds was marked by a calcareous sandy bone-bed, 0 to 25 mm thick. The bone-bed was not ubiquitous in the cutting at this level, but was best exposed at the southern end. It displayed a ripple-marked upper surface, and in places filled hollows on the surface of the Tea Green Marl. Sole markings and sporadic burrows were present on the undersurface of the bone-bed, which was well sorted, medium-grained, and had a high ratio of vertebrate remains to other clastics. Some fragments and fossils derived from the Carboniferous Limestone were present. An unusual feature was the presence of large numbers of idiomorphic quartz crystals (some bipyramidal) measuring up to 2 mm in length. Kent (1970, p.365) has recognised similar crystals of localised development, and believes them to be authigenic. Antia (1979, p.146) considers overgrowths of crypto-crystalline silica on quartz crystals to be important in considering bone-bed origins, and figures silica plastering on quartz grains from the Rhaetic Beds of Blue Anchor Point, Somerset (Antia, 1979, pl.18, fig.h). In the basal bone-bed of Chilcompton, quartz crystals of purely clastic origin were fairly well rounded.

Directly overlying the bone-bed was a series of laminated black shales, 1.1 to 1.17 m thick, yielding a fairly rich fauna of typical lower Rhaetic invertebrates, and a rather sparse vertebrate fauna. The vertebrates occurred sporadically throughout these shales, whereas the tendency of the invertebrate fauna was to be located in pockets. The valves of bivalve molluscs were found in the stable position (convex surface upward) and disarticulated, although usually entire. They were occasionally found in the unstable position, and representatives of a single size and species were often concentrated together. These invertebrate remains were mostly represented by internal casts, but occasional specimens with a representation of the original shell material have been collected.

The laminated black shales were overlain by a 200 to 240 mm thick sandy limestone with shale partings. These lithologies were very poor in fossils, but badly preserved trace fossils (*Ophiomorpha* and *Rhizocorallium*) have been found.

This unit was succeeded by a thick (1.4 to 2 m) sequence of non-laminated black shales, with occasional sandstone lenses and with a somewhat richer vertebrate fauna than the underlying laminated shale, but with a less well-preserved invertebrate fauna. The shales appeared to show poorly-defined cross-bedding in places, an unusual feature.

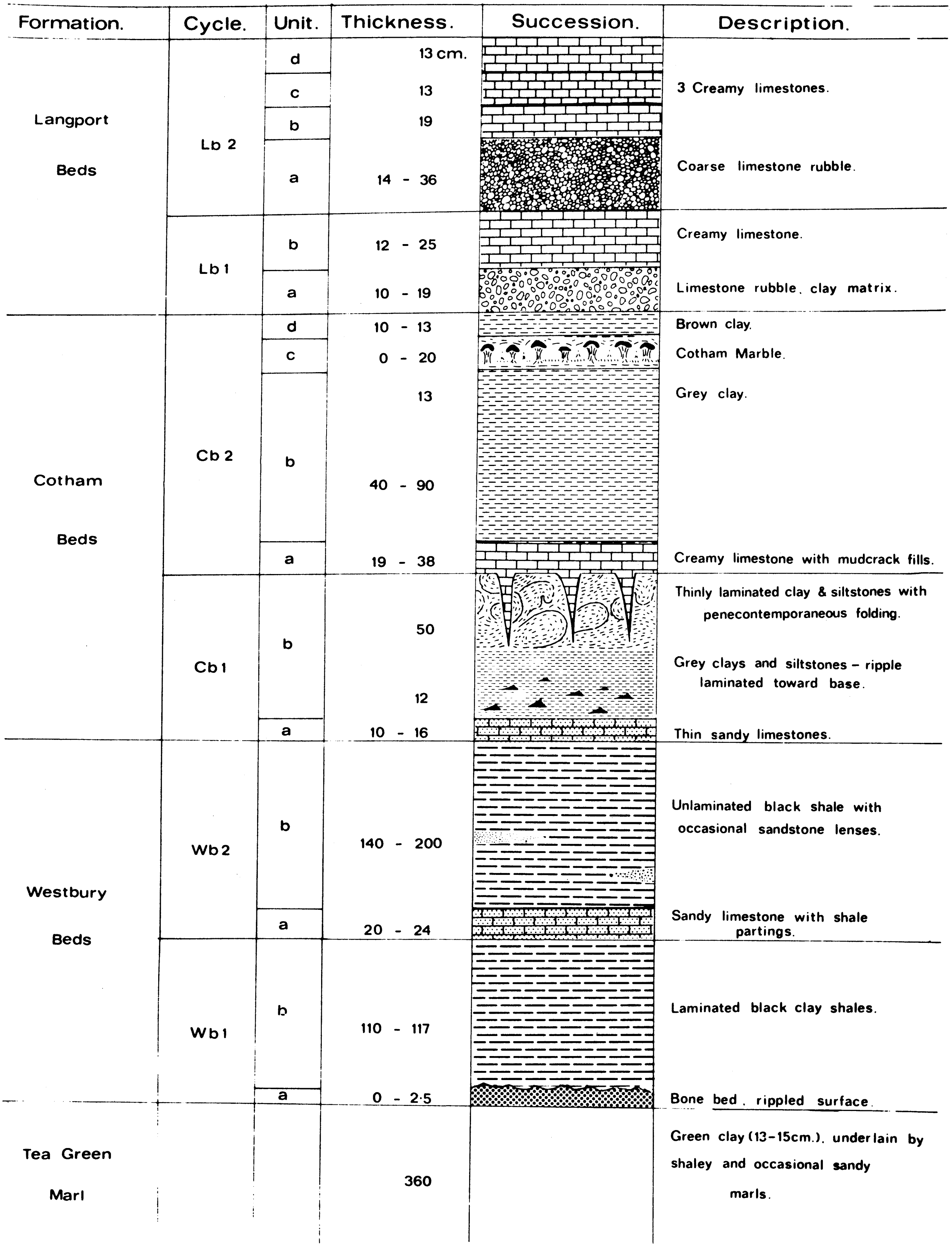
Cotham Beds

The base of the Cotham Beds is usually defined as the level at which the predominantly black shale sequence of the Westbury Beds gives way upwards to a more calcareous series of rocks which are lighter in colour; they usually comprise grey, greenish or creamy marls, mudstones or siltstones (cf. Hamilton, 1962; Savage, 1962; Kellaway & Oakley, 1934, for reference to local sections, and Ivimey-Cook, 1975, for sections in South Wales). With reference to the procedure in earlier works, the junction between the Westbury and Cotham Beds at Chilcompton was placed at the very top of the non-laminated black shales (text-fig.2).

The non-laminated shales were overlain by 100 mm to 160 mm of thinly bedded sandy limestones, with occasional black shale or stiff black clay lenses. Invertebrate remains were uncommon in this unit, the top of which was marked by a thin, locally fissile, calcareous sandstone with a very rich vertebrate fauna and invertebrate fauna.

Above this bed, the sequence continued with 620 mm of thinly laminated grey marls and limestones, with ripple lenticles of calcareous sandstone occurring near the base. The top 100 mm or so of the grey marls exhibited a marked reduction in the number of lenticles, and there was evidence of penecontemporaneous deformation.

The next unit was a 190 mm to 380 mm thick, apparently unfossiliferous creamy limestone with calcite cement. The crude bedding of this unit was distorted, although to a lesser extent than that exhibited by the underlying lithology. The most prominent feature of this horizon was the preservation of large mudcracks, which extend downwards into the grey marls beneath. The mudcracks were deep (200 mm to 250 mm on average) and taper downwards to a fine point (pl.24, fig.d). They were spaced horizontally at fairly regular intervals (220 mm apart on average). The grey marls immediately underlying and adjacent to the mudcracks were usually soft and clayey with a brown colouring, presumably a weathering effect. In places the contorted bedding of the grey marls appeared to pass through the mudcracks, although the substance of the latter was consistently a hard, fairly massive limestone. A series of horizontal shrinkage cracks was usually located in and directly above the mudcracks. The shrinkage cracks extended vertically through the thickness of the bed above the mudcracks. In some cases, the lines of shrinkage cracks tended to deviate from the vertical, and in these instances the sense of the deviation was towards the north east in all of the examples found. The shrinkage cracks themselves were almost always filled with calcite and occasional lines of them occurred where there was no mudcrack. Sporadic examples of vertical shrinkage cracks have been seen in this lithology.



Formation.	Cycle.	Unit.	Thickness.	Succession.	Description.
Langport Beds	Lb 2	d	13 cm.		3 Creamy limestones.
		c	13		
		b	19		
		a	14 - 36		Coarse limestone rubble.
	Lb 1	b	12 - 25		Creamy limestone.
		a	10 - 19		Limestone rubble, clay matrix.
Cotham Beds	Cb 2	d	10 - 13		Brown clay.
		c	0 - 20		Cotham Marble.
		b	13 40 - 90		Grey clay.
		a	19 - 38		Creamy limestone with mudcrack fills.
	Cb 1	b	50		Thinly laminated clay & siltstones with penecontemporaneous folding.
			12		Grey clays and siltstones – ripple laminated toward base.
		a	10 - 16		Thin sandy limestones.
Westbury Beds	Wb 2	b	140 - 200		Unlaminated black shale with occasional sandstone lenses.
		a	20 - 24		Sandy limestone with shale partings.
	Wb 1	b	110 - 117		Laminated black clay shales.
		a	0 - 2·5		Bone bed, rippled surface.
Tea Green Marl			360		Green clay (13-15cm.), underlain by shaley and occasional sandy marls.

Text-fig. 2: The Rhaetic succession of Chilcompton railway cutting.

Above the creamy limestone a 400 mm to 900 mm thick grey clay unit was found, with occasional sandy limestones and siltstones. Towards the top of the sequence, siltstones became less common, and the lithology graded into a brown clay, 130 mm thick. The fossil content of this clay was poor, although a thin layer of well preserved invertebrate remains was found near the top.

Next in the sequence came the Cotham Marble, which was very variable in thickness, ranging from 0 to at least 200 mm thick within a distance of less than 5 m along the cutting face. The upper surface was usually mammillated, the individual protuberances on the upper surface of the bed being greatly pronounced in the thicker portions of the bed, elongate, and often oriented. The various features of the Cotham Marble have been shown to be algal in origin for the 'landscape type', and of sedimentary origin for the 'crazy Cotham type' (Hamilton, 1961). Examples of double landscape features (one landscape feature overlain by another within the same bedded unit) have been found at this locality. Thinly bedded mudstones showing sporadic evidence of small-scale channelling were common at this level. No mudstone flakes were preserved within the channels. The impression was obtained, however, that the mudstones were lateral equivalents of the landscape Cotham Marble, although the precise field relationships of the two lithologies was difficult to judge because of the state of the section at the time of examination. No fossils have been found in the Cotham Marble at this locality.

Langport Beds

The Langport Beds comprise a number of beds of limestone of rather uniform thickness. The basal bed was a rubbly limestone, 100 mm to 190 mm thick, with interstitial clay and abundant invertebrate remains. It was overlain by a 120 mm to 250 mm thick creamy limestone, again rich in invertebrates. A second rubbly limestone bed with fairly numerous specimens of *Ophiomorpha* and invertebrates followed, measuring 140 mm to 360 mm thick. The remainder of the Langport Beds comprised three well-bedded limestones, 190 mm, 130 mm, and 130 mm thick respectively, veined with calcite and devoid of fossils.

Discussion of the stratigraphy

Sedimentary cycles, defined by repetitions of lithological types, or the recurrence of specific sets of sedimentological conditions throughout a succession of beds, were apparent in the Chilcompton section. The concept of cyclicity in the Rhaetic sequence has been previously considered by Ivimey-Cook (1962, 1974), who related sedimentary cycles to faunal composition and diversity in the Penarth area (near Cardiff), and also by Hamilton (1962, 1977) in describing the rocks exposed in the construction of the Filton By-Pass Substitute, and those exposed in the cliff section at Aust, Avon. Hallam (1969, p.159) considered that the entire Rhaetic sequence was itself a cyclothem, while Hamilton (1962, p.285) made the interesting comment that in this case, the lithological sequence of individual cycles within the Rhaetic is the reverse of that of Hallam's Rhaetic cyclothem. Cyclicity may prove a useful tool in the correlation of Rhaetic sediments over a limited geographical area, since it must reflect local variation in either tectonic or climatic control of sedimentation. The cycles observed in the Rhaetic sediments at Chilcompton relate primarily to the energy conditions prevalent at the time of deposition, as reflected in a repetition of certain lithological types.

Two cycles were recognised in the Westbury Beds at Chilcompton. Cycle 1 (Wb 1) has the well sorted bone-bed at its base (text-fig. 2), and is completed by the overlying laminated black shales. The sandy limestone with shale partings marks a return to rather higher energy conditions, and forms the base of cycle 2 (Wb 2). The remainder of this cycle comprises the overlying non-laminated black shales, the absence of laminations possibly suggesting that energy conditions were greater for the deposition of this lithology than for the shales of Wb 1.

Cycle 3 (Cb 1) deposition opens with a thin sandy limestone overlain by a mudstone sequence with ripple laminations at the base (plate 24, fig.B), and gradually decreasing in incidence through the unit. This gradual reduction records the change from an initial higher energy depositional phase toward quiet water deposition with little clastic influence. The penecontemporaneous folding at the top of this cycle (plate 24, fig.B) marks an isolated interference with the quiet water sedimentation, perhaps related to tectonic activity.

Cotham Bed deposition continues after a period of subaerial exposure, as evidenced by the presence of large mudcracks at the base of the 4th cycle (Cb 2) (plate 24, figs.A,D). The basal creamy limestone is overlain by a grey clay, which is followed by the Cotham Marble. The 'landscape type' of development of this lithology can be interpreted as representing low energy, extremely shallow water conditions (Hamilton, 1961). In contrast, the 'crazy Cotham' development represents high energy conditions. At Chilcompton, the Cotham Marble horizon appears to be composed entirely of low energy components - 'landscape' marble and well bedded mudstones. For this reason, it is probably best to consider that this horizon, plus the overlying brown clay, represent the closing stages of Cb 2.

The Langport Beds displayed well developed cycles of rubbly limestone and well bedded limestone layers. Two cycles of this type are discernible in the Langport Beds at Chilcompton (Lb 1, Lb 2).

Discussion of the palaeontology

As much collecting of palaeontological material was made as time would allow, but because of the progress of the tipping, the Upper Rhaetic succession was best sampled. The distribution of fossils throughout the Chilcompton Rhaetic section is shown in Table 2, p.258.

Invertebrates

Invertebrate remains were totally lacking from the basal bone-bed (Wb 1) of Chilcompton. This is not always the case at other localities of Rhaetic age.

The black shales of Wb 1 yielded a reasonably good invertebrate fauna comprising *Rhaetavicula contorta* (Portlock), *Protocardia rhaetica* (Mérian), *Palaeocardita cloacina* (Quenstedt), *Eotrapezium* sp. and ? *Placunopsis alpina* (Winkler). This assemblage differs somewhat from the shales of Wb 2, from which *Rhaetavicula contorta*, *Palaeocardita cloacina*, *Eotrapezium concentricus* (Moore), *Plicatula intusstriata* Emmrich and ? *Modiolus hillanus* (J. Sowerby), were obtained. The basal limestone of Wb 2, which separates these two shale members was devoid of fossils, with the exception of the trace fossils mentioned above.

The limestone at the base of Cb 1 showed a slight difference in the invertebrate fauna, as compared with beds lower in the sequence. *Protocardia rhaetica* and *Plicatula intusstriata* survive from the previous cycles, and valves of *Chlamys valoniensis* (Defrance), *Isocyprina ewaldi* Bornemann and internal casts of gastropods appear as new faunal elements. In the case of the latter, two species - *Promathilda nitida* (Moore) and *Cylindrites fusiformis* (Moore) - are represented in almost exactly equal proportions.

The occurrence of *Plicatula intusstriata* in the Westbury Beds is interesting. This small bivalve is often regarded as more typical of the Upper Rhaetic, but has been recorded in the Lower Rhaetic at various localities (Richardson, 1905). Michalik (1975) reports *Plicatula intusstriata* as epifaunal components on the valves of *Rhaetina gregaria* (Suess), a brachiopod typical of the European Upper Triassic. The valves found in the bone-bed at the base of Cb 1 and in the shales of Wb 2 are isolated, but others from the Langport Beds occur as epifaunal elements on larger bivalves. Such commensalism has not apparently been reported from other British Rhaetic localities.

The occurrence of echinoid spines at the base of Cb 1, and higher in the Cotham Beds is interesting. Very few echinoderms are reported from the British Rhaetic. Those recorded and described so far are all ophiuroids. The spines found at Chilcompton, and also retrieved by the present author from the Westbury Beds of Penarth, and the Holwell fissure fauna collected by Moore (now held in the Bath Geology Museum), belong to a regular echinoid.

Table 2. Distribution of vertebrate and invertebrate fossils in the Rhaetic section at Chilcompton

Unit	
Lb 2. b-d.	Rare *Ostrea liassica*.
Lb 2. a.	Bivalves - *Myloconcha psilonota*, *Chlamys valoniensis*; indeterminate gastropods; trace fossils - *Ophiomorpha*.
Lb 1. b.	Bivalves - *Modiola langportensis*, *M. laevis*, *Pseudomonotis fallax*, *Pleurophorus elongatus*, *Pleuromya* sp., *Protocardia phillipiana*, *Atreta intus-striata*; indeterminate gastropods; rare, indeterminate insects.
Lb 1. a.	Barren.
Cb. 2. d.	Bivalves - *Pseudomonotis* sp.
Cb 2. c.	Barren.
Cb 2. b.	Regular echinoid spines; indeterminate internal casts of gastropods.
Cb 2. a.	Barren.
Cb 1. b.	Ostracods - *Rhombocyethere penarthensis*.
Cb 1. a.	Bivalves - *Chlamys valoniensis*, *Isocyprina ewaldi*, *Protocardia rhaetica*, *Atreta intus-striata*; gastropods - *Promathilda nitida*, *Cylindrites fusiformis*; hybodont sharks - *Acrodus minimus*, *Polyacrodus* sp.; palaeoniscid chondrosteans - *Birgeria acuminata*, *Saurichthys longidens*, *Gyrolepis albertii*; holosteans - *Sargodon tomicus*; reptiles - *Ichthyosaurus* sp.; dermal denticles, euselachian vertebrae echinoid spines, coprolites.
Wb 2. b.	Palaeoniscid chondrosteans - *Saurichthys longidens*, *Gyrolepis albertii*, fin rays; rare plant remains.
Wb 2. a.	Badly preserved trace fossils - *Ophiomorpha*, *Rhizocorallium*.
Wb 1. b.	Palaeoniscid chondrostean - *Gyrolepis albertii*; bivalves - *Eotrapezium* sp., *Protocardia rhaetica*, *Rhaetavicula contorta*; fin rays, coprolites.
Wb 1. a.	Hybodonts - *Acrodus minimus*, *Hybodus minor*; euselachians - *Nemacanthus monilifer*; palaeoniscid chondrosteans - *Birgeria acuminata*, *Saurichthys longidens*, *Gyrolepis albertii*; holostean - *Sargodon tomicus*; reptile - *Rysosteus oweni*; dermal denticles, fin rays.
Tea Green Marl	Barren.

Ivimey-Cook (1962) reports that ostracods, when present in the Lower Rhaetic, are typical of cycle 3 in the Westbury Beds. *Rhombocyethere penarthensis* Anderson occurs in the grey siltstones of the Chilcompton succession (Wb 3), and is the definitive lower Rhaetic ostracod (Anderson, 1964).

The invertebrate remains of the lower Rhaetic appear, for the most part, to occur at definite levels in the sequence, and as such, appear to reflect specific communities, with little or no transport involved (i.e. autochthonous).

Apart from the echinoid spines and internal casts of gastropods found in the clay beneath the Cotham Marble, the Cotham Beds are relatively poor in fossil content. The only exception is a thin layer rich in *Pseudomonotis* sp. in the brown clay directly overlying the Cotham Marble.

In the Langport Beds, the lower rubbly bed is devoid of recognisable fossil remains. However, the succeeding limestone contains a rich invertebrate fauna comprising *Modiola langportensis* Richardson and Tutcher, *Modiola laevis*, *Pleuromya* sp., *Pseudomonotis fallax* Pflücker, *Pleurophorus elongatus* Moore, *Protocardia phillipiana* Dunker, *Plicatula intusstriata*, internal casts of gastropods, and sporadic indeterminate insect remains. The overlying well-bedded limestones yield only sporadic examples of *Ostrea liassica.*

Vertebrates

The vertebrate remains from the basal Rhaetic bone-bed at Chilcompton were highly fragmented, abraded and polished. Reif (1971) used density, fracture patterns and polish to determine that remains from the Muschelkalk bone-beds of Southern Germany were fossilised prior to their incorporation into those deposits. He termed these remains 'pre-fossilised' (cf. also Duffin & Gaździcki, 1977; Sykes, 1977). This interpretation has recently been challenged by Antia (1979, p.98 *et seq.*) who states that the criteria used by Reif are either unsatisfactory, or could be the products of diagenesis in all cases.

In the example of the Wb 1 bone-bed, the presence of idiomorphic quartz crystals may be used as evidence for typical diagenetic effects within a stabilised bone-bed deposit composed of vertebrate remains which are primary components of the sediment (Antia & Whitaker, 1978; Antia, 1979). On the other hand, the well sorted nature of sediment and the fact that it was laid down under relatively high energy conditions, opening a sedimentary cycle at the base of a sequence, which is discrete in terms of stratigraphy and environment of deposition, does not preclude the possibility that this bed may indeed be comprised of prefossilised vertebrate remains.

The vertebrate remains occurring in the bone-bed which sees the commencement of deposition of cycle Cb 1, however, although disarticulated, are beautifully preserved, and are thus less likely to have been reworked than those in the basal bone-bed of Wb 1.

The Wb 1 and Cb 1 bone-beds yielded good samples of vertebrate remains, from which a faunal comparison can be made. In order to facilitate this, 100 remains were identified and recorded from the residues of material broken down in 10% acetic acid, and graded through four sieve sizes (850, 600, 500 and 420 micromillimetres mesh sizes). This gave a total of 500 vertebrate fragments counted from each of the two horizons (see table 3).

Table 3. Frequency distribution of vertebrate remains in bone-bed deposits at the Rhaetic section of Chilcompton.

	Wb 1 basal bone-bed	Cb 1 bone-bed
Gyrolepis albertii Ag.	140	390
Hybodus minor Ag.	78	-
Acrodus minimus Ag.	200	5
Birgeria acuminata (Ag.)	25	34
Saurichthys longidens Ag.	51	70
Sargodon tomicus Plieninger	6	1

In the basal bone-bed (Wb 1) residues, the selachians *Acrodus minimus* Agassiz and *Hybodus minor* Agassiz together form almost three-fifths of the vertebrate remains. Scales and teeth of the palaeoniscid chondrosteans *Gyrolepis albertii* Agassiz are well represented, with *Birgeria acuminata* (Agassiz) and *Saurichthys longidens* Agassiz making a small contribution. The teeth of these latter three species have been greatly confused in the literature, but have been recognised as distinct from each other by Griffith (MS), Sykes, Cargill & Fryer (1970) and Duffin (1974). The teeth of the holostean *Sargodon tomicus* Plieninger are very subordinate faunal elements in this horizon. Other sporadically occurring remains from the basal bone-bed (Wb 1) include a single vertebral centrum of the archosaur *Rysosteus oweni* Owen (Duffin Collection, Bristol City Museum - the genus never yields fin spines, as reported by Antia, 1979, p.142), and a few examples of the fin spines of the selachian *Nemacanthus monilifer* Agassiz. Dermal denticles of placoid morphotype (cf. Reif, 1978; Sykes, 1974) are also present. Vertebrate coprolites (cf. Duffin 1979) also form a subordinate component of the fauna.

Selachian remains are virtually absent from the Cb 1 bone-bed residues. There is, however, a concomitant increase in the representation of the palaeoniscids, especially *Gyrolepis*; remains of *Sargodon tomicus* are once again very rare. No examples of *Rysosteus* or *Nemacanthus* were recovered from the Cb 1 bone-bed, but a single large limb bone of *Ichthyosaurus* sp. was identified (plate 24, fig.E). Dermal denticles from the Cb 1 bone-bed belong to the hybodontid and placoid morphotypes (Reif, 1978) and include several new forms which will be described elsewhere. Additional remains from the Cb 1 bone-bed include sporadic examples of a new hybodont shark, to be described elsewhere, and fragments of selachian prismatic cartilage (cf. Applegate, 1967).

It is possible that the faunal differences between the two bone-beds is an artifact of sampling, reflecting slightly differing depositional conditions. An alternative possibility is that the significant selachian population of the Wb 1 deposit was replaced by a palaeoniscid dominated community preserved in that of Cb 1. The present author is conducting a detailed investigation of Rhaetian vertebrate faunas in an attempt to resolve this problem.

Vertebrate remains were uncommon in the black shales of Wb 1 and Wb 2 cycles, comprising only sporadic palaeoniscid remains and coprolites. It is interesting to note that the faunal list made by Richardson (1911, p.66) does not include any Upper Rhaetic species (i.e. Cotham Beds), and only a few lower Rhaetic forms are recorded by that author from the basal bone-bed (Wb 1) and beds number 7 and 5b of his designation.

Palynology

A representative series of samples from various levels in the Chilcompton succession are being examined by Dr. G. Warrington for palynological content.

Regional Correlation

Many records of Rhaetic sections in the Radstock area were made at the turn of the century, during the construction of expanding road and rail networks. Until recently, the Chilcompton railway cutting was one of the few remaining Rhaetic sections available for study in the Mendip area, the others having become overgrown or lost in some way. Those sections which can be compared with Chilcompton vary in usefulness according to the method of measurement and presentation of data employed by the original researcher, but in some instances, correlation can be made between the cycles of deposition at Chilcompton and those at other localities.

(i) Old Down, Emborough (ST 626509)

A temporary exposure at this locality, 2.5 km west of Chilcompton (text-fig. 1), was reported by Savage (1962). Two cycles (Wb 1, Wb 2) are apparent in the Westbury Beds, two cycles (Cb 1, Cb 2) in the Cotham Beds, and a single cycle in the Langport Beds. At this locality, Wb 1 begins with a bone-bed, as at Chilcompton, although at Emborough this is succeeded by a thin calcareous sandstone, and is of greater thickness. The black shales overlying the sandstone contains intercalations of fine micaceous sandstones with ripple marks and trace fossils. A "beef" layer towards the top of this shale sequence is peculiar to the Old Down locality. A thin, yellow-brown decalcified sandstone with a rich bivalve fauna (moulds only) interrupts this shale sequence. Wb 1 deposition continues with further shales and subordinate sandstones. The Wb 2 cycle opens with the deposition of a hard calcareous shelly limestone, succeeded by black shales and mudstones. According to Savage, the next bed, a grey-white, thinly-bedded limestone (bed 10 of his designation), crowded with vertebrate fragments, marks the beginning of the deposition of the Cotham Beds. Bed 10 compares favourably with the bone-bed located at the base of Cb 1 at Chilcompton. Emphasising the probability of this correlation, the bed at Old Down is succeeded by a sequence of grey marls and limestones. The mudcracks characterising the horizon basal to Cb 2 at Chilcompton appear to be absent at Old Down. Instead, Cb 2 appears to begin with a 150 mm thick grey-white limestone (bed 12 of Savage's designation). Higher in cycle Cb 2 at Old Down, the Cotham Marble is noted by Savage as including the landscape type, some of the specimens found showing a double landscape feature, as is the case with certain specimens from Chilcompton. The Cotham Marble is succeeded by a yellow-brown clay. The Langport Beds have a fossiliferous rubbly limestone at their base, giving way upwards to bedded creamy limestones, as at Chilcompton.

In overall view, the Westbury Beds appear to be more arenaceous at Old Down than at Chilcompton (note the thick, coarse bone-bed, extra sandstone horizons, and apparently more frequent sandstones in the shale sequence at Old Down). This is reasonable, since the nearest land areas in Rhaetic times were closer to the Old Down cutting than to Chilcompton (cf. Emborough Quarry and Gurney Slade fissure deposits, Robinson, 1957).

(ii) Three-Arch Bridge, Shepton Mallett (ST 618446)

This section (text-fig. 1) (Richardson, 1911), 7.8 km south west of Chilcompton, also demonstrates the influence of a nearby land area on the nature of the Rhaetic deposits (cf. Windsor Hill fissure, Kühne, 1956). It is possible to see some similarity in cyclicity with Chilcompton, but it is difficult to correlate the two sections precisely. The sequence at Shepton Mallett (Wb 1) does not commence with a bone-bed, but with a series of shales and pyritised limestones (beds 8 to 15 of Richardson, 1911). These beds are here considered to represent cycle Wb 1 of Chilcompton. The probable equivalent of Wb 2 at Shepton Mallett begins with bed 7 of Richardson, a 100 mm thick limestone, overlain by black and occasionally marly shales. Next in the succession is what Richardson terms "Thin hard grey layers with many quartz grains and fish remains, passing down into a hard conglomeratic limestone with small pebbles of Carboniferous Limestone" (Richardson, 1911, p.60). This horizon is very reminiscent of the bone-bed which opens Cotham Beds deposition at Chilcompton, with which it is probably equivalent. The conglomeratic nature of the deposits at Shepton Mallett emphasises the intertidal nature of deposition, and the Carboniferous Limestone pebbles indicate the proximity of an area where active erosion was taking place.

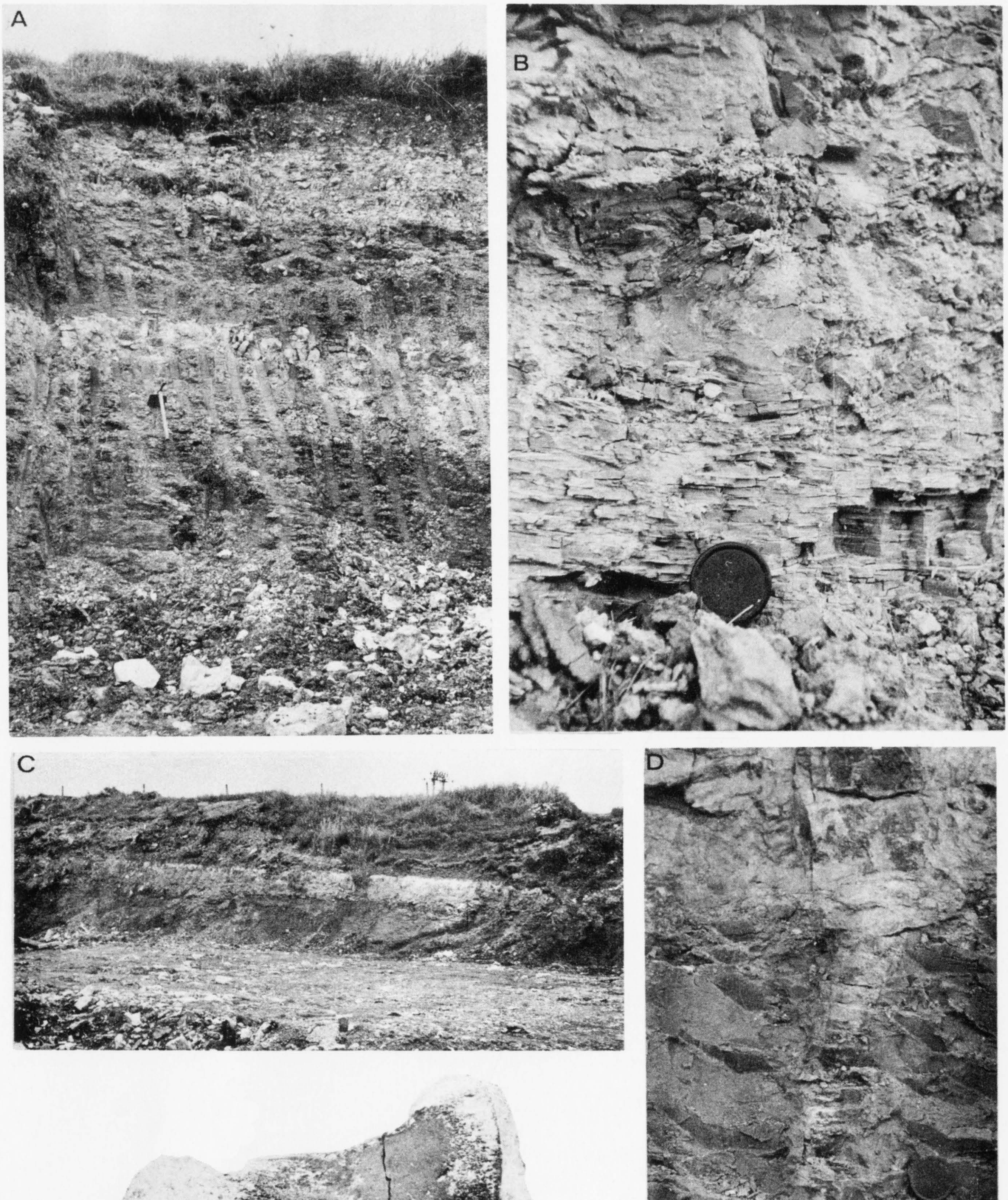
(iii) Uphill (ST 327583)

This cutting, 32 km west of Chilcompton (text-fig. 1) has received a good deal of attention in the literature (Wright, 1860; Moore, 1860; Woodward, 1870; Bristow & Etheridge, 1873; Sollas, 1880; Richardson, 1911; Kellaway & Oakley, 1934). The succession exposed at this locality has a closer affinity to those of the Blue Anchor to Lilstock coast section (north Somerset coast), and the Lavernock to Penarth coast section (South Wales), rather than to Rhaetic sections in the Mendips. This is highlighted by the presence beneath the Westbury Beds of Uphill and the coastal sections, of a series of Grey Marls (Sully Beds of

Explanation for Plate 24

Fig. A	Part of the Upper Rhaetic succession at Chilcompton railway cutting (north face).
Fig. B	The siltstones of cycle Cb 1, showing penecontemporaneous folding.
Fig. C	General view of the Rhaetic succession of the north face of Chilcompton railway cutting.
Fig. D	The junction of cycles Cb 1 and Cb 2, showing the development of a mudcrack descending into the contorted siltstones of Cb 1.
Fig. E	Ichthyosaur left humerus recovered from the Cb 1 bone-bed.

Plate 24



Richardson, 1911). Kellaway & Oakley (1934) take the base of the Westbury Beds as the base of the first series of black shales, which underlie a bone-bed. These shales could, however, represent a continuation of Grey Marl deposition, and the bone-bed itself may more reasonably be taken to represent the base of Wb 1, which is then followed by 2 m of black shales. Three cycles of deposition can be recognised in the Westbury Beds, the basal beds for each cycle being taken as the bone-bed mentioned above, the 'Lower Pecten Bed' and 'Upper Pecten Bed' for Wb 1, Wb 2 and Wb 3 respectively (thus comparing closely with the cliff section at Aust, Avon - ST 567895 - cf. Hamilton, 1977, p.116). The beginning of Cotham Bed deposition is marked by a colour change as the black shales of the Westbury Beds are succeeded by thinly-bedded marls and a limestone (Cb 1). Cb 2 begins with an 'argillaceous, sun-cracked deposit (Kellaway & Oakley, 1934, p.473), very reminiscent indeed of the mudcrack horizon opening Cb 2 deposition at Chilcompton, with which it is almost certainly equivalent. The Cotham Marble equivalent is fairly confidently identified as Bed 19 of Kellaway & Oakley, and the overlying brown calcareous clay-shale is similar to that overlying the Cotham Marble at Chilcompton.

(iv) Newbridge Hill, Bath (ST 718658)

This section (Winwood 1871; text-fig. 1) compares very well with that of Chilcompton, even though Newbridge Hill is situated 14.9 km north of Chilcompton. Wb 1 opens with a basal bone-bed, followed by a sequence of grey shales. The shales are overlain by a 'Marlstone' band (Winwood, 1871), which is here interpreted as the base of Cb 1. If this interpretation is correct, Wb 2 of Chilcompton is missing from the sequence at Newbridge Hill. According to Winwood, the marlstone band contains fish remains, an observation which might strengthen correlation of this bed with the bone-bed at the base of Cb 1 at Chilcompton. Cb 2 deposition began with a thin limestone, succeeded by further grey shales, directly overlain by the Cotham Marble. The Cotham Marble at this locality is reported by Winwood to be of the 'landscape type', and to contain *Pseudomonotis fallax*. The Cotham Marble is here succeeded by a brown clay, as at Chilcompton, terminating Cb 2 deposition. A well-bedded limestone gives way upwards to a series of rubbly beds which must be equivalent to the Langport Beds at Chilcompton.

(v) Kelston Station, Bath (ST 677668)

This section presents a fuller exposure of Rhaetic deposits (Winwood, 1884), situated to the west of Newbridge Hill, and 15 km to the north of Chilcompton (text-fig. 1). Like the Newbridge Hill section, that at Kelston appears to represent only one cycle in the Westbury Beds (Wb 1), which opened with a bone-bed overlying the Tea Green Marl, and was succeeded by black shales. The fact that the lower portion of the shales is laminated, and the upper part apparently non-laminated suggests that this shale sequence may be correlated with both Wb 1 and Wb 2 of Chilcompton. At Kelston, Cb 1 begins with a grey marl directly overlying the non-laminated black shales, and is succeeded by a well-bedded limestone, followed by a further marl band. A second limestone band, possibly the lateral equivalent of the limestone filling mudcracks at Chilcompton and Uphill, opened Cb 2 deposition. This is succeeded by a series of marls, followed in turn by the Cotham Marble, once again of the 'landscape type'. A thick (over 1 m) series of rubbly beds directly overlies the Cotham Marble, marking the transition to Langport Beds deposition. Cyclicity is not easy to discern in the Langport Beds at this locality, the rubbly beds giving way upwards to a series of well-bedded limestones.

(vi) Other localities

Certain sections in the area cannot, because of facies variations induced by nearby contemporary land masses be closely correlated with the Chilcompton section. These sections include a cutting at ST 631512 (Winwood, 1876 - records only a small patch of 'blue Rhaetic clays'), Luckington Quarry (ST 695497, Winwood, 1890), Vallis and Hapsford Hill (Moore, 1860; Richardson, 1911), Marston Road, near Holwell (Moore, 1867), and Milton Lane near Wells (Brodie, 1866; Woodward, 1873; Richardson, 1911).

Well documented sections such as those of the west Somerset coast and the Filton By-Pass Substitute can be usefully compared with Chilcompton, however. In a critical review of Richardson's (1911) work on the Blue Anchor Point to Lilstock coast sections, Whittaker (1978) successfully correlates the Upper Triassic and lowermost Liassic strata of these sites with the Glamorgan outcrops. Particularly interesting is the fact that Whittaker (1978, p.64) notes the presence of "contorted, deformed and possibly slumped calcareous siltstones" in the lower part of the Cotham Beds exposed on the west Somerset coast. Furthermore, the top of these contorted beds "commonly shows a crudely polygonal network of presumed shrinkage cracks" which penetrate the underlying strata to various levels. This is exactly the case at the transition between cycles Cb 1 and Cb 2 at Chilcompton.

At the temporary section of the Filton By-Pass Substitute (ST 797570 to ST 835606) (Hamilton, 1962), four cycles are recognised in the Cotham Beds. Deformed mudstones with sand lenticles are present at the base of Cb 2, and desiccation cracks are present at the base of Cb 4. This section therefore shows similar features to that of Chilcompton and the west Somerset coastal exposures, but differs in stratigraphical detail.

Conclusions

The temporary section at Chilcompton Railway cutting exposed rocks of Keuper (Tea Green Marl) to Rhaetic age. The stratigraphy is interpreted in terms of cyclic deposition. Two cycles (Wb 1, Wb 2) are present in the Westbury Beds, two in the Cotham Beds (Cb 1, Cb 2) and two in the Langport Beds (Lb 1, Lb 2). Both Westbury Bed and Cotham Bed deposition began with a bone-bed. A distinctive mudcrack horizon marks the base of Cb 2, and landscape Cotham Marble is present higher in the cycle. Invertebrates collected from the section are typical of the Rhaetic of the West of England. The selachian fauna may be replaced by a dominantly palaeoniscid fauna at the base of Cb 1.

The sedimentary cycles recognised at Chilcompton can be correlated with moderate success with previously reported sections in the Mendip area. Facies variation hinders such correlation in a number of cases, due to the proximity of contemporary land masses. With the exception of the Three-Arch Bridge section at Shepton Mallett, cycle Wb 1 commences with a bone-bed, as is the tendency with Cb 1. Two cycles are usually present in the Westbury Beds, except at Kelston Station and Newbridge Hill, near Bath, in which only one cycle survives, and at Uphill, near Weston-super-Mare, where three cycles are present. Two cycles are consistently encountered in the Cotham Beds, and the mudcrack horizon at the base of Cb 2 is also present in this position at Uphill, and coastal sections in South Wales and west Somerset (also at Selworthy, south Devon and the Winterbourne Kingston borehole, Whittaker pers. comm.). The Cotham Marble is consistently of the landscape type. The Langport Beds always show development of limestone rubble at cycle bases, succeeded by well-bedded limestones.

The small scale fining upwards sequences represented by the cycles, were laid down in a marine environment, as proved by the fossil content. Some fresh or brackish water influence may have been present at the top of the Cotham Beds, but conditions were once again thoroughly marine in the Langport Beds.

The probability of tectonic activity influencing Cb 1 deposition is illustrated by the presence of penecontemporaneous folds in the upper part of that cycle. As is the case with the mudcrack horizon, these contorted beds are of considerable use in fairly long range correlations. Such folding is also known from the Cotham Beds of the west Somerset coast and sections in Avon.

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C. J. Duffin
126 Central Road
Morden
Surrey, SM4 5RL

DEPOSITIONAL ENVIRONMENT OF LATE-PLEISTOCENE TERRACE GRAVELS OF THE VALE OF BOURTON, GLOUCESTERSHIRE

by

R.C. Brown, D.J. Briggs and D.D. Gilbertson

Summary

The distribution, stratigraphy, and frost structures of limestone terrace gravels in the Vale of Bourton, Gloucestershire, are described. The terrace is shown to be composite in both age and origin. Roman riverine deposits overlie mid- and late-Devensian gravels attributed to solifluction processes on hillslopes, and to fluvial re-working by streams with nival regimes on the valley floors.

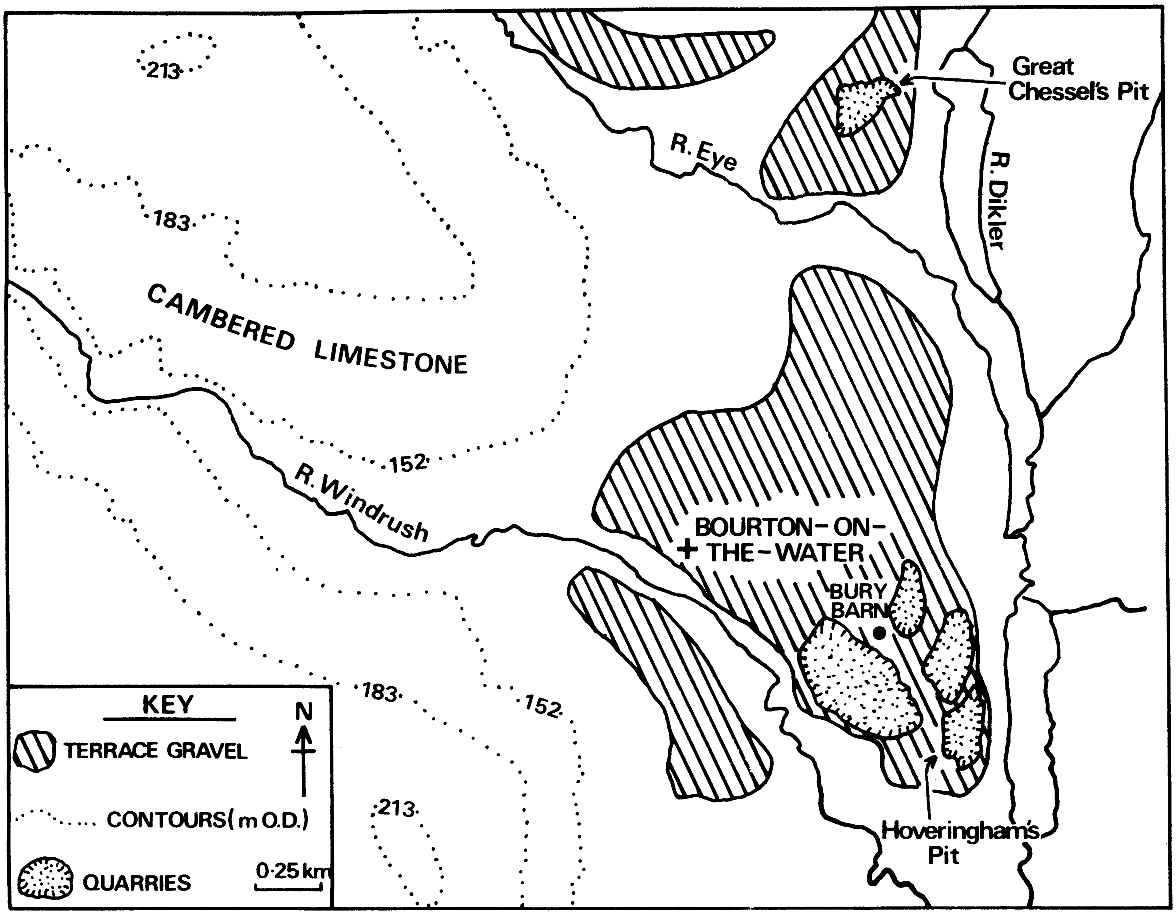
Pollen and non-marine molluscan analyses of a fossiliferous sandy-silt lens in the lower part of the terrace gravels indicate a treeless vegetation cover dominated by grass and/or grass sedge communities with a river flood-plain consisting of a mosaic of marshy, aquatic pools separated by drier gravel ridges. The molluscan fauna was very impoverished whilst the flora contained moderately thermophilous marsh and aquatic species.

The severity of the prevailing climate during the mid-Devensian is difficult to deduce from this evidence since factors other than climate may be responsible for the lack of tree cover. The presence of an ice-wedge cast tentatively correlated with the main Devensian glaciation at about 20,000 years BP, suggests that mean annual air temperatures were in the order of -6°C at that time.

Introduction

Extensive deposits of coarse limestone gravels rest on Lower Lias Clay (Jurassic) in the floor of the Vale of Bourton (text-fig. 1), which is a broad basin eroded into the Jurassic sands and gravels of the Cotswolds. These gravels were described by Richardson and Sandford in 1960, and were attributed to the late Wolstonian/early Ipswichian period on the basis of their textural similarity to the terrace gravels of the Summertown-Radley terrace of the Upper Thames basin (Worsamm & Bisson, 1961). A later investigation of superficial tectonic structures in the north Cotswolds by Briggs & Courtney (1972) linked both the terrace gravels of the Vale, and the tectonic structures, with periglacial conditions prevailing during the Devensian (last) cold stage of the Pleistocene. The results are presented here of a study of exposures in the terrace gravels at Bury Barn (text-fig. 1, Nat. Grid Ref. SP 177208). These studies throw new light on the age and environmental significance of the limestone gravels.

Mercian Geol. vol.7, no.4, 1980
pp.269-278, 2 text-figs.



Text-fig. 1: Terrace deposits of the Vale of Bourton.

The Bourton Terrace

Distribution and sediments

The distribution of terrace gravels in the Vale of Bourton is shown in text-fig. 2. A study of its morphology and fauna indicates that the Vale is composite in both age and origin. The terrace is principally composed of limestone gravels (over 90% of the 4-16 mm fraction). Near the river, the terrace stands about 5 m above present alluvium, and is essentially flat-topped. Away from the present rivers, it rises up the Cotswold scarp and becomes more rubbly and irregular, forming a well-marked solifluction apron at the scarp foot. Morphologically, therefore, the terrace represents a continuum from soliflucted material at the scarp-foot, to fluvially transported material in the more central parts of the valley. In this respect it is akin to the Beckford terrace of the Carrant Valley to the west of the Cotswold scarp (Briggs *et al.*, 1975).

The internal sedimentary character of the terrace similarly alters with a progressive improvement in particle sorting away from the scarp. In overgrown exposures north of Bourton (SP 174226 & SP 175224), the gravels can be seen to be roughly bedded, coarse, and angular. In the more extensive sections at the old Hoveringham Company's pit (text-fig. 1; SP 177208) the gravels are much better sorted and bedded and show features indicative of braided stream deposits (Briggs & Gilbertson, in press). Locally overlying these gravels occur channel sets and enclosed depressions filled with silts and fine sands which are rich in molluscan remains and, near the surface, Roman pottery. The lower gravels are not known to have yielded any pottery, and are poorly fossiliferous. However in the nearby Great Chessil's pit (text-fig. 1, SP 174226), near Bourton-on-the-Water, coarse gravels have yielded a small mammalian fauna, including mammoth (*Elephas primigenius*) and woolly rhinoceros (*Rhinoceros* *tichorinus*), described by Richardson & Sandford (1960). The polygenetic nature of this terrace feature makes it extremely difficult to trace downstream. Consequently it cannot be correlated with other deposits in the upper Thames Basin on simple altimetric grounds alone.

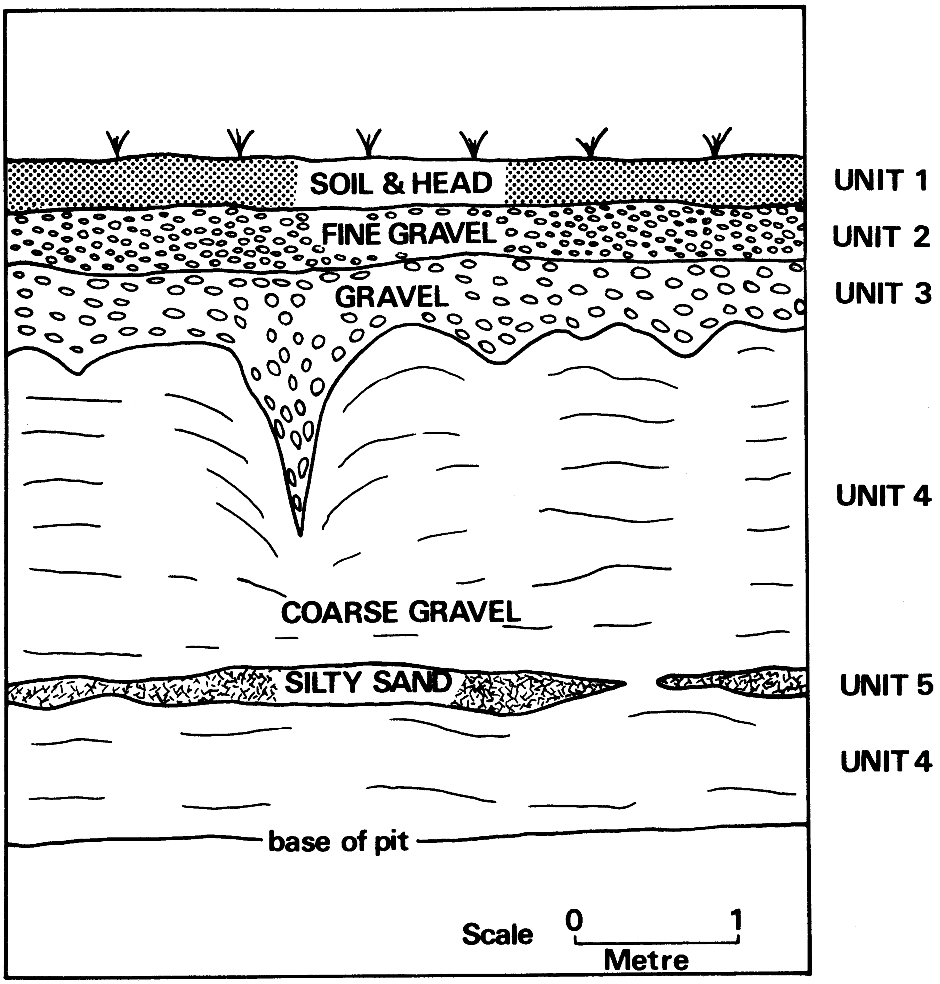
In 1972, the following section was noted in the Hoveringham Company's gravel pit (text-figs. 1 and 2) at Bury Barn (SP 177208).

Unit	Stratum	Depth	Thickness
1	Soil developing on a brown loamy head - a solifluction deposit.	0.3 m	0.3 m
2	Fine limestone gravel, particles up to 0.02 m diameter.	0.6	0.3
3	Coarse, greyish limestone gravel. Particles up to 0.08 m diameter, let down in large ice-wedge cast and involutions into unit 4.	1.0	0.4
4	Plane-bedded, coarse, yellowish limestone gravel, particles up to 0.10 m. diameter: (braided stream deposits).	3.3	2.3
5	Contorted lense of grey-green sandy silt with occasional non-marine Mollusca; discontinuous lens over 30 m. (channel fill).	3.6	0.3
4	Plane-bedded, coarse, yellowish limestone gravel; locally shallow cross-bedded sets; (braided stream deposits?).	4.1	0.5
	Lower Lias Clay.		

Samples taken from this section were investigated using pollen and molluscan analyses.

Periglacial structures

The upper parts of the gravels are disturbed and disrupted by features similar to those normally associated with discontinuous permafrost (Kerney, 1963). These layers are penetrated by substantial ice-wedge casts which occur at the surface of the gravels at Bury Barn, indicating that after aggradation the river gravels have been subjected to more continuous permafrost. Péwé (1966) has indicated that the initiation of ice-wedge growth is dependent upon the size of materials being frozen. The coarseness of the Bury Barn gravels suggests mean annual air temperatures may have been below the -6 to -8°C found necessary for ice-wedge growth in Alaska. As there is no evidence of prolonged weathering between the termination of the main phase of terrace aggradation and the formation of the ice-wedge, it is assumed there is little temporal gap represented between them. In addition, since ice-wedge development at this scale is only possible given a substantial supply of water, it is reasonable to assume that the wedges grew before the terrace was dissected by the river and the regional water table fell.



Text-fig. 2: Section in the river terrace at Bury Barn, Vale of Bourton.

Pollen Analysis

Material from the grey-green sandy silt was prepared for pollen analysis by treatment with 7% HCl, 7% NaOH, 20N HF, a simple acetolysis, and chlorate bleaching. The pollen grains were mounted in silicone oil.

Identification

Unlike some other full-glacial sites from limestone areas, pollen and spores are moderately abundant in the sample analysed, but are often poorly preserved. The taxa identified are listed in table 1 along with unidentifiable material.

Many grains are fragmentary, squashed and distorted, and decay is apparent where pores and furrows have ragged edges and sculpturing has been removed in patches. As a result, identification is difficult and some of the uncommon, poorly preserved grains have only been classified tentatively. A significant quantity of the material is recognisable as pollen but is too poorly preserved to be identified. Many of the better preserved spores could not be ascribed to any group and are probably derived from the Jurassic rocks. Some of the easily recognisable pollen, such as *Pinus*, may be identified even when severely abraded, and is therefore liable to be over-represented in the pollen count (table 1).

Table 1: Pollen identified in late-Devensian river silts from terrace gravels in the Vale of Bourton, Cotswold Hills, England.

Abies fragment	31
whole	10
Quercus	25
Pinus fragment	10
whole	6
? *Salix*	5
? *Betula*	1
Carva	1
Ranunculus	59
Cyperaceae	28
Graminae	21
Plantago maritima	11
Thalictrum	4
? Ericaceae	4
Chenopodiaceae	3
Sparganium	2
Saxifraga oppositifolia	2
Polygonum sect. *persicaria*	2
Artemisia	1
Nymphaea	1
? *Nuphar*	1
? *Filipendula*	1
? *Hydrocharis*	1
? *Dryas*	1
Peplis	1
Lycopodium	6
Polypodium	4
Dryopteris	2
Pteridium	2
Total	227
(with fragments divided by 2)	
unidentified pollen	
fragments	131
whole	11

Three broad groups of pollen are present:

1. Arboreal

The arboreal pollen is less well preserved than the herbaceous pollen. Most is squashed, of small size and has holes and thin areas as if it was being eaten away. This is particularly true of *Abies* and *Quercus*. Some *Abies* and *Pinus* grains are barely recognisable.

2. Herbaceous - marsh and aquatic group

This pollen is better preserved and includes *Sparganium* type, *Polygonum* sect. *persicaria*, *Nymphaea*, ? *Nuphar*, ? *Filipendula*, ? *Hydrocharis* and *Peplis*. Also included here is *Ranunculus*; although it is a taxon of uncertain habitat, its pollen is well represented in the spectrum suggesting local dominance. Such dominance is usual only by aquatic species, although when open ground is being made available by fluvial processes a substantial cover of *Ranunculus repens* might be anticipated.

3. Herbaceous - terrestrial group

This pollen is also better preserved than the arboreal pollen and includes *Plantago maritima*, *Thalictrum*, Ericaceae, Chenopodiaceae, *Saxifraga oppositifolia*, *Artemisia*, ? *Dryas*, *Lycopodium*, *Polypodium*, *Pteridium* and *Dryopteris*. Most of the Graminae and Cyperaceae pollen also probably belongs to this group, but small amounts might have been contributed by marsh and aquatic species.

Interpretation

The poor state of preservation and low numbers of identified grains, invalidate any but the broadest interpretation. Taken as a whole, the spectrum represents an odd and, superficially, a most unlikely assemblage of northern, arctic-alpine, thermophilous and halophytic plants. It is probable that some of the pollen is derived, although unusual fossil assemblages of halophytic, thermophilous, steppe and northern herbaceous and shrub species have been recorded from interstadial and full-glacial deposits at Brandon (Kelly, 1968), Earith (Bell,

1970) and other sites, and these assemblages have been reviewed by Bell (1969). They probably result from a continental climate and open vegetation conditions in which competition was not severe. Similar assemblages which include the pollen of oak and coniferous species have not been recorded. This factor and the comparatively poor preservation of the arboreal pollen suggest that at least some of it has been derived from a pre-existing sediment. This can only be determined approximately since all the pollen is poorly preserved by normal standards. Additional evidence that some of the arboreal pollen is derived is provided by the intrinsically unusual association of pollen of *Abies*, *Pinus* and *Quercus*, without *Corylus* and with only one doubtful grain of *Betula*, and by the presence of a single grain of *Carya*. Grains of *Quercus* may have been eroded from soils in the area. A few of the *Pinus* pollen grains are better preserved and may be contemporaneous. These exist in quantities which are consistent with them having been blown into the area. The probabilities of long distance transport by wind being responsible for similar representations of *Pinus* in late Devensian deposits in the Lake District of England has been discussed by Pennington (1970).

The pollen evidence suggests that much local vegetation was dominated by marsh and aquatic species. Contemporary aquatic species of *Ranunculus* usually dominate shallow, sluggish streams or pools (except *R. fluitans*) and the remaining aquatic genera are usually confined to still and shallow water. The genera *Ranunculus*, *Polygonum* sect. *persicaria*, *Nymphaea*, *Nuphar* and *Hydrocharis* include species which are only moderately tolerant of severe winter conditions and as a result the whole group, it is believed, could be moderately thermophilous. However *Ranunculus* spp. can dominate aquatic sites in Greenland and it is possible that some of the rarer pollen has been derived along with the arboreal group. The presence of *Hydrocharis* suggests a base-rich situation likely to be found in an eroding limestone terrain, although *Peplis* is usually absent from calcareous areas.

The remaining herbaceous pollen is, with the presence of *Dryas* and *Saxifraga oppositifolia* and a probable absence of arboreal species, indicative of a regional vegetation characterized by plants of open, probably arctic-alpine habitat. This contrasts with the moderately thermophilous aspect of the aquatic vegetation. This pollen is sparsely represented in the sample and was probably sparse in the environment. Most of the genera in the group have arctic-alpine representatives. *Artemisia borealis* has been collected in Greenland in open, dry, riverine gravels and outwash sand, and other *Artemisia* species occur in arctic continental environments. *Plantago maritima* is sometimes regarded as a halophytic coastal species but it can be found at over 914 m O.D. in Scotland in an open habitat. Both *Plantago maritima* and *Artemisia* pollen occur in British full-glacial floras. *Lycopodium* species are often alpine although they might be derived from the Jurassic, in which they were common, for the spores preserve well. Dwarf *Salix* and *Betula*, and ericaceous species are usually present in arctic-alpine associations, yet their pollen is virtually absent from the spectrum. This could be accounted for if, as the moderately high grass and sedge pollen suggest, the regional vegetation was grass and/or grass and sedge dominated, although some of this pollen might have been contributed from the marsh and aquatic group or have been derived along with the arboreal group. Such vegetation associations commonly occur in the arctic-alpine formation, especially in eroding calcareous terrains. The presence of *Saxifraga oppositifolia*, the ferns and possibly Thalictrum suggest that there were rocky niches nearby.

Unfortunately, until more organic layers capable of being dated by radiocarbon are located in this terrace the precise position of this pollen assemblage within the Mid-Devensian cannot be determined.

Non-marine Mollusca

A 4kg air dried sample from the sandy silt (Unit 5) was washed through a 250 μm sieve, and the residue identified under a low-powered binocular microscope. 454 individual molluscs were found and identified as belonging to 5 taxa (table 2).

Table 2: Pleistocene non-marine molluscan fauna from Bury Barn.

	No.	%
Valvata piscinalis (Müller)	1	0.2
Lymnaea peregra (Müller)	1	0.2
Succinea pfeifferi cf var *schumacheri* Andreae	164	36.1
Pupilla muscorum (L)	215	45.2
Agriolimax cf. *agrostis* (L)	73	16.1
Total	454	-

Identification

The specimens of *Valvata piscinalis* and *Lymnaea peregra* are juveniles. The specimens of *Succinea* present are variable in shape recalling both *S. pfeifferi* Rossmassler and *S. oblonga* (Drap.). The range of forms present is similar to those illustrated by Van Regteren Altena (1957) for Weichselian deposits in the Netherlands. This form is extinct in Europe, but is known from 'cold' deposits in the British Isles at Brandon (Shotton, 1968), Wretton (West *et al.*, 1974) and nearby Beckford (Briggs, *et al.*, 1975).

There is a complete size range of *Pupilla muscorum* present. Up to 7 whorls may be present with the typical form being the "more cylindrical, less tapered form with whorls wider in proportion to their height" which Kerney *et al.*, (1964, p.160) and Kerney (1963) have described from late-Devensian deposits in the Chalk Downs of south east England. Large & Sparks (1961) have recorded a similar form at Stroud in terrace deposits. The Bury Barn shells are thin, sometimes broken. 50% of the specimens whose aperture could be examined bore no teeth on the inner lip, and in the remainder, the lip was only poorly developed.

The shells of *Agriolimax* species are not reliably identifiable from shell characteristics only.

Environmental implications

Molluscan faunas associated with riverine situations may be anticipated to be normally rich in molluscan species, since the constant erosion of river bank, stream bed and associated vegetation should contribute specimens from many micro-habitats. The great lack of diversity in the Bury Barn fauna, coupled with the known associations of the particular forms of *Succinea* and *Pupilla* present suggests an exposed, cold, periglacial climate. The combination of so many succineids which favour a marsh environment with the occasional specimens of *Valvata piscinalis* which would favour deeper, quieter running water, indicates the local environment comprised many marshy pools with perhaps the occasional pool or deeper stream. *Pupilla muscorum*, nowadays regarded as a xerophile (see Ellis, 1969), has been identified in this type of Pleistocene cold floodplain environment in other studies (Kerney, 1963; Briggs *et al.*, 1975). It appears probable that the species had a greater tolerance of marshy situations during the Devensian, and that it may have been occupying drier gravelly ridges on the floodplain. Much mixing has no doubt occurred before final deposition in the pool represented by the sandy silts.

The fauna has fairly close parallels with those recorded from Devensian deposits at Beckford (Briggs *et al.*, 1975), Stroud (Large & Sparks, 1961), Brandon (Shotton, 1968), and other sites in the Avon II terrace (Tomlinson, 1925). Notable absentees at Bury Barn are *Lymnaea truncatula* (Müller), *Planorbis laevis* Alder, and *Planorbis leucostoma* Millet. This may be the result of chance rather than any local ecological or climatic cause.

Dating and Correlation

All the evidence presented here indicates that the pre-Roman deposits collected in a periglacial environment characterised by cold but seasonally variable conditions. The stratigraphical evidence found indicates that there is no reason to believe the periglacial sequence found belongs to other than the Devensian (last) cold stage of the Pleistocene, and consequently the view of Richardson & Sandford (1960) and Worssam & Bisson (1961) is rejected.

The sequence of deposits and frost structures found is essentially similar to that at Beckford where a radiocarbon date of 27,650 ± 250 years BP (BIRM 293) has been obtained from woody detritus in a silty lens essentially similar in stratigraphical significance to that at Bury Barn (Briggs *et al.*, 1975). There, the main terrace aggradation was attributed to the mid-Devensian, and the phase of ice-wedge growth associated with the main late-Devensian glaciation of the British Isles, c. 20,000 years BP. Ice-wedge casts are similarly common in the terraces of the Upton Warren interstadial in both the Avon (Shotton, 1968), and the Thames (Briggs & Gilbertson, in press). They have not been widely noted in the younger facet of the Floodplain Terrace of the Thames which has been dated at Northmoor to 11,250 yrs. BP (BIRM 105) to 10,931 yrs. BP (IGS-162). The older Summertown-Radley Terrace of Ipswichian age and Hanborough Terrace of early Wolstonian age (Sandford, 1924; Briggs & Gilbertson, 1973; Briggs & Gilbertson, in press) have been far more severely affected by frost action than the deposits at Bourton or Beckford. Consequently the terrace is regarded as considerably older than the later facet of the Floodplain Terrace and to post-date the Summertown-Radley and Hanborough Terraces; an interpretation supported by the relationship to the modern river level. Thus it seems likely to correlate with the older phase of the Floodplain Terrace of the Thames; dates from this have ranged from 39,300 ± 1,350 radiocarbon years BP at Dorchester (BIRM 333) to 29,500 ± 300 radiocarbon years BP at Standlake (BIRM 334). This dating is possibly supported by the date of 34,500 ± 800 years BP obtained from the gravels of the Windrush at Little Rissington (BIRM 466).

Terrace deposition seems to have been characterised by active mass-movement and rapid aggradation of debris in the valley floor. It is tempting to relate this activity to the development of the tectonic structures (ridge-and-trough topography) preserved on the surrounding valley sides (Briggs & Courtney, 1972). In conditions of repeated freeze-thaw and marked seasonal fluctuations of both temperature and run off, sapping of the Lias Clay exposed in the valley floor may well have caused instability of the slopes, leading to a variety of slope movements including cambering, gulling and planar sliding.

Conclusions

The main (pre-Roman) terrace gravels of the Vale of Bourton are shown to be the result of a combination of a mass movement and fluvial reworking in a periglacial environment during the mid-Devensian, rather than the early-Ipswichian. The pollen evidence suggests that during the aggradation the regional vegetation cover was treeless, and dominated by grass, or grass-sedge communities. Within this landscape, base-rich marshes and streams occurred on limestone gravel floodplains. These were dominated by moderately thermophilous marsh and aquatic species. Arboreal pollen is present in the spectrum, but is interpreted as a result of transportation to the site by stream and wind. Molluscan evidence similarly suggests an open periglacial climate with the river floodplain consisting of a mosaic of drier gravelly ridges, marshy pools, and streams. It is difficult to assess the severity of the climate from the biological remains. The moderately thermophilous marsh and aquatic species present may indicate that warm summers were prevalent, as suggested for other sites by Bell (1969). If such conditions existed the lack of similarly thermophilous tree species, accounted for by factors such as soil instability (Bell, 1970), may be associated with arduous winters; and the presence of arctic-alpines by the lack of severe competition consequent upon the absence of a tree cover.

Climate deteriorated shortly after the main terrace aggradation at about 20,000 years BP, when ice wedges formed. Fluvial incision may be broadly associated with this stage in the late-Devensian, initiating the development of superficial tectonic structures on local hillsides. During the later stages of the Devensian, further mass-movement, perhaps associated with aeolian activity produced a veneer of soliflucted regolith now identified as head.

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R.C. Brown,
I.L.E.A.,
Advanced Field Studies Centre,
Abergavenny.

D.J. Briggs,
Department of Geography,
University of Sheffield,
Sheffield, S10 2TN.

D.D. Gilbertson,
Department of Prehistory and Archaeology,
University of Sheffield,
Sheffield, S10 2TN.

SOME RESULTS FROM A VLF ELECTROMAGNETIC SURVEY IN BRADGATE PARK, LEICESTERSHIRE

by

T.R. Seaborne

Summary

Results from a Very Low Frequency (VLF) electromagnetic survey conducted in Bradgate Park, Leicestershire, are presented. Certain anomalous zones, displayed on a map of contoured Fraser filtered values, correlate with known geological features. The results suggest that surface deposits of Keuper Marl and Pleistocene boulder clay are the principal causes of anomalous readings, and that the present distribution of these deposits is controlled by the underlying structure and lithology.

Introduction

Electromagnetic (EM) prospecting methods use electromagnetic fields to induce current flow in conductive material in the ground. By measuring the secondary magnetic field produced by these currents, information about the distribution of conductive material may be obtained. Zones of high conductivity often relate to lithological horizons and geological structures, such as fault zones.

A Very Low Frequency (VLF) electromagnetic survey was undertaken in Bradgate Park, near Anstey, Leicestershire, as part of a project to investigate the potential of EM prospecting techniques for geological mapping. In Bradgate Park there are outcrops of steeply dipping Pre-Cambrian strata, and the contacts of an igneous intrusion, a porphyritic microdiorite known as markfieldite. This study was designed to illustrate the response of these geological features to electromagnetic fields.

In this paper some results of the survey are presented and discussed in relation to the known geology. It is stressed that the survey was not intended as a rigorous geophysical investigation of the park, and that scope exists both for further interpretation of the results obtained so far, and for more detailed VLF surveys.

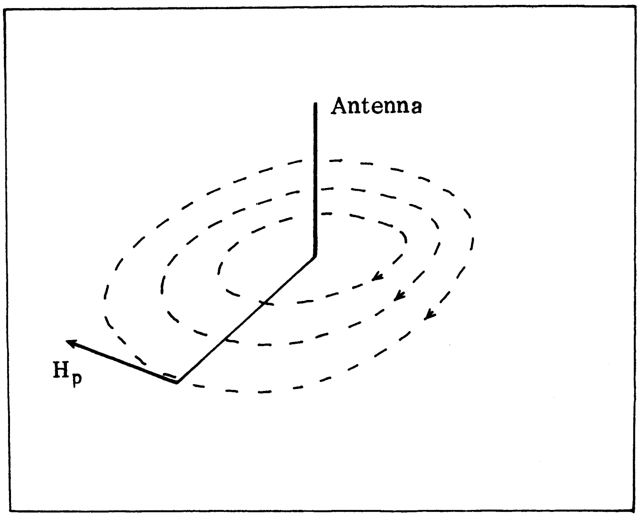
Theory

The theory of VLF electromagnetic surveying has been thoroughly reviewed by Patterson & Ronka (1971). The method uses EM fields generated by military radio transmitters. The transmissions are in the frequency range 15-25 KHz, and at present give essentially worldwide coverage.

The transmitting antennae, which can be considered as electric dipoles, produce three modes of wave; a ground wave, a sky wave and a space wave. At distances greater than several wavelengths, the main mode of propagation is as a sky wave in a waveguide bounded by the Earth's surface and the ionosphere.

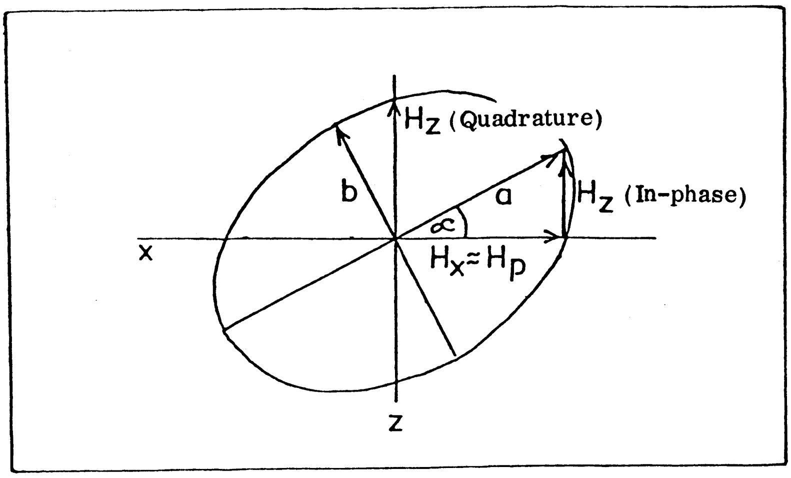
Mercian Geologist, Vol 7, No.4,
1980, pp.279-289, 8 text-figs.

An electromagnetic wave can be resolved into electric and magnetic components. At large distances from the transmitter, the primary magnetic field component (Hp) of the sky wave is effectively horizontal, and is polarised cylindrically about the transmitter (text-fig.1).



Text-fig. 1: Cylindrical polarisation of the primary magnetic field about a transmitter antenna.

A primary magnetic field passing through a conductive body induces within it electrical currents. The flow of these currents induces a secondary magnetic field which combines with the primary field to give a resultant magnetic field which is elliptically polarised in the vertical plane containing the traverse direction (text-fig. 2).



Text-fig. 2: Ellipse of polarisation of the resultant magnetic field.

Measurements of the tangent to the tilt angle (α) of the resultant field, and its ellipticity (b/a), approximate to measurements of the components of the vertical magnetic field which are in-phase, and $\pi/2$ radians out-of-phase (quadrature) with the primary magnetic field.

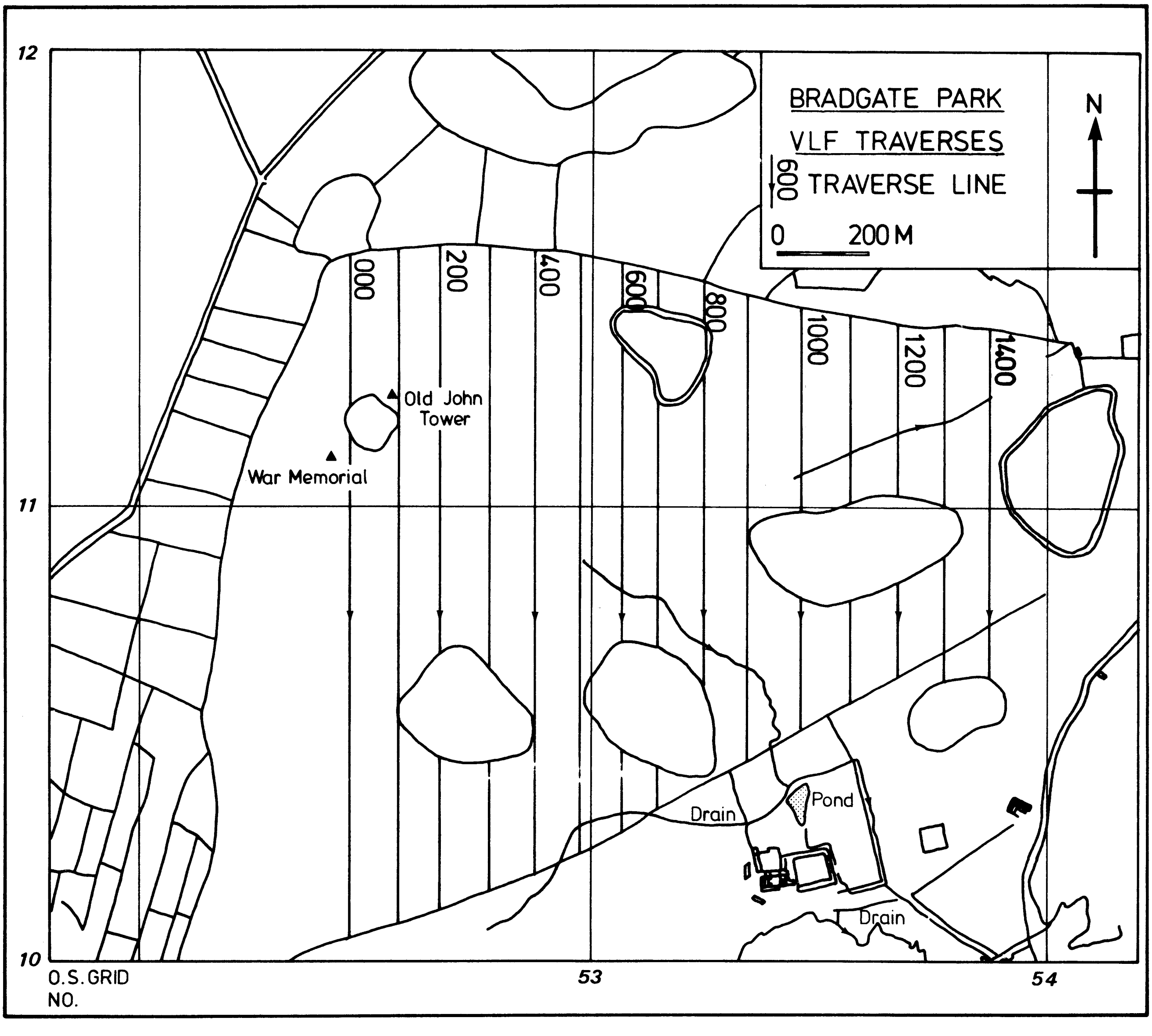
The tilt angle and ellipticity of the polarisation ellipse are measured by manual nulling of the signal detected by search coils in a receiver. Readings are generally displayed as approximate in-phase and quadrature components of the vertical magnetic field, expressed as percentages of the primary magnetic field.

Survey Method

The direction in which traverses are made is dictated partly by the position of the transmitter, and partly by geological strike. Ideally, a transmitter is chosen that will give a primary magnetic field direction perpendicular to the geological strike. Since induced currents flow perpendicular to the primary magnetic field, such a transmitter induces the maximum amount of current.

Olsson (1978) stated that the most useful traverse direction is perpendicular to geological strike. This is true even when the primary magnetic field vector is not perpendicular to strike. Traverse lines should therefore be perpendicular to strike, and the transmitter used which generates a primary magnetic field closest to the traverse direction. This condition usually limits the choice to one or two transmitters. When more than one suitable transmitter is available, that giving the clearest signal is used.

The transmitter chosen for this survey was NAA, Cutler, Maine, U.S.A. (17.8 KHz), and traverse lines were set out as in text-fig. 3. The receiver used was a Geonics EM 16, which requires only one operator.



Text-fig. 3: Traverse lines used in Bradgate Park for transmitter station NAA, Cutler, Maine, U.S.A. (Long.67°17'W., Lat.44°39'N.).

An interval of 100 m between traverses was chosen to enable rapid completion of the survey. Resolution of anomalous zones could be improved by using a 50 m interval, although Parasnis (1973) states that lateral resolution in VLF surveying is generally poor, due to the essentially two dimensional nature of most anomalies.

Fourteen traverse lines were surveyed, although readings were not taken in certain wooded enclosures designated as conservation areas. Readings along traverses were taken at 10 m intervals, which was chosen to permit numerical processing of the readings.

Presentation of Data

Initial presentation of data is as simple profiles of receiver readings plotted against position along traverse. Anomalies are easily recognised, but detailed interpretation requires the use of digital filtering techniques coupled with a certain amount of geological information.

The filtering technique devised by Fraser (1969) calculates the differences between the sums of consecutive pairs of readings. The filter converts the typical inflexion type anomaly into maximum values which are amenable to contouring. Only in-phase values are generally used in this filter.

A second type of digital filter, devised by Karous and Hjelt (1977) was used to compute an apparent sub-surface current distribution (Ia). If H_{1-7} are seven consecutive, equi-spaced VLF readings, either in-phase or quadrature, then:

$$Ia_4 = 0.102H_1 - 0.059H_2 + 0.561H_3 - 0.561H_5 + 0.059H_6 - 0.102H_7$$

Values computed using this equation are normally plotted and contoured to give a vertical cross-section. Maximum positive values of current concentration in such sections can be used to estimate the dip and depth of conductive bodies.

Results

Positive Fraser filtered VLF values have been plotted on a map (text-fig. 4) and contoured. An exponential contour interval has been used to permit display of anomalies of different intensity. Three examples of anomalies related to geological features have been selected for discussion using the geological map shown in text-fig. 5.

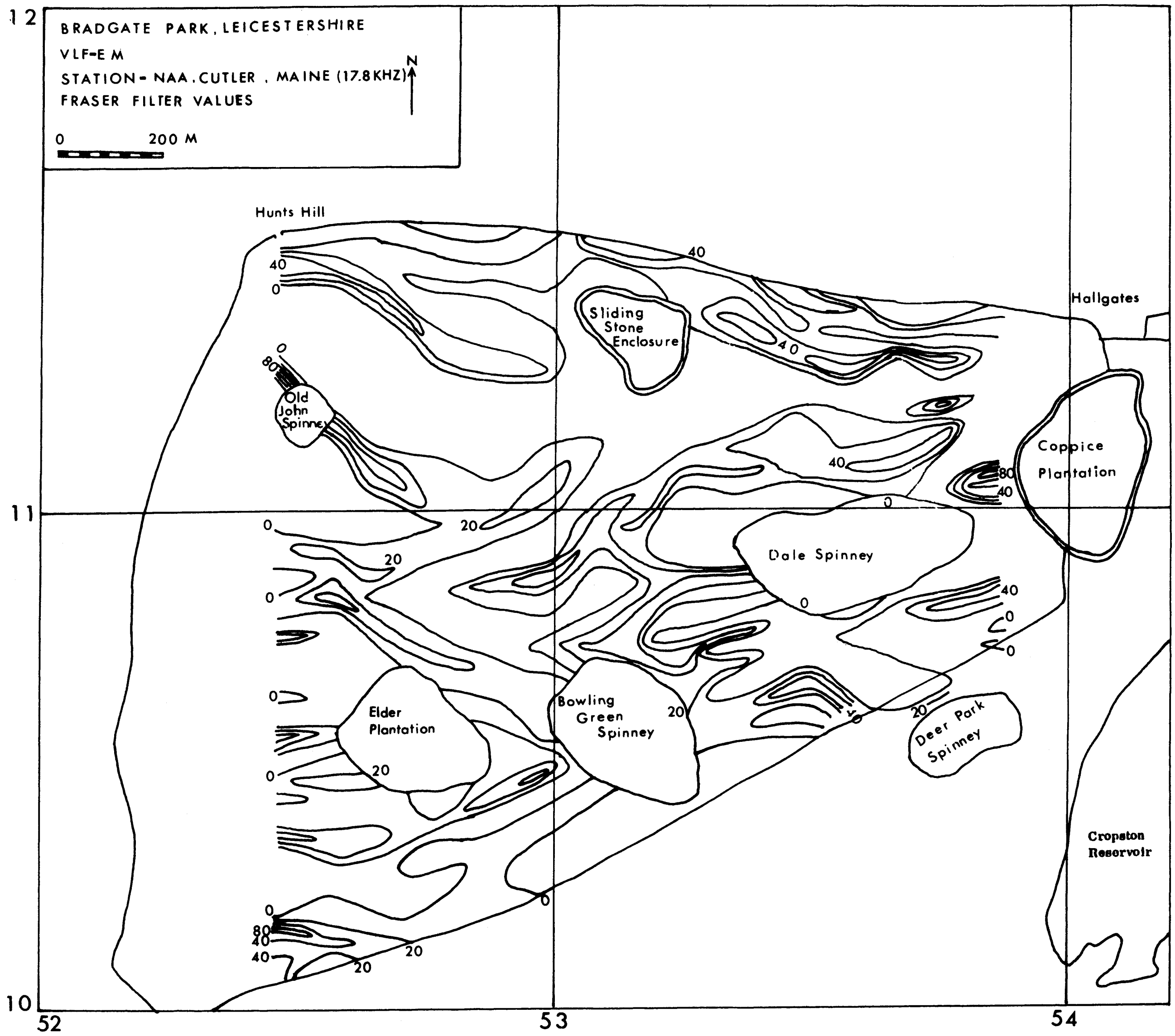
The anomalies east of Sliding Stone Enclosure and passing between Dale Spinney and Coppice Plantation are caused by a covered reservoir and a 30 inch diameter water pipe, and are not considered further.

Example 1

The north-west corner of the park is underlain by an accumulation of boulder clay, possibly covering Keuper Marl in a buried basin. The south-west margin of this basin is bounded by a fault which runs through Old John Spinney. This fault is clearly delineated by the VLF measurements, as is the northern edge of the basin. Both features correlate with zones of large positive Fraser filtered values, shown in text-fig. 4.

A Karous-Hjelt section (text-fig. 6) shows current concentration, associated with the fault, reaching a maximum very close to the surface, and decreasing with depth. This suggests that the source of the anomaly is shallow. If the source of the anomaly were a conductive fault zone, the lines of maximum current concentration would probably extend to a greater depth than shown. The source is therefore likely to be a small buried valley, infilled with boulder clay, whose position is controlled by that of the fault.

The plot of apparent current distribution is not for a line perpendicular to that of the fault, so any angles determined from the section will only be apparent angles.



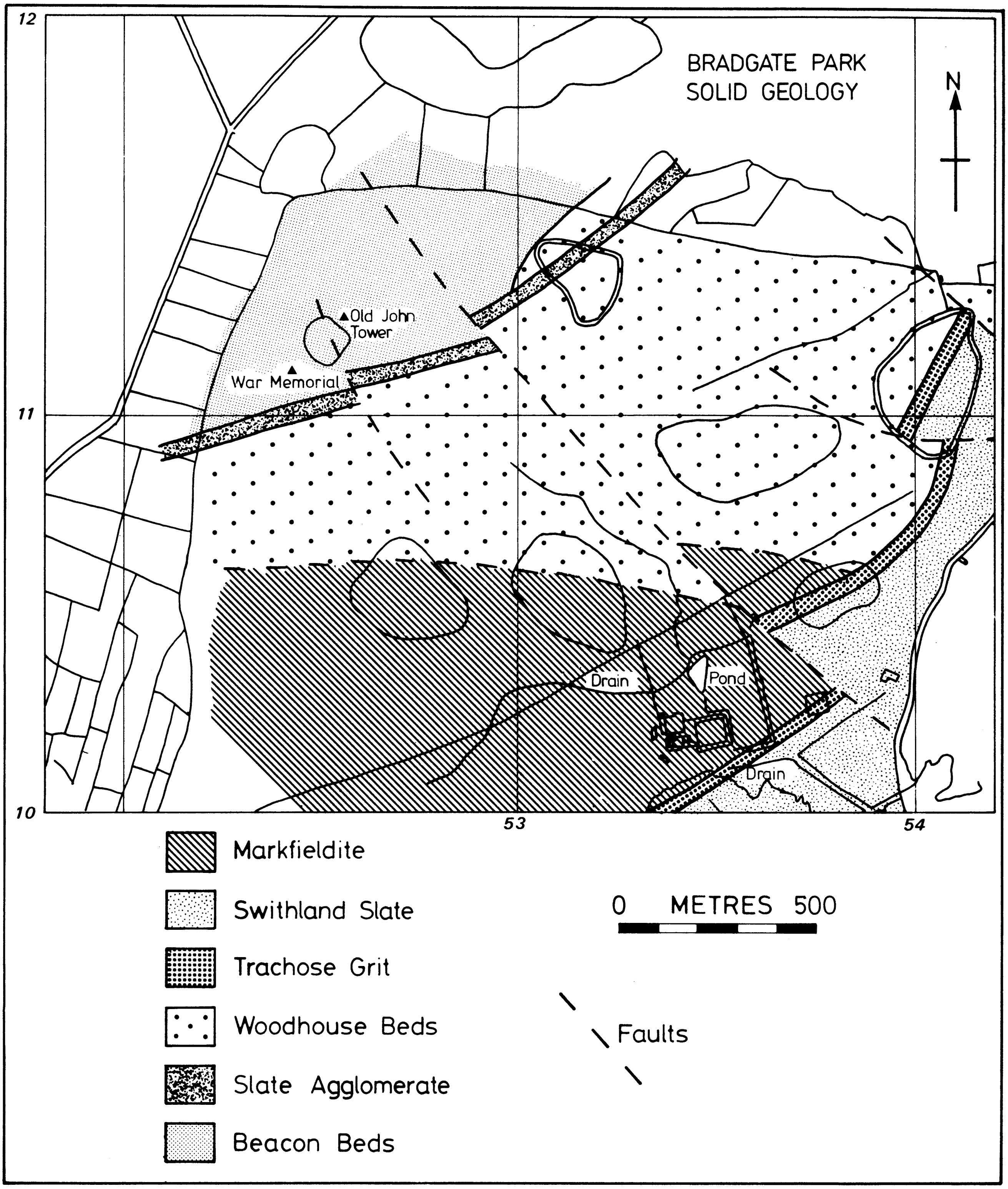
Text-fig. 4: Contoured positive, Fraser filtered VLF electromagnetic measurements, Bradgate Park.

Example 2

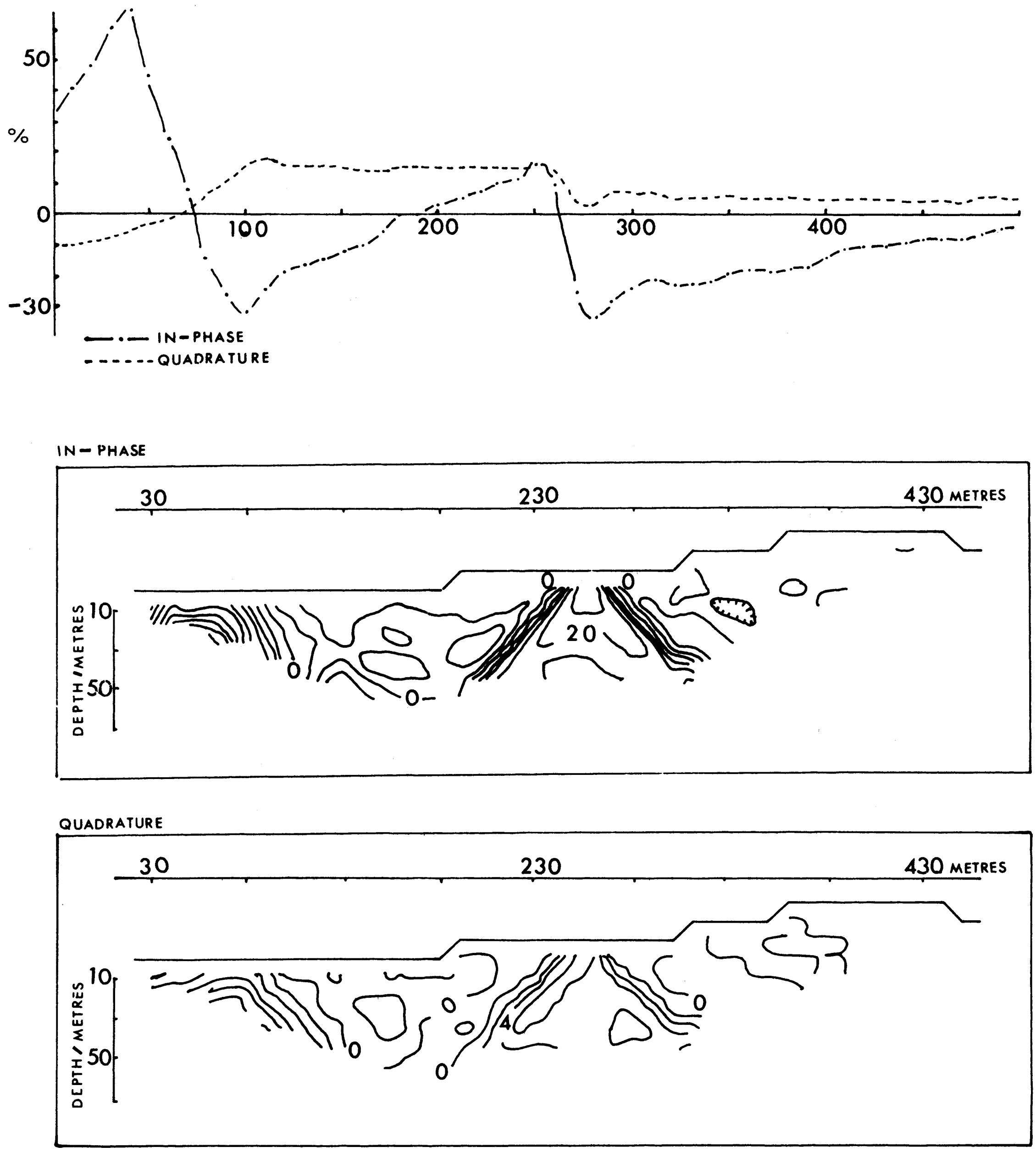
Text-fig. 7 shows results from part of a traverse beginning about 350 m south of the War Memorial. This shows a pair of anomalies about 200 m apart. These are almost certainly due to the margins of a sheet of boulder clay. This is indicated by the Karous-Hjelt section which shows regions of maximum current concentration corresponding to the edges of the boulder clay.

The northern edge of the boulder clay is about 800 m along the traverse, and dips steeply to the north. The southern edge appears to be controlled by the large markfieldite intrusion whose contact has been mapped in the vicinity of the 930 m point. Maximum current concentration suggests a near vertical contact. This could be the edge of the clay abutted against a buried scarp.

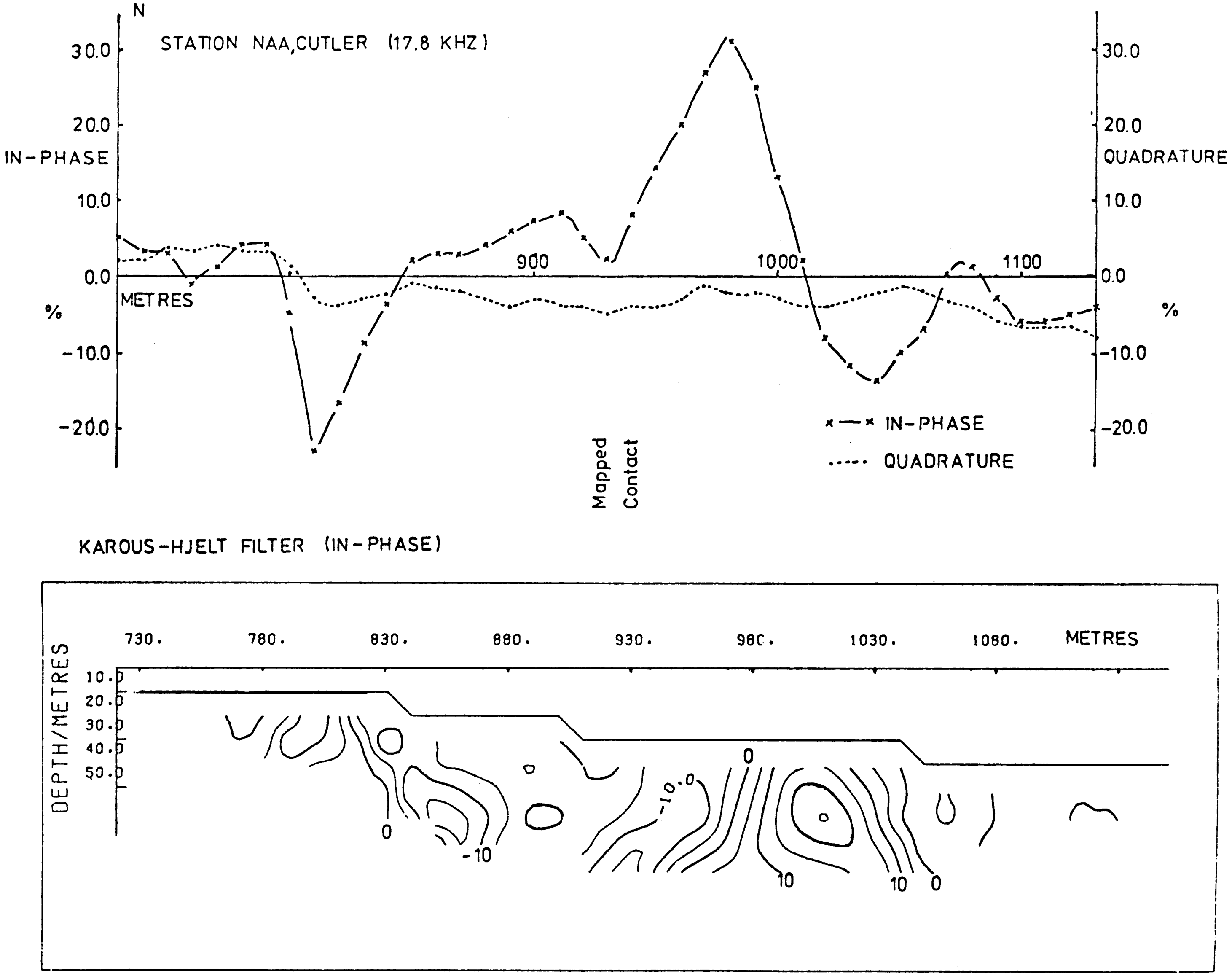
The maximum current concentration occurs at about 30 m depth. This suggests that the thickness of the boulder clay against the scarp is about 30 m. Two points should be noted, however. Firstly, the deeper parts of the section may not correspond to real features but may merely be a response of the filter to the use of values from two adjacent anomalous



Text-fig. 5: Map of the Precambrian Geology of Bradgate Park. (Adapted with kind permission from Ford, 1975)



Text-fig. 6: VLF electromagnetic profile (top) and corresponding apparent current distribution sections, line 000.



Text-fig. 7: VLF electromagnetic profile (top) and corresponding apparent current distribution section (in-phase), line 000.

zones. More experimental studies, possibly using scale models, are needed to enable the response of the filter to be understood in such situations.

The second point is that the depth of penetration of the VLF signals is uncertain. Electromagnetic methods usually detect meaningful signals down to one skin depth (t_s) of conductive strata, where

$$t_s = \sqrt{\frac{2\rho}{\mu w}} \text{ metres}$$

and ρ = resistivity in ohm-metres

μ = magnetic permeability (usually $4\pi.10^{-7}$Henries/m.)

w = angular frequency (= $2\pi f$ radians/sec.)

The frequency (f) used in the survey was 17.8 KHz.A Schlumberger DC resistivity sounding made near the Hallgates entrance, gave resistivity values for boulder clay in the range 5-45 ohm-metres. This would limit VLF penetration to between 8 and 25 m. Three other resitivity soundings gave much higher resistivity values for the boulder clay, of over 1000 ohm-metres. The problem of uncertain depth of penetration must lead to cautious treatment of apparent current distribution sections, and an awareness that deeper features indicated by the section may not be real.

The implication of the steep southern contact between boulder clay and markfieldite is that the contact is a buried fault scarp. The possibility that the northern edge of the markfieldite is faulted has been mentioned by Ford (1975) among others, but surface evidence for this is poor. In addition, the previously mapped position of the contact is 60-70 m north of the position suggested by the VLF measurements. Since exposure is poor in this region, the VLF measurements may offer a better indication of the true position of the contact than the results of surface mapping.

By comparing text-figs. 4 and 5, it can be seen that although the contact extends to the east of Bowling Green Spinney, the anomaly is not continuous along its length. This is not surprising since the boulder clay cover is known to be irregular. Where the markfieldite is deeply buried by boulder clay, no anomaly would be expected because of signal attenuation by the boulder clay. The north-eastern corner of the intrusion is defined by an anomalous zone 150 m north-west of Deer Park Spinney. This anomaly is probably caused partly by the major N.W.-S.E. trending fault, and partly by the edge of the boulder clay against the intrusion.

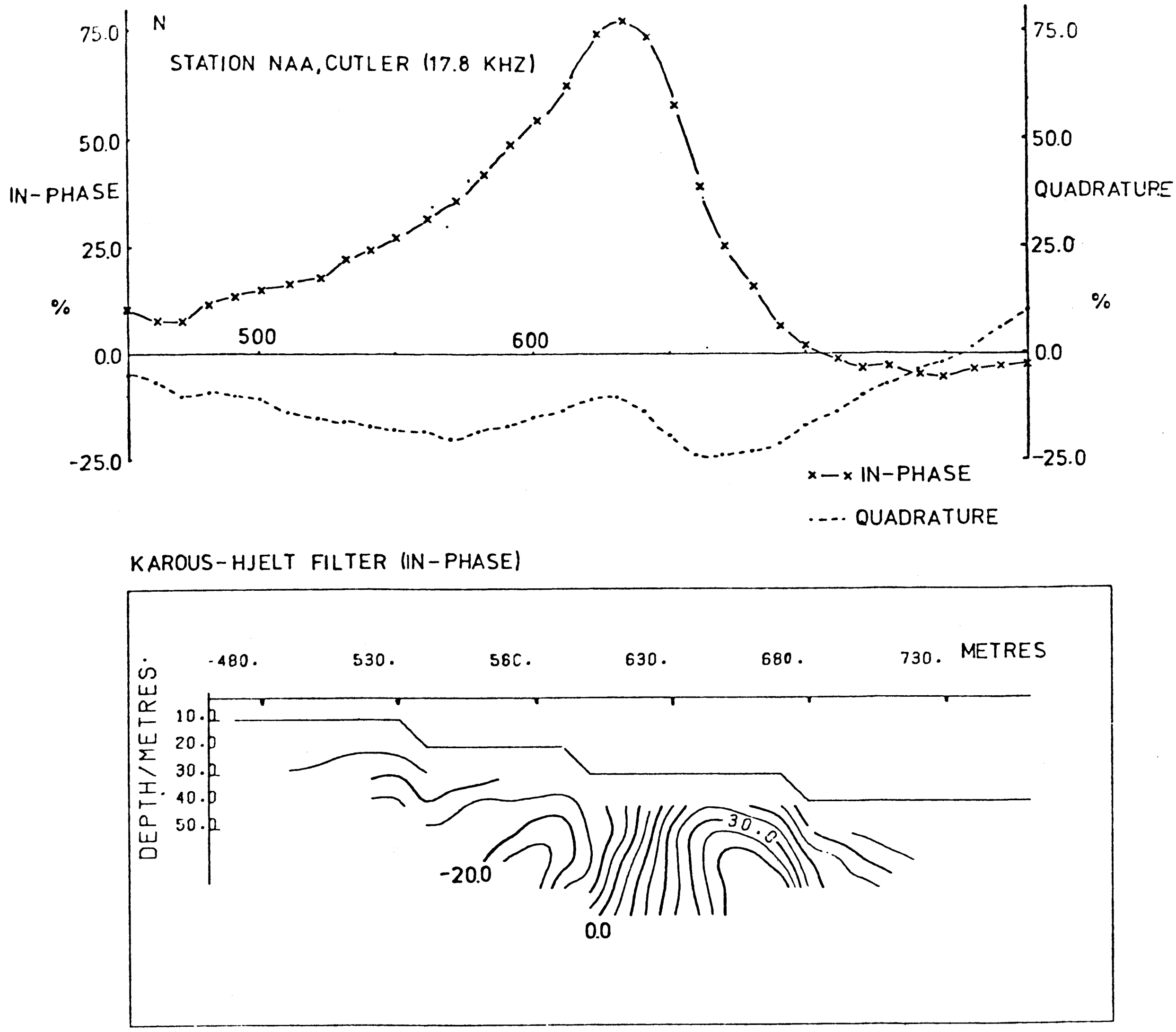
Example 3

A major fault is known to cross the park, running N.W.-S.E. from about 100 m east of the Hunts Hill entrance, between Bowling Green Plantation and Deer Park Spinney, towards Deer Barn. The mapped position of the fault coincides with intermittent VLF anomalies. This is considered to be a consequence of the fault acting as a control on accumulations of boulder clay and Keuper Marl, in a similar manner to that of the markfieldite intrusion.

Text-fig. 8 shows an apparent current distribution section for a line extending south from a point 300 m south of the eastern edge of Sliding Stone Spinney. A zone of maximum positive current concentration reaches the surface about 650 m along the profile, and dips south at about 65°.

The mapped position of the fault is 20-30 m to the south of this point. The VLF measurements may again, however, indicate the true position of the fault, in view of the limited exposure. Similar patterns of current concentration occur in the two adjacent lines to the west, and Fraser filtered values (text-fig. 4) in grid area 531109 also suggest a fault controlled anomaly.

The absence of substantial anomalies in regions of high ground supports the suggestion that boulder clay abutted against a buried fault scarp, and not a conductive fault zone, causes the anomalies.



Text-fig. 8: VLF electromagnetic profile (top) and corresponding apparent current distribution section (in-phase), line 800.

Summary and Conclusions

A map of Bradgate Park showing contoured, positive Fraser filtered VLF values (text-fig. 4) is presented, and three examples of anomalies caused by geological features have been discussed. In each case, anomalies are shown to be caused primarily by current flowing in Pleistocene boulder clay, and possibly Keuper Marl, known to cover much of the park, and whose distribution is partially controlled by the underlying Pre-Cambrian geology.

VLF measurements have enabled delineation of two faults, and results support the suggestion that the northern contact of the markfieldite intrusion is faulted. Several constraints on the credence given to the interpretation must be noted. These provide suggestions for further study, both in terms of VLF surveying in general, and for VLF surveying in Bradgate Park in particular.

Firstly, the Karous-Hjelt filter has yet to be fully assessed. Members of the Applied Geophysics Unit of the Institute of Geological Sciences have undertaken some investigations into its response to a variety of conductive structures (Patrick, 1978), and their findings should shortly be available as an open-file report. Work is clearly needed to assess the affect on VLF anomalies, of two or more conductors in close proximity, and of topography, especially when using the Karous-Hjelt filter.

No topographic corrections have been applied to measurements made in this work. Fraser filtering attenuates anomalies due to topography (Whittles, 1969) so that the results shown in text-fig. 4 are largely unaffected by topographically generated anomalies.

Finally, although regional geological strike appears to exert some control on the VLF anomaly pattern, no clear indication of either Pre-Cambrian lithological boundaries, or the dip of strata, was obtained from the survey.

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T.R. Seaborne,
Esso Exploration & Production UK,
Block 5
The Centre
Walton–on-Thames
Surrey KT12 1QN

SEDIMENTOLOGY OF THE TYPE SECTION OF THE UPPER SILURIAN LUDLOW-DOWNTON SERIES BOUNDARY AT LUDLOW, SALOP, ENGLAND

by

David D. J. Antia

Summary

The fauna, sediment, facies, mineral, grain size and quartz grain sphericity distributions through the holostratotype section of the Upper Silurian Ludlow-Downton Series Boundary at Ludlow are examined. It is concluded that four facies, A - D are represented and that the Ludlow Bone-Bed rests conformably on the top Ludlovian sediments in the section. The section is considered to represent a transition from a subtidal micrite environment through into first intertidal sand and mud flats (containing a poorly developed mudmound topography) and then intertidal beach or backbeach environments.

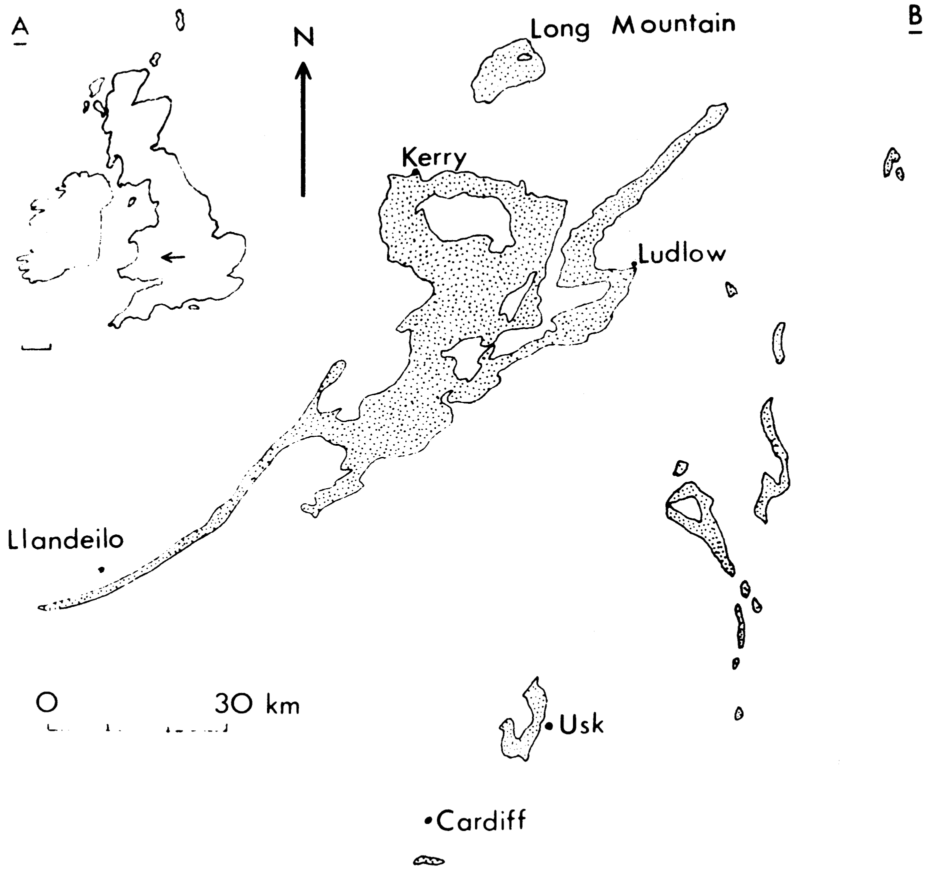
Introduction

The most distinctive layer in the sedimentary sequence at the Ludlovian-Downtonian boundary is the Ludlow Bone-Bed. It dominates the literature on the subject. Adjacent sediments have received scant attention. The present paper presents a study by the author to correct this imbalance of knowledge and present the Bone-Bed in its correct context. The area studied, is the holostratotype locality at Ludlow, Salop, (G.R. SO 5123 7913), for the Upper Silurian Ludlovian-Downtonian series boundary (text-fig. 1).

Stratotype Sequence

The faunas and sediments of the holostratotype Ludlow-Downton series boundary section at Ludlow were first described by Murchison (1839, 1859). Later studies by Elles & Slater (1906), Holland *et al.* (1963), Shaw (1969), and Allen (1974), established the nature of faunal, sedimentary and biostratigraphic changes across the section. They noted a distinct faunal and lithological change at the base of the Ludlow Bone-Bed with a sequence of calcareous siltstones containing a low diversity "Ludlovian" fauna of grey calcareous articulate brachiopods (e.g. *Protochonetes ludloviensis* and *Salopina lunata*) immediately below the Ludlow Bone-Bed, and a sequence of olive green siltstones and buff sandstones containing a low diversity Downtonian fauna of lingulid brachiopods, bivalves, ostracods, eurypterids and plants above. Consequently the section was designated (Elles & Slater, 1906; Holland *et al.*, 1963) as the holostratotype section for the Ludlovian-Downtonian series boundary, in which the actual boundary was placed at the base of the Ludlow Bone-Bed. The Ludlovian sediments have been assigned to the Upper Whitcliffe Beds and the Downtonian sediments to the Downton Castle Formation (Holland *et al.*, 1963; Allen, 1974).

Mercian Geologist, Vol.7, No.4,
1980, pp.291-321 13 text-figs.

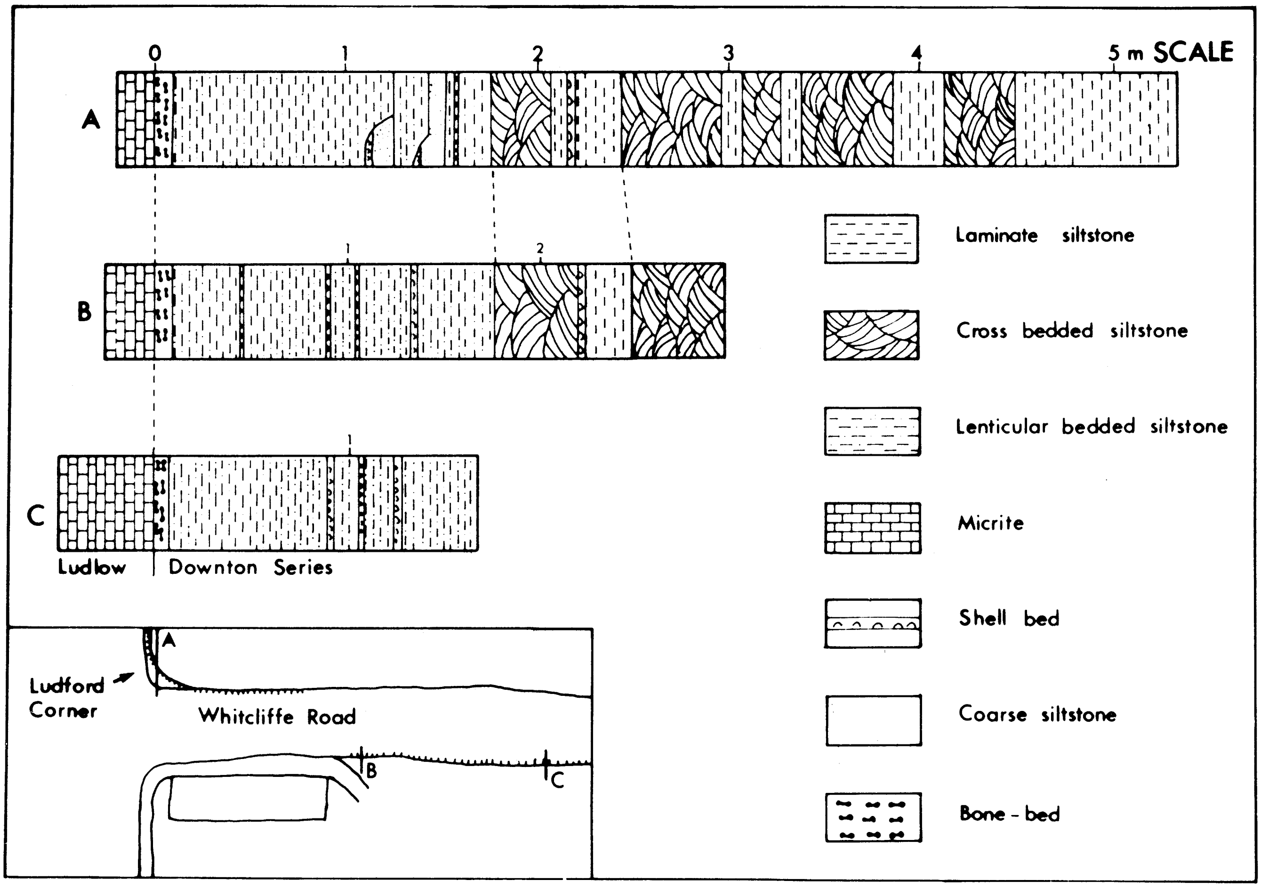


Text-fig. 1: Location map showing the outcrop of Ludlovian sediments in the Welsh Borderlands.

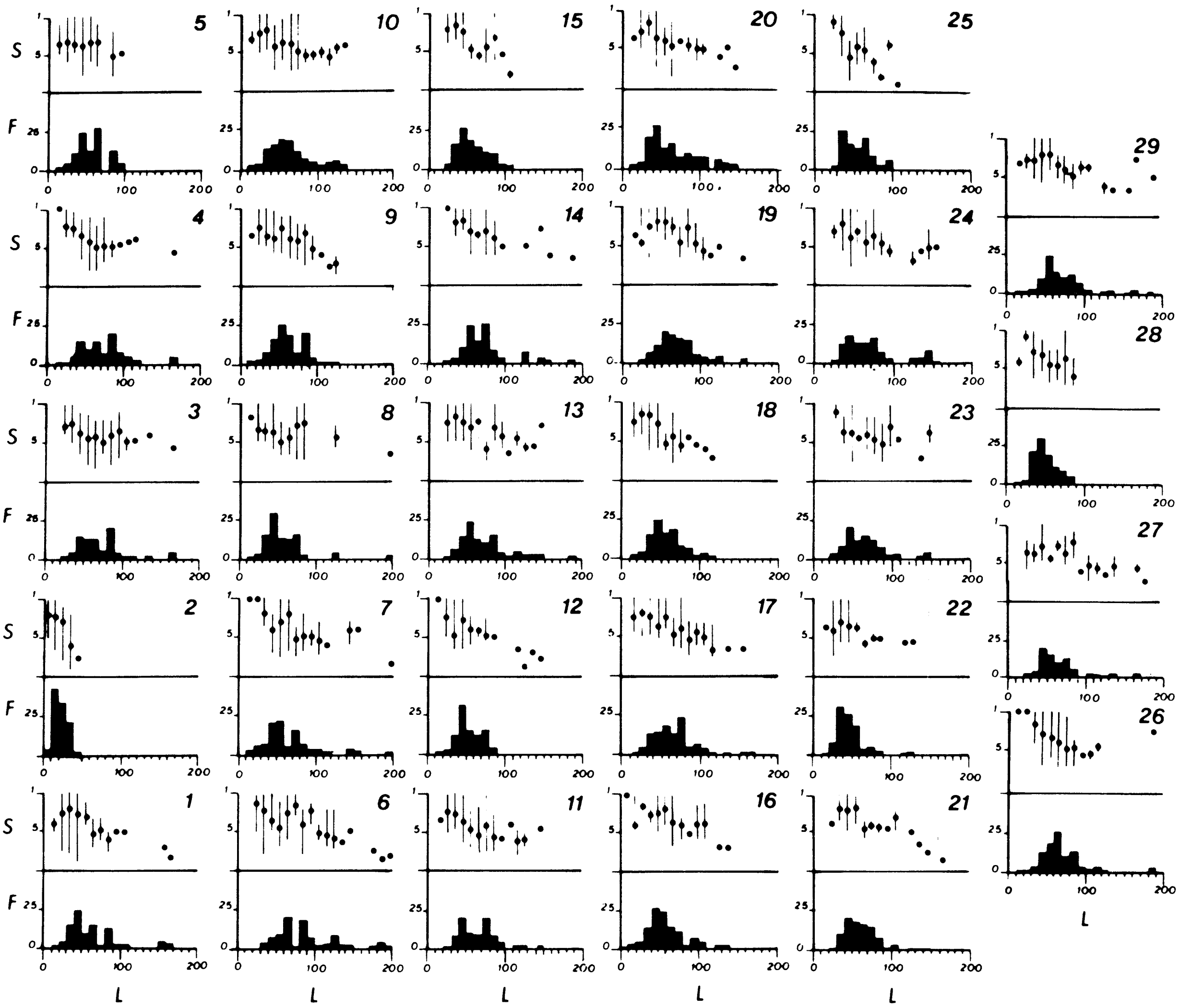
The sediments in the section have been assigned to a number of palaeoenvironments in the past. Initially, the Ludlovian sediments were considered to represent a marine environment and those of the Downtonian a brackish marine environment (e.g. Murchison, 1859; Stamp, 1923). The Downtonian sediments were later interpreted as having been deposited in a deltaic environment (Hobson, 1960; Allen & Tarlo, 1963). More recently four different sedimentary facies, A - D, have been recognised (Allen, 1979) in the section, and these are considered, (Allen, 1979; Antia & Whitaker, 1979; Antia, 1979), to indicate a change from a shallow marine Ludlovian environment to Downtonian intertidal mud flats and beach sands. The facies are now described in full and illustrated in text-fig. 2.

Facies A - Upper Whitcliffe Beds

This facies consists of an interbedded sequence of shelly calcareous siltstones and dark mudstones. The grain size distributions of the siltstones and mudstones are illustrated in text-fig. 3. The mudstones have a mean quartz grain size of about 0.01 mm, whilst that of the siltstones is about 0.05 mm. Bedding type varies from lenticular to wavey. Herring bone cross-bedding is not uncommon locally. Shells are well sorted and patchly distributed. About 40% are fragmented and most of the bivalved shells are disarticulated. About 90% of the concavo-convex particles (shells) overlying un-bioturbated sediment are orientated concave down. In the bioturbated sediment orientations vary from mainly concave down to concave up. Most isolated particles in this sediment type are orientated concave up. No burrowing bivalves were observed *in situ* in the facies. Most of the sessile epifaunal brachiopods occur as disarticulated valves (e.g. *Salopina*, *Microsphaeridiorhynchus*, *Howella*, (Fursich & Hurst, 1974) and motile swimming brachiopods (e.g. *Protochonetes* (Rudwick, M. personal communication, 1978). Joined valves are commonest amongst the species



Text-fig. 2: Sediments logged at three points on the Ludford corner - Whitcliffe Road Section (GR. S05123 7413). The micrite corresponds to Facies A, the Bone-bed to Facies B, the lenticular bedded siltstones to Facies C, and the laminate and cross bedded siltstones to Facies D.



Text-fig. 3: Quartz grain size distributions and sphericity plots for the Ludford lane section for slides 1-19. A key to slide Numbers is given in text-fig. 5. Slides 1-4 are in Facies A, slides 5-7 in Facies B, slides 8-23 in Facies C and slides 24-29 in Facies D.

Grain size (L) in m is given on the x axis. F = frequency (%) and S = sphericity (values 0-1). The mean sphericity and sphericity range are given for each size grouping. Sphericity is calculated as the shortest axis/longest axis of a grain on the slide.

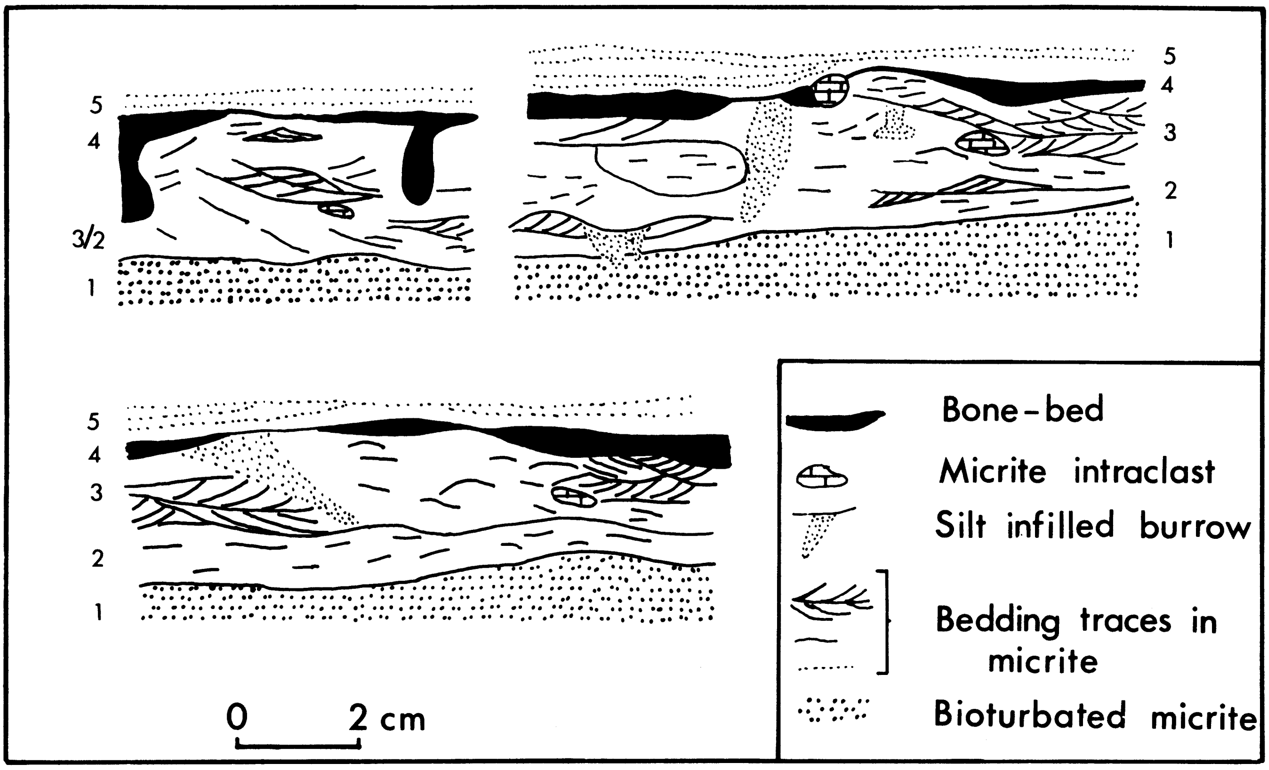
Table 1: Orientations of dead articulated *Cerastoderma edule* shells at Sales Point, Bradwell, Essex.

Orientation	Number	%
Shells posterior facing upwards	10	23.25
Shells anterior facing upwards	16	37.20
Shells ventral margin facing upwards	12	27.90
Shells dorsal margin facing upwards	5	11.62

M. nucula, which has a very strong hinge. Since it is difficult to disarticulate a brachiopod with a strong hinge, it could be argued that the presence of such brachiopods provides no real indication as to where an animal lived, as their shells would survive considerable transport (Jones, 1969; Lingwood, 1976). For example, a transported assemblage of the recent bivalve *Cerastoderma edule*, observed by the author in July 1976 just below the high tide mark in the shelly pebble and muddy sand habitat (Antia, 1977) of Sales Point, Bradwell, Essex (G.R. TM 032 087) consisted entirely of dead closed articulated valves, many of which had been reorientated into a "life orientation" on the surface of the substrate. Details of these shell orientations are given in table 1.

Ripples present in this facies vary from symmetrical crescentic current ripples (wavelength 5 to 20 cm; amplitude 3 to 30 mm) to linguloid (wavelength 4 to 10 cm; amplitude 5 to 15 mm) and mini-ripples (wavelength 4 to 9 mm; amplitude 1 to 2 mm). The wavey and lenticular bedded nature of the sediment suggest (Reineck & Singh, 1973) that the facies formed in a region of tidal flow. This is confirmed by the poorly developed herring bone cross-bedding present in the sediments (text-fig. 4). The mineralogy of the facies is indicated in text-fig. 5 and table 2. Its dominant constituent is quartz occurring as grains varying in diameter from 0.005 to 0.18 mm. The smaller quartz grains tend to be compact, while the larger grains tend to be elongate. Details of the relative elongation (sphericity) of the grains are given in text-fig. 3. The smaller quartz grains are apparently unstrained angular and non-composite. Some quartz grains greater than 0.1 mm in length are strained, others are composite. Most are angular, though some rare, well rounded grains are present. Leucoxene is the most common heavy mineral. Since some of the leucoxene grains contain an ilmenite core, it is possible that much of the leucoxene present may result from the diagenetic replacement of ilmenite by leucoxene after sediment deposition (Hobson, 1960). Micas (both biotite and muscovite) when present tend to be represented by both rounded and angular grains frequently containing frayed edges. These grains vary in diameter from 0.08 mm to 0.35 mm. Clays and micritic clays form a large part of the sediment, and show several phases of diagenetic growth. The initial growth appears to have been of platy and honeycomb clays around quartz nuclei, followed by a subsequent microcrystalline coprecipitation of clays and calcite within the "newly created" sediment pores. At the present time chlorite is the dominant clay (Antia, 1979; Antia & Whitaker, 1979) though traces of montmorillonite, kaolinite and illite are present.

Within the articulated shells, different diagenetic microenvironments appear to have operated. Most contain a geopetal infill of micrite overlain in some instances by a coarse sparite. Many of the calcareous shells have been replaced by sparite, though some micritic envelopes are present. In the latter instance the micritisation appears to involve either the emplacement of micritic aragonite or high-magnesium calcite in the shell punctae, or a centripetal replacement of whole shells by micrite leaving only scattered shell relics. The process of micritisation is poorly understood (Bathurst, 1975, p.391) but could relate to immediate post depositional bacterial activity or later localised diagenetic reactions. The



Text-fig. 4: Traces of vertical sections through the Ludlow Bone-Bed (layer 4) showing herring bone cross-bedding in the Whitcliffian micrites (layers 1-3) and the bone-bed infilling burrows in the underlying sediment.

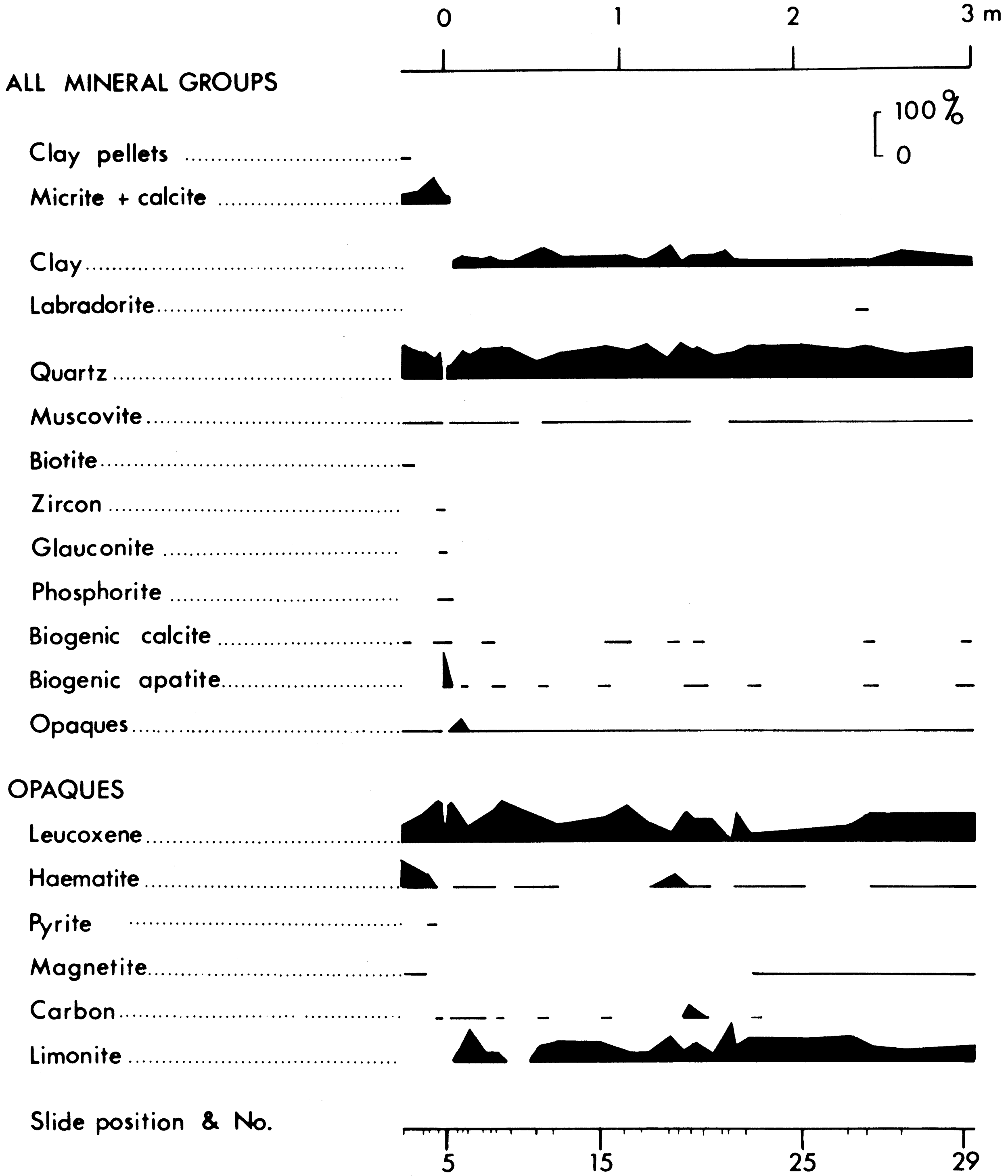
source of the micrite in the sediment is unknown. Among the more probable sources are the diagenetic dissolution and reprecipitation of calcite from shell debris and the reprecipitation of aragonite needles on the sea bed.

Within the facies, sediment type, faunal diversity and composition are variable along a bedding plane surface (text-fig. 6). Sample data is presented in table 3.

The faunal distributions (text-fig. 6) show that laterally three species become abundant in turn (*P. ludloviensis*, *S. lunata*, and *M. nucula*) on a single bedding plane. These changes could result from either three distinct clumps of living species with some post-mortem faunal mixing between the individual clumps (Boucot, personal communication, 1978), or from a marked post-mortem mixing and sorting of shells (cf. Lingwood, 1976; Antia, 1977) from differing environments and facies or even within the same facies.

An examination of particle size and shape can produce important information regarding the influence of currents and waves on current distribution and strength in the sediment. The CM diagram (text-fig. 7) for the facies (calculated after Passega, 1964, 1977) suggests that much of the sediment in the facies originally formed part of a suspension load. Since the effective settling velocity of both clastic and carbonate grains can be calculated, it may be possible to produce an estimate of the effective current strength on the sea bed.

Studies on shell particle settling velocities are rare (e.g. Macklem, 1968; Grubert, 1971; Futterer, 1978a, 1978b, 1978c). However, they have demonstrated that the mathematical functions currently used to calculate the settling velocities of particles (cf. Blatt *et al.*, 1972) are only valid for spherical particles (Futterer, 1978a) and that the effective settling velocities of biogenic particles approximate to:



Text-fig. 5. Mineralogy of the Ludford section B (see text-fig. 2).

Table 2: Mineral abundances across the Ludlow-Downton Boundary at Ludlow.
2a = burrow infill; 5a = -1 - 0 cm below the Ludlow Bone-Bed; 5b = Ludlow Bone-Bed; 5c = 0.2-0.5 cm above the Ludlow Bone-Bed.
The position of each slide in the section is indicated in text-fig.5. 1 = Clay pellets; 2 = Quartz; 3 = Micrite-calcite; 4 = Shell fragments;
5 = Muscovite; 6 = Opaques; 7 = Biotite; 8 = Fish debris; 9 = Phosphatic nodules; 10 = glauconite; 11 = Zircon; 12 = Clays;
13 = Labradorite. A = Leucoxene; B = Haematite; C = Magnetite; D = Pyrite; E = Carbonaceous debris; F = Limonite.

Slide	Minerals													Opaques					
No.	1	2	3	4	5	6	7	8	9	10	11	12	13	A	B	C	D	E	F
1	2.2	78.6	16.8	0.3	0.9	0.3	0.3	-	-	-	-	-	-	42.0	56.0	2.0	-	-	-
2	-	60.2	32.7	-	5.32	1.7	-	-	-	-	-	-	-	71.2	27.1	1.6	-	-	-
2a	-	80.7	-	-	13.4	5.7	-	-	-	-	-	-	-	10.0	-	-	-	-	-
3	-	56.6	37.5	0.3	1.4	1.8	-	-	-	-	-	-	-	94.2	5.7	-	-	-	-
4	-	37.0	50.7	0.5	3.0	8.6	-	-	-	-	-	-	-	55.7	10.7	-	3.5	-	-
5a	-	59.6	28.0	-	3.0	8.6	-	-	-	0.5	0.5	-	-	83.0	-	-	-	6.4	-
5b	-	-	19.7	-	-	-	-	77.9	4.6	-	-	-	-	-	-	-	-	-	-
5c	-	34.1	23.5	-	3.5	4.7	-	34.1	-	-	-	-	-	94.1	-	-	-	5.9	-
6	-	40.0	-	-	7.9	26.9	-	-	-	-	-	25.1	-	61.6	2.5	-	-	7.8	28.2
7	-	59.5	-	-	5.5	3.9	-	0.2	-	-	-	30.5	-	39.4	9.8	-	-	1.4	49.2
8	-	63.3	-	-	4.7	3.1	-	-	-	-	-	28.6	-	5.3	1.7	-	-	4.0	88.9
9	-	65.3	-	-	1.0	0.7	0.3	-	-	-	-	32.1	-	58.1	6.4	-	-	12.9	22.5
10	-	70.8	-	0.5	3.0	1.5	-	0.5	-	-	-	23.4	-	71.1	4.4	-	-	-	24.4
11	-	69.3	-	-	4.5	3.0	-	1.0	-	-	-	22.1	-	91.3	-	-	-	1.0	7.6
12	-	67.5	-	-	-	0.7	-	-	-	-	-	31.7	-	88.8	1.1	-	-	-	-
13	-	44.6	-	-	1.8	7.5	-	0.6	-	-	-	45.2	-	54.8	1.6	-	-	1.6	41.9
14	-	64.4	-	-	3.1	8.1	-	-	-	-	-	24.3	-	48.9	3.0	-	-	-	47.9
15	-	69.5	-	0.9	0.6	3.0	-	0.6	-	-	-	25.2	-	52.8	-	-	-	3.7	43.4
16	-	69.3	-	0.5	0.5	0.5	-	-	-	-	-	29.1	-	77.9	-	-	-	-	22.7
17	-	76.6	-	-	4.2	1.2	-	-	-	-	-	17.8	-	41.5	3.8	-	-	-	28.5
18	-	47.5	-	0.3	2.4	4.0	-	-	-	-	-	45.6	-	17.6	20.5	-	-	-	61.8
19	-	76.3	-	-	0.9	1.9	-	0.9	-	-	-	19.2	-	65.2	3.0	-	-	-	31.8
20	-	66.8	-	1.0	0.3	1.6	-	0.6	-	-	-	29.5	-	52.5	9.3	-	-	-	38.1
21	-	72.3	-	-	-	1.6	-	0.5	-	-	-	25.4	-	51.8	3.9	-	-	21.7	22.8
22	-	57.9	-	-	1.1	4.5	-	-	-	-	-	38.6	-	10.8	-	-	-	1.2	86.6
23	-	60.9	-	1.4	2.5	1.4	-	-	-	-	-	19.2	-	65.7	2.7	-	-	-	31.5
24	-	73.2	-	-	1.3	0.9	-	0.3	-	-	-	24.1	-	19.3	11.2	1.6	-	6.4	61.2
25	-	78.5	-	-	1.4	0.9	-	-	-	-	-	19.0	-	26.9	9.9	11.3	-	-	51.7
26	-	76.1	-	-	0.2	0.8	-	-	-	-	-	22.7	-	35.5	-	5.7	-	-	55.6
27	-	75.8	-	0.9	1.4	1.9	-	0.7	-	-	-	19.3	0.5	53.4	7.7	1.7	-	-	37.0
28	-	52.6	-	-	4.8	3.8	-	-	-	-	-	38.6	-	58.6	0.4	10.2	-	-	31.1
29	-	61.2	-	14.4	1.6	0.7	-	0.7	-	-	-	21.4	-	32.7	11.8	-	-	-	34.4

Table 3: Faunal data for the transect illustrated in text-fig. 6. The position of Sample 1 is arrowed in text-fig. 6, the remainder are indicated by a tick.

Species	Sample No. 1	2	3	4	5	6	7
Brachiopods							
Craniops implicatus	1	8	-	-	1	-	12
Lingula sp. nov.	1	1	-	-	-	-	-
Lingula lata	-	2	-	-	-	-	6
Howellella elegans	1	4	1	3	-	-	-
Microsphaeridiorhynchia nucula	12	22	8	41	35	82	23
Protochonetes ludloviensis	38	163	28	6	57	13	17
Salopina lunata	24	28	624	321	126	17	84
Bivalves							
Fuchsella amygdalina	-	1	1	-	-	-	2
Modiolopsis complanata	-	-	-	-	1	-	-
Pteronitella retroflexa	-	1	2	-	-	-	4
Other Molluscs							
Bucanopsis expansus	-	-	1	1	-	-	-
Hyolithes forbesi	-	-	-	-	-	1	-
Ostracods							
Cytherellina siliqua	-	3	-	-	-	-	-
Kuresaaria circulata	1	-	-	-	-	-	-
Nodibeyrichia verrucosa	-	1	-	-	-	-	1
Sample Size	78	234	695	371	220	113	149

$s = k\,w/FD$ (cm/sec) (Futterer 1978c)

where s = settling velocity in cm/sec

k = proportion factor dependent on particle shape

w = particle weight

F = effective settling area of the particle

D = density of water

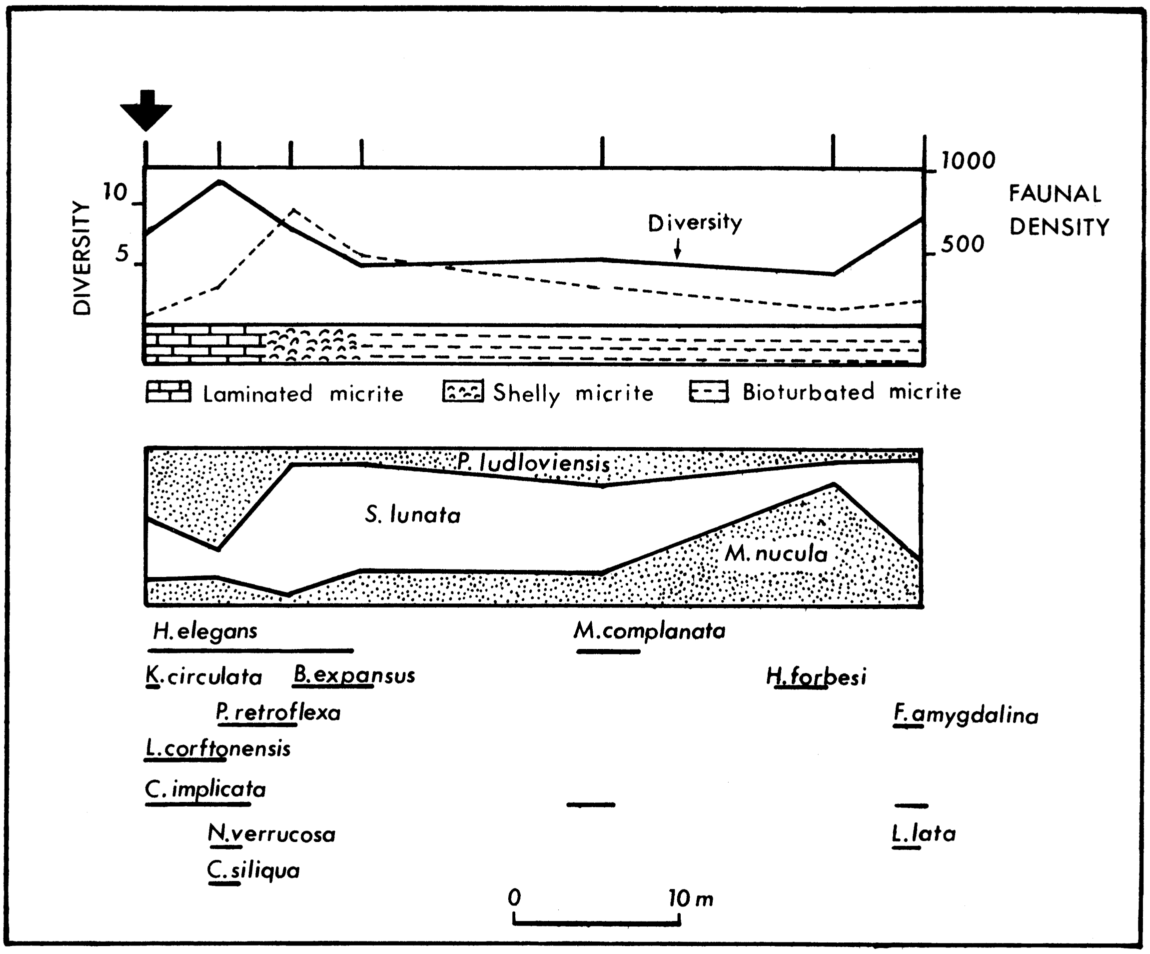
The proportion factor k need not be calculated since Futterer (1978a,c) has demonstrated a direct graphical relationship between the w/F ratio and the settling velocity of molluscan shells (bivalves and gastropods).

Shells and shell fragments are transported by flotation (Lingwood, 1976), rolling (Futterer, 1978b) and sliding (Futterer, 1978c). The mean grain size (0.04-0.07 mm) of the sediment and shell fragments (1-3 mm) suggests that their effective settling velocity from suspension was about 10 cm/sec.

Trace fossils are abundant in the sediment and can be grouped in three forms; vertical burrows - these include *Bifungites*, *Arenicolites* and *Skolithus*; oblique burrows - these include *Chondrites* like burrows and horizontal burrows and trails - these include *Agrichnium* and *Dendrotichnium*. The identifications given here are tentative. Pye (personal communication,1978) regards *Bifungites* as a polychaete worm burrow. Text-fig.4 illustrates the size distribution of burrows assigned to this species. A bedding plane drawing

Table 4: Fish scale composition of the 12 Bone-Beds observed in the section.

	Bone-Bed No.												
	0	1	2	3	4	5	6	7	8	9	10	11	12
Thelodonts													
Thelodus bicostatus (Hoppe)	0.1	0.3	0.1	-	-	0.1	-	0.7	0.6	-	-	-	-
Thelodus costatus (Pander)	-	-	-	-	0.1	0.1	-	-	-	-	-	-	-
Thelodus pugniformis Gross	0.5	0.7	-	1.8	0.1	0.7	0.3	-	0.6	-	0.3	0.5	0.2
Thelodus trilobatus (Hoppe)	-	2.1	0.1	0.9	1.5	2.0	0.3	5.7	-	1.4	0.3	-	0.6
Thelodus parvidens Ag.	69.9	82.9	78.0	63.4	51.0	45.8	42.8	28.5	26.3	21.3	7.1	5.5	16.2
Logania ludloviensis Gross	29.3	13.4	21.7	33.2	46.6	51.1	56.2	64.2	71.7	77.2	92.0	93.9	82.5
Katoporus tricavus Gross	0.1	-	-	-	-	-	-	-	0.6	-	-	-	-
Gonioporus alatus Gross	-	-	-	0.6	-	-	-	0.7	-	-	-	-	-
Acanthodians													
Nosteolepis sp.	-	0.2	-	-	-	-	0.3	-	-	-	-	-	-
Gomphonchus sp.	-	0.2	-	-	0.4	-	-	-	-	-	-	-	0.2
Sample Size	1432	521	834	331	643	986	322	140	152	136	278	781	431
Height above Ludlow-Downton Boundary (cm)	0	1	3.3	4.9	7.1	8.9	9.1	9.7	10.1	24.2	53.7	110.2	124.9



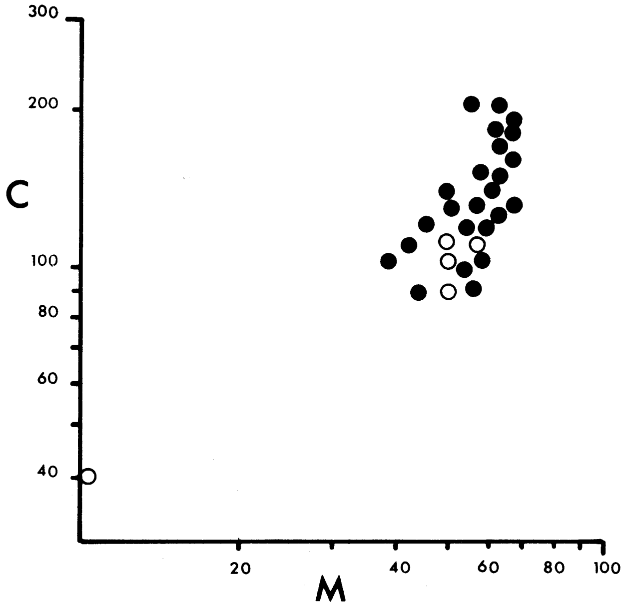
Text-fig. 6: Variation in sediment type, faunal diversity and faunal composition along a bedding plane surface 14 cm below the Ludford Bone-Bed. Arrow indicates Ludford Corner. Transect is along Whitcliffe Road. The raw data used to compile this diagram is presented in Table 2.

of trace fossils in this facies is given in text-fig. 8. Note that the trace fossils indicate the presence of a major NE-SW trending current.

Facies B - Downtonian

The bone-bed part of facies B (Allen, 1974) has been extensively described in the literature (Murchison, 1837, 1839, 1859; Elles & Slater, 1906; Stamp, 1923; King, 1934; Allen, 1962, 1974; Allen & Tarlo, 1963; Antia & Whitaker, 1979; Antia, 1979, etc.). Originally the facies was considered to contain just one bone-bed and was described as "a gingerbread coloured layer of a thickness of three to four inches dwindling away to quarter of an inch' (Murchison, 1859). More recent work has shown the section to contain a number of bone-beds (Allen, 1974; Antia, 1979), none of which are as thick as that described by Murchison. However, it is possible that a thick bone-bed did exist at Ludlow, and has now been removed by geologists, etc., as bone-beds elsewhere in the Welsh borderlands exhibit very rapid thickening and thinning within the space of a few metres, e.g., Corfton and Aston Munslow (SO 4965 8535 & SO 512 866).

The basal bone-bed in the facies is considered (Elles & Slater, 1906; Stamp, 1920; Holland *et al.*, 1963; Antia, 1979) to be the Ludlow Bone-Bed. It rests on a rippled silt, containing a crescentic rippled upper surface (wavelength 5-10 cm; amplitude 5-10 mm).

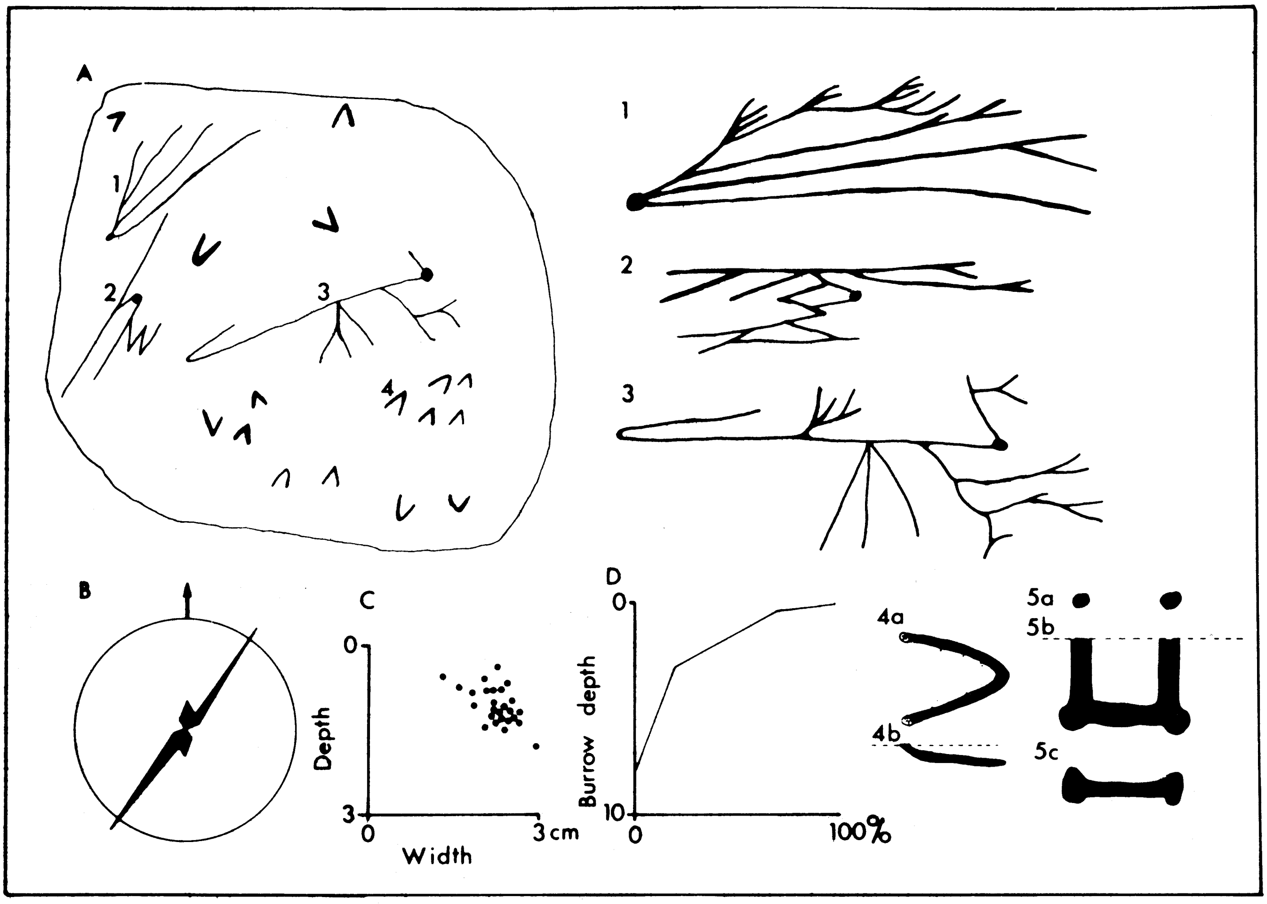


Text-fig. 7: C/M diagram for the Ludford transect. Open circles are Whitcliffian samples. Closed circles are Downtonian samples.

The ripple troughs are bioturbated containing *Bifungites* burrows infilled with coarse silt and vertebrate debris (text-fig. 4, p.296). These burrows penetrate the sediment to a depth of 1.5 cm, and cover the sediment surface in burrow densities ranging between 35 and 75 burrows per sq. m. Other burrow types present on this bedding plane surface include *Dendrotichnium*, *Skolithus*, *Lobichnus* and *Agrichnium*. Occasional specimens of *Goniophora cymbaeformis* occur half buried in the sediment in apparent life orientation (cf. Scott, 1978).

The basal bone-bed consists of a thin discontinuous (0-6 mm thick) gingerbread coloured vertebrate sand, infilling ripple troughs and scour hollows in the underlying sediment. Its matrix is dominated by a quartz rich micrite. The mean grain size of the quartz grains is about 0.045 mm (text-fig. 3, p.294. Calcareous shell debris is absent from the layer. However, the larger quartz grains and fish debris in the layer have acted as centres of calcite and micrite growth. This bone-bed is overlain by a thin (3-5 cm thick) layer of calcareous grey laminated mudstone containing a shelly brachiopod fauna and casts and moulds of ostracods and molluscs, perhaps suggesting that the ostracods and molluscs had aragonitic skeletons, while the brachiopods had phosphatic calcareous or calcite shells (Bathurst, 1975). Also present in these muds are bedding planes strewn with fish debris (10 fragments per cm^2) and shell fragments. Some rippled strata and bone-beds are present in this sediment. The top of this mudstone is marked by a thick (15 mm) discontinuous rippled bone-bed which is overlain in some places by a lenticular bedded silt sand sequence containing discontinuous bone-bed horizons. In other places an intervening layer is present consisting of a soft clay containing quartz, biotite and muscovite.

The relative position of each discontinuous bone-bed present in Facies B, to the facies base noted by Antia (1979) is listed in table 4. As already noted, individual bone-beds in the section vary in thickness from 0.5 to 25 mm and are mostly rippled or infill ripple hollows, though some consist of a dense scattering of vertebrate grains on a flat surface. Elsewhere bone-beds of this latter type have been termed scatter bone-beds (Sykes, 1977). All the bone-beds are locally discontinuous, though some can be traced for 30 m laterally along the section.



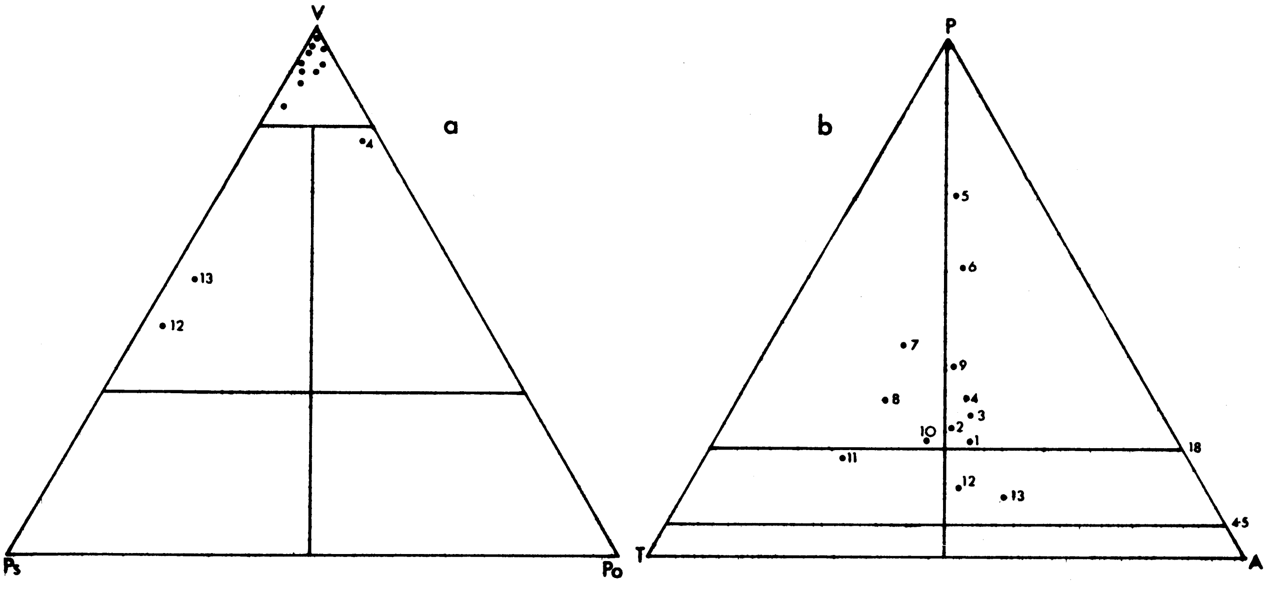
Text-fig. 8: Trace fossils in Facies A:

(a) Bedding plane trace (25 cm in diameter) of trace fossils 14 cm below the Ludlow-Downton Boundary at Ludford corner. The four types of trace fossils observed are labelled 1-4 and illustrated. Type 4 is termed here ?*Zoophychus* sp. Burrow Type 5 is common throughout Facies A, and termed here *Bifungites* sp.

(b) Axial orientation of ?*Zoophychus* sp. indicating a NE-SW current orientation.

(c) Plot of burrow depth against % of burrow width for *Bifungites* sp.

(d) Plot of burrow depth against % of burrows reaching that depth of penetration from the sediment surface.



Text-fig. 9: Composition and classification of Bone-Beds in the Ludford section:

(a) Relative proportions of vertebrate remains (V), Phosphatic shells (Ps) and Phosphatic nodules (Po). This graph indicates that most of the bone-beds are lithobonebeds, 4 is pelbonebed, 12 and 13 are biobonebeds (classification after Antia, 1979).

(b) Relative proportions of phosphatic material (P), terregenous clasts (T) and allochems (A) in each bone-bed. Bone-beds 11-13 are subbone-beds (cf. Antia, 1979). The position of each bone-bed in the section is given in Antia (1979).

The individual bone-bed layers are sparitic, micritic and clayey lithobonebeds, biobonebeds and pelbonebeds (see text-fig. 9) and are composed of vertebrate and phosphatic shell debris, quartz, feldspar, phosphate and clay grains within a diagenetic matrix. The composition of individual bone-beds is variable both laterally and vertically. However, all contain between 5 and 85% phosphate of which between 30 and 95% is fish debris and phosphatised invertebrate shells.

The chemical composition of the phosphate in the individual bone-beds is variable ranging from a fluorapative to a carbonate apatite. There also appears to be a relationship between the chemical composition of the phosphatic clasts and the nature of the bone-bed sediment type (Antia, 1979).

1. Faunal composition

The faunal composition of each bone-bed is outlined in table 4. Note that at the facies base the fish faunas are dominated by *Thelodus parvidens* while at the facies top *Logania ludlowiensis* dominates. This domination could either result from a change in the composition of the fish schools of the sea (Antia, 1979) or the effects of differential particle size and shape sorting by currents and waves, since the effective settling size spherocities and rollability of the two species would be very different. As the facies was deposited during marine regression, it could be suggested that the upper part of the facies was deposited in a more onshore environment than its lower part. Consequently, the difference in clast composition observed could reflect an original depositional sorting of material within the lower part of the intertidal zone.

2. Fish remains

Within the bone-beds fish remains are common. Most of the species present have been described or illustrated by Murchison (1859), Gross (1967, 1972), Turner (1973), Antia (1979) and Antia & Whitaker (1979). The species recorded by the author are listed in table 3.

Most of the fish remains are unabraded. However, individual grains do show some abrasion features and weathering features, whilst others contain microborings (Antia & Whitaker, 1979; Antia, 1979).

(a) Weathering features

During decomposition vertebrate grains produce a series of distinctive external morphological features. On large grains (e.g. mammalian bones) many of these features are visible to the naked eye. On smaller grains (e.g. Thelodont fish scales) they only become obvious when examined at high magnification (i.e. greater than x 200). From this bone-bed facies Antia (1979) has recorded a number of weathering features and has suggested that the individual bone-beds formed over a very short period of time, i.e., within 10 years of the death of the fish constituting the bone-bed.

(b) Abrasion features

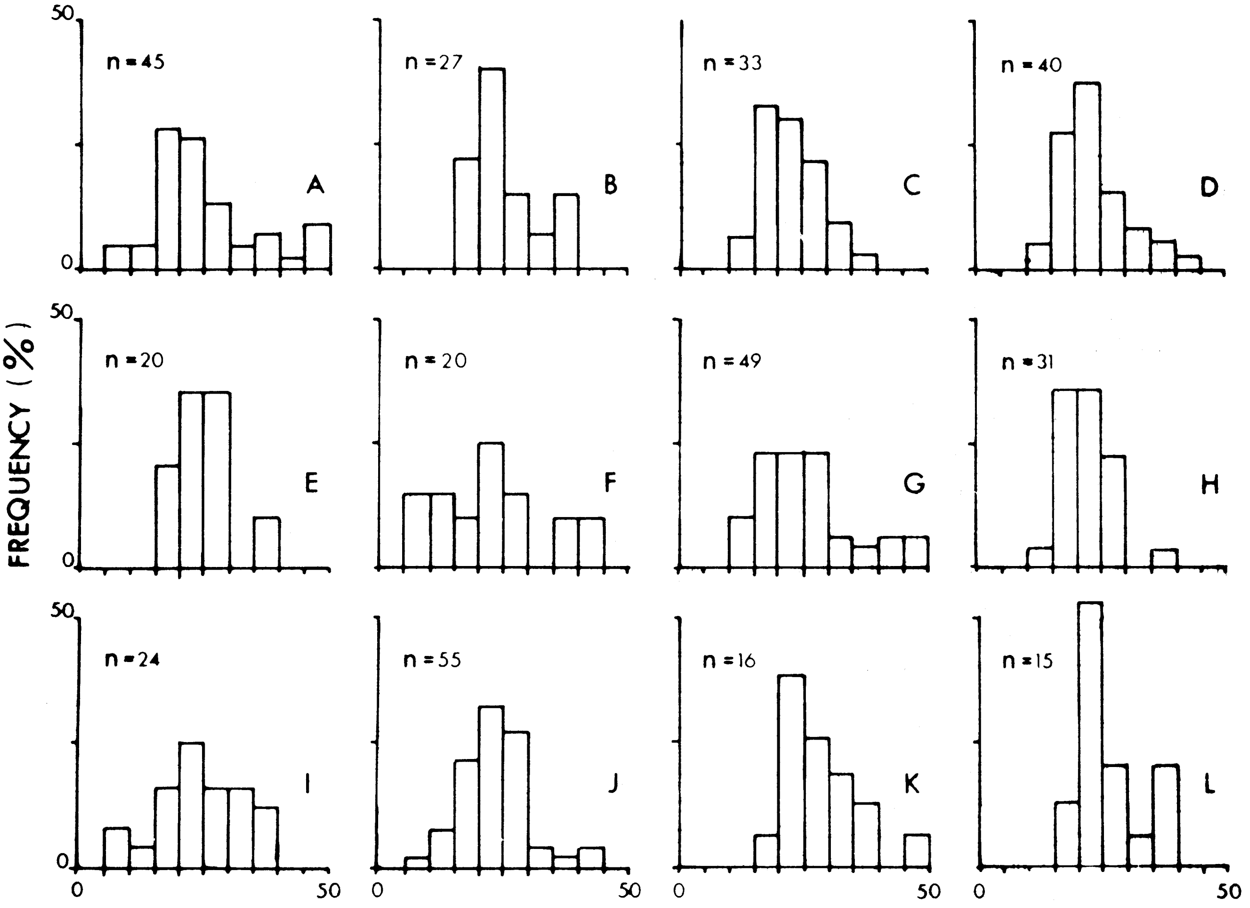
Thelodont grains are usually complete and show little evidence of abrasive rounding. However, chip marks and abrasion scratches are present on their outer surfaces (Antia & Whitaker, 1979). Some grains have been broken in half during deposition. In such cases the break has developed along cracks parallel to the net radial fibrous structure of the grain (cf. Antia, 1979). These cracks may be a result of bone weathering processes (Behrensmayer, 1978; Antia, 1979). Similar abrasion cracks have been recorded (Antia, 1979) on vertebrate grains from the Muschelkalk Grenzbonebed, the Rhaetic Bone-Bed and the Suffolk Bone-Bed.

Acanthodian spines, scales, teeth and fragments present in the bone-bed also contain abrasion scratches. Fractures produced by abrasive weathering are commonly orientated parallel to the spines axis, though some specimens contain breaks orientated perpendicular to their axis. Other acanthodian fragments are well abraded with fracture surfaces orientated parallel to histological tubes revealing their complex morphology.

(c) Microborings

Microborings are abundant on thelodont scales. Two types are present and have been termed Algal Form A and Algal Form B (Antia, 1979). Algal Form A consists of small (0.01 mm) diameter tubes, while Algal Form B consists of hemispherical cup shaped hollows on the scales surface (0.005-0.065 mm in diameter). Size data pertaining to this latter form is presented in text-fig.10.

Similar borings are present on Eifelian and Gedinnian thelodonts from Iran and France (Material examined in Dr. D. Goujet's collection, Paris), *Acrodus* fragments from the Muschelkalk Grenzbonebed and on recent otoliths from the Rockall Bank. The borings also occur on acanthodian spine fragments as either isolated borings on their surface or densely packed in the grooves of the spines. It has been suggested (Antia, 1979) that the distribution of this species might be controlled by the level of light penetration into the water.



Text-fig. 10: Size/frequency histograms of the diameter (x axis) of Algal form B borings on 12 thelodont (*T. parvidens*) scales. Size measurements are in mm.

3. Conodonts

Conodonts are a rare constituent of the bone-bed facies and all occur as worn and fragmentary remains. The species present include *Ozarkodina confluens*, *O. eosteinhornensis*, *Distomodus dubius*, *Pelekysgnathus dubius*, and *O. excavata* (Aldridge, 1975).

4. Quartz grains

Quartz grains in the bone-beds occur in two size groups. The first has a modal peak of about 0.05 mm and the second, of about 0.6 mm. Quartz grains in the first category range in size from about 0.01 to 0.23 mm and have a negatively skewed, leptokurtosic size distribution (text-fig. 3, p.292). These grains are generally compact though grains longer than 0.065 mm tend to be elongate (e.g. text-figs. 3 & 6). None of the quartz grains examined were composite or strained. Quartz grains in the larger model group are rare

Table 5: Faunas present above the Ludlow-Downton Boundary at the Junction of the Leominster-Ludlow Road and Whitcliffe Road (Transect A, text-fig. 2).

	Height above boundary (cm)					
	0	55	122	157	246	493
Brachiopods						
Lingula cornea (J. de C. Sowerby)	-	-	-	-	0.26	
Lingula minima (J. de C. Sowerby)	47.97	13.97	5.72	66.24	7.59	
Bivalves						
Grammysia sp.	-	-	0.03	-	-	
Leodispis barrowsi Reed	-	-	-	-	0.26	
Modiolopsis complanta (J. de C. Sowerby)	2.70	5.18	1.75	5.71	-	
Sdenamya sp.	-	0.14	-	-	-	
Gastropods						
Loxonema gregarium (J. de C. Sowerby)	9.48	0.14	0.03	-	-	
'Platyschisma' williamsi (J. de C. Sowerby)	0.67	0.14	-	-	-	
Turbocheilus helicites (J. de C. Sowerby)	-	13.68	0.42	0.57	-	
Ostracods						
Cytherellina siliqua Jones	7.43	1.44	2.81	5.79	12.56	
Hermmania cf. *marginata*	0.67	-	-	-	-	
Londinia kiesowi (Krause)	8.78	1.58	1.12	1.71	13.87	
Frostiella groenvalliana Martinsson	13.51	18.44	48.84	16.00	18.84	
Hebellum cf. *tetragonum* (Krause)	-	0.14	4.92	0.57	-	
Nynamella sp.	0.67	0.57	4.72	0.57	2.35	
Primitia cf. *mundula* Jones	-	0.28	0.26	-	-	
Fish						
Cythaspis sp.	2.02	-	-	-	-	
Logania ludlowiensis Gross	4.05	41.06	25.59	-	0.26	
Gomphonchus tenuistriata Ag.	-	0.14	0.03	-	-	
Thelodus parvidens Ag.	5.40	0.28	3.50	-	-	
Other Fossils						
Calcareous tubes (< 3 mm length)	-	1.58	0.06	2.85	-	
Ceratiocaris sp.	0.67	-	-	-	-	
Pterygotus sp.	2.70	0.14	0.06	-	0.26	
Plant debris						
Pachytheca sphaerica Hooker	3.37	-	0.39	-	40.57	
Sample Size	148	694	3024	175	382	

Table 6: Faunas across the Ludlow-Downton Boundary at Ludlow (Transect B, text-fig. 2).

	Height above the boundary (cm)						
	-18	0	23	67	114	154	254
Brachiopods							
Lingula sp. nov.	2.00	-	-	-	-	-	
Lingula lata (J. de C. Sowerby)	7.63	-	-	-	-	-	
Lingula minima	-	20.67	14.11	6.00	11.70	12.92	
Howellella elegans	4.01	-	-	-	-	-	
Microsphaeridiorhynchus nucula (J. de C. Sowerby)	23.29	1.11	-	-	-	-	
Orbiculoidea rugata (J. de C. Sowerby)	0.80	-	-	-	-	-	
Protochonetes ludloviensis Muir Wood	10.84	2.79	-	-	-	-	
Salopina lunata (J. de C. Sowerby)	40.16	10.61	-	-	-	-	
Bivalves							
Fuchsella amygdalina (J. de C. Sowerby)	1.20	-	-	-	-	-	
Goniophora cymbaeformis (J. de C. Sowerby)	2.00	-	-	-	-	-	
Leodispis barrowsi	-	-	-	-	-	0.38	
Modiolopsis sp.	0.80	-	-	-	-	-	
Modiolopsis complanata	-	7.26	65.88	14.00	14.88	27.86	
Pteronitella retroflexa (Wahlenberg)	0.40	-	-	-	-	-	
Gastropods							
Loxonema gregarium	-	0.55	-	-	-	-	
Loxonema obsoletum (J. de C. Sowerby)	0.80	-	-	-	-	-	
Turbocheilus helicites	-	7.26	2.94	9.00	-	0.38	
Ostracods							
Calcaribeyrichia torosa Jones	0.80	-	-	-	-	-	
Cytherellina siliqua	0.80	16.20	4.70	16.00	6.38	11.45	
Frostiella groenvalliana	-	21.22	-	51.50	58.51	40.07	
Londinia kiesowi	-	11.73	8.23	3.00	3.19	3.81	
Nodibeyrichia verrucosa Shaw	1.60	0.55	-	-	-	-	
Nynamella sp.	-	-	-	-	-	0.76	
Other Fossils							
Calcareous tubes (< 3 mm length)	-	-	-	-	-	1.90	
Cornulites sp.	0.40	-	-	-	-	-	
Hyolithes forbesi (Sharpe)	0.80	-	-	-	-	-	
Pachytheca sp.	-	-	4.11	0.50	5.31	0.38	
Thelodus sp.	-	C					
Gomphonchus tenuistriata	0.40	-	-	-	-	-	
Sample Size	249	179	170	200	94	262	

(Antia & Whitaker, 1979). They vary in shape from euhedral crystals to well rounded grains and angular shards (Antia & Whitaker, 1979; Antia, 1979). Many of the grains contain diagenetic overgrowths, which together with their order of precipitation during diagenesis, have been illustrated and described by Antia & Whitaker (1979), Antia (1979). They also showed that the quartz grains contain intertidal abrasion features and a silicified microbial flora on their outer surface. Many of the quartz euhedra present contain abrasion rounded edges and microplates on their outer surfaces. Such observations suggest that they have been transported in excess of 20 km from their source, since quartz euhedra can be transported in excess of 16 km in river systems without showing any abrasion chips or rounded features (Mulgrew, personal communication, 1978).

5. Phosphatised invertebrate shell fragments

Phosphatic invertebrate shell fragments are a common constituent of the bone-beds. Their geochemistry has been described by Antia (1979). Three phosphatised shell species are present as distinctive clasts. They are *Lingula* sp., *Orbiculoidea rugata* and *'Serpulites'* sp. All the invertebrate clasts are fragmentary. In many instances shell abrasion has removed the outer layers of the brachiopod shells to reveal their punctae. The clasts of *Serpulites* sp. occasionally reach 4 cm in length, but more commonly occur as fragments.

6. Phosphatic nodules

Phosphatic nodules present in the facies were originally described as fish coprolites (e.g. Murchison, 1859). They consist of small rounded pellets up to 2 cm in length, which are occasionally bored and frequently nucleate around crinoids and other shell fragments. Many of the nodules are internal moulds (Antia & Whitaker, 1979) of gastropods, monoplocophorans and hyolithids and appear to have been formed by the early diagenetic phosphate replacement of diagenetic clays (Antia & Whitaker, 1979). Most of the nodules are rich in limonite, quartz grains and fish scales, and may have formed by the same processes as modern phosphatic nodules on the continental shelf (Baturin, 1971; Burnett, 1977).

7. Other clast types

For details of the other clast types present in the bone-bed see Antia & Whitaker (1979).

Facies C

Facies C may be divided into two portions. A lower portion consisting of lenticular bedded mudstones, siltstones and fine sandstones, and an upper portion containing channels and mudcracks cutting into lenticular and wavey bedded mudstones, siltstones and sandstones. The transition from the lower to upper portion of the facies is gradual.

The mudstones are commonly rippled and frequently contain streaks of bone sand. Shell debris is fairly common and consists mainly of ostracods (tables 5-7, pp.307-311). *In situ* species observed in the mudstones include *Lingula minima* and *Modiolopsis complanata*. They are rare, commonly occurring in densities of about 1 or 2 per m^2 bedding plane surface area. *L.minima* appear to have preferred the lenticular bedded silts and fine sand environments within this facies, while *M. complanata* appears to have preferred the mudstones where it is found occasionally in clumps of up to 20 *in situ* individuals with orientated hinge lines.

At two levels in the section a pale olive-green siltstone (0.6 m and 0.3 m above the Ludlow-Downton Boundary) is present. These siltstones are rich in eurypterid segments containing up to 100 segments per m^2 bedding plane surface area. The lamination of this siltstone varies from poorly developed wrinkle marks and mini ripple lamination through to crescentic current ripples (wavelength 20-30 cm).

In the upper portion of this facies, layers of drifted macerated plant remains are common. These plants belong to *Cooksonia* sp., *Nematophyton*, *Prototaxites* sp. and *Pachytheca* sp. Most of the sediment in these facies consist of lenticular bedded siltstones

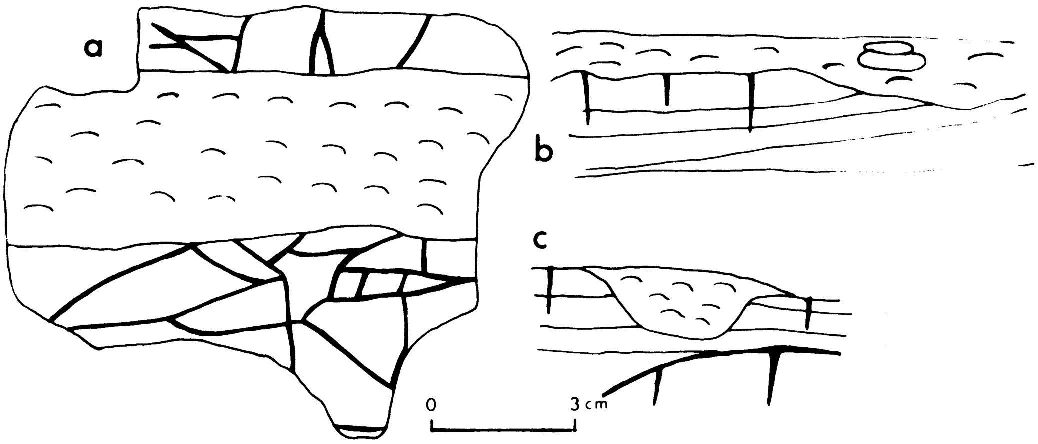
Table 7: Faunas across the Ludlow-Downton Boundary on Whitcliffe Road, Ludford. (Transect C, text-fig. 2) - Vertebrate faunas have been excluded from this layer.

	Height above boundary (cm)										
	-35	-25	-15	0	10	20	41	67	89	119	147
Brachiopods											
Craniops implicatus (J. de C. Sowerby)	3.92	16.59	0.88	0.46	1.20	-	-	-	-	-	
Howellella elegans	0.41	0.42	5.30	0.34	-	-	-	-	-	-	
Lingula sp. nov.	0.20	1.70	3.53	0.81	-	-	-	-	-	-	
Lingula lata	0.61	8.08	7.96	1.27	-	-	-	-	-	-	
Lingula minima	-	-	-	9.53	29.51	16.49	52.68	31.57	4.87	-	
Microsphaeridiorhynchus nucula	8.67	3.40	7.07	12.32	-	-	-	-	-	-	
Orbiculoidea rugata	-	0.42	0.88	-	0.60	-	-	-	-	-	
Protochonetes ludloviensis	46.28	5.95	16.81	5.69	1.20	-	-	-	-	-	
Salopina lunata	36.98	60.42	57.52	38.37	2.40	-	-	-	-	-	
Bivalves											
Fuchsella amygdalina	-	-	0.88	-	-	-	-	-	-	-	
Goniophora cymbaeformis	0.61	0.85	-	0.23	-	-	-	-	-	-	
Modiolopsis complanata	-	-	-	-	-	4.89	-	5.26	17.07	55.20	
Nuculites ovata (J. de C. Sowerby)	-	0.42	-	0.23	-	-	-	-	0.48	-	
Pterinea tenuistriata	-	0.42	-	0.46	-	-	-	-	-	-	
Pteronitella retroflexa	0.61	-	-	0.23	-	-	-	-	-	-	
Solenamya sp.	-	-	-	-	-	0.51	-	-	-	0.45	
Gastropods											
Cymbularia carinata (J. de C. Sowerby)	-	-	-	-	-	0.25	-	-	-	-	
Loxonema conicum (J. de C. Sowerby)	-	-	-	0.11	-	-	-	-	-	-	
Loxonema gregarium	-	-	-	0.46	1.20	6.95	2.15	5.26	1.95	-	
Loxonema obsoletum	-	-	0.88	0.58	-	0.25	-	-	-	-	
Turbocheilus helicites	-	-	-	3.60	0.60	5.41	-	-	7.31	2.71	

Other Molluscs										
Bucanopsis expansus (J. de C. Sowerby)	-	0.42	-	0.34	-	-	-	-	-	-
Leurocycloceras sp.	-	0.42	-	-	-	-	-	-	-	-
Ostracods										
Calcaribeyrichia torosa	0.61	-	-	-	-	-	-	-	-	-
Cytherellina siliqua	-	-	-	0.11	-	-	2.15	-	8.78	3.16
Frostiella groenvalliana	-	-	-	9.53	14.45	23.96	15.05	38.59	14.14	33.48
Hebellum cf. *tetragonum*	-	-	-	0.93	-	0.77	4.30	-	0.48	-
Kuresaaria circulata	-	-	-	0.58	0.48	2.06	-	-	-	0.44
Londinia kiesowi	-	-	-	10.46	22.89	18.04	23.65	10.52	42.43	2.71
Lophoctonella sp.	-	-	-	0.23	-	-	-	-	-	-
Nynamella sp.	-	-	-	2.20	0.60	0.51	-	-	-	0.44
Nodibeyrichia verrucosa	0.61	-	-	0.46	-	-	-	-	-	-
Bryozoan Colonies										
Leioclema sp.	-	-	-	0.23	-	-	-	-	-	-
Rhopalonaria sp.	-	0.42	-	0.11	-	-	-	-	-	-
Other Fossils										
Calcareous tubes (< 3 mm length)	-	-	-	-	-	-	-	7.01	1.46	0.44
Cornulites sp.	-	-	-	0.34	-	-	-	-	-	-
Eurypterid fragments	-	-	-	6.81	15.66	18.04	-	1.75	0.97	0.90
Ozarkodina sp.	-	-	-	-	0.60	-	-	-	-	-
Pachytheca sp.	-	-	-	-	3.61	1.80	-	-	-	-
'*Serpulites*' sp.	-	-	-	-	0.60	-	-	-	-	-
Plant debris	-	-	-							
Sample Size	484	235	113	860	166	388	93	57	205	221

and claystones. Locally flat bottomed channels with steep sides (10-25 cm deep and 65-75 cm wide) are present. Their sediment infill commonly consists of parallel laminated fine siltstones at their base, frequently containing abundant shell and vertebrate debris, which are overlain by cross-bedded siltstones and sandstones. This cross lamination consists of both symmetrical and asymmetrical ripple marks and grade upwards into fine siltstones and mudstones.

Allen (1974) compares these channels with the Rinnen of Hantzchel & Reineck (1968). However, they are morphologically similar to the Essex Mud Mound facies described by Davis (1964) and Greensmith & Tucker (1967, 1969, 1975). The channels in the section are separated by 'mounds' some 1 to 6 m apart. The upper surface of these mounds is frequently mudcracked and often contains abundant plant debris. Locally structures similar to gutter casts are present on the mound surfaces. They cut the mudcracks and are infilled with shelly sand (text-fig. 11).



Text-fig. 11: Mudcracked sediment surface cut by a 'gutter-cast' infilled with shell debris from the upper part of Facies C:
(a) Plan view showing gutter-cast cutting through mudcracked sediment.
(b) Longitudinal section along the gutter-cast showing that it has an irregular erosive base.
(c) Section normal to the gutter-cast axis illustrating its channel-like morphology. Note the presence of a relict mudcracked surface beneath the channel. The mudcracks are all infilled with coarse silt.

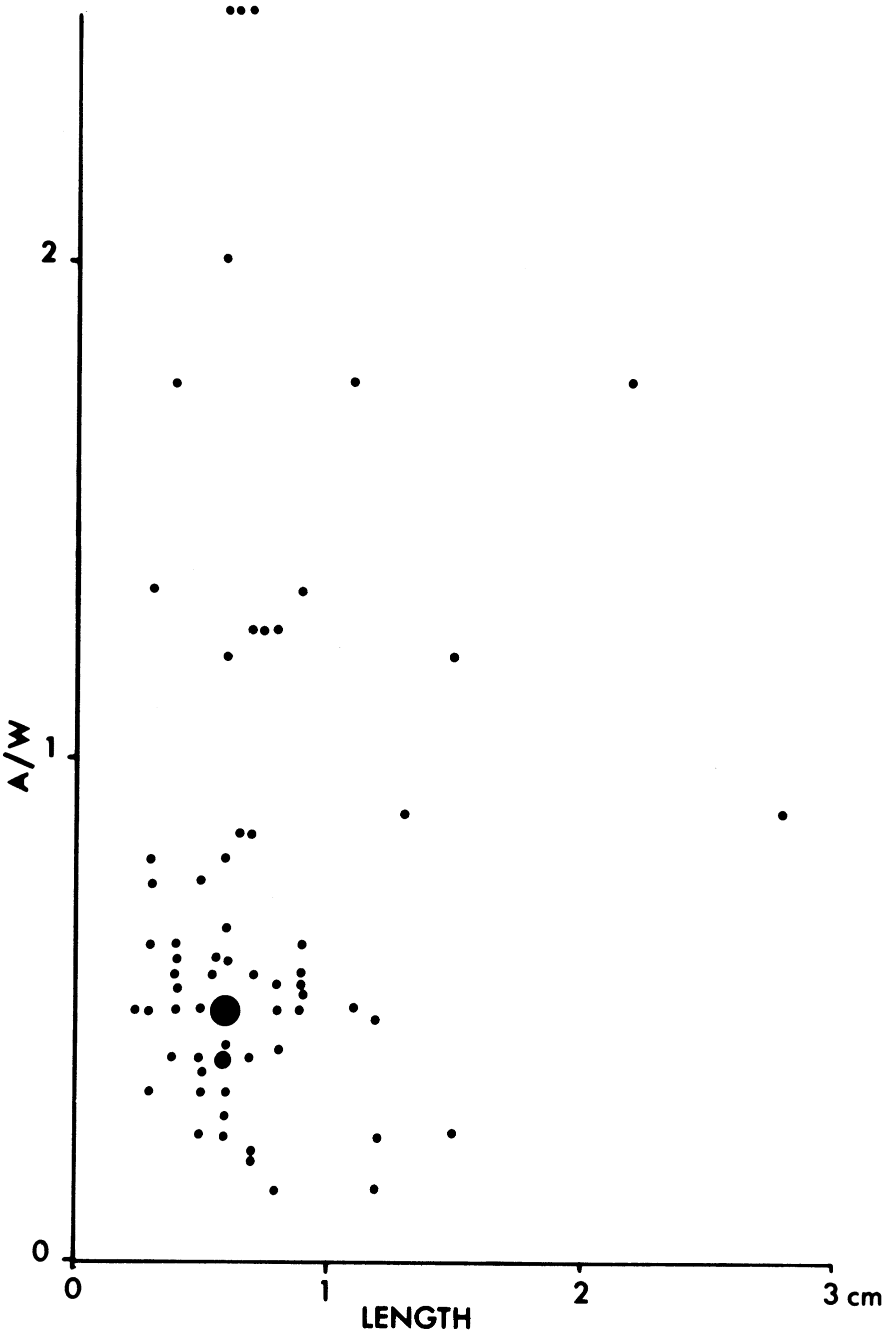
In the mounds, limonite replaced burrows and trails, limonitised and phosphatised complete internal moulds of *Loxonema gregarium* and *Leodispis barrowsi* are present. Mudcracks rarely penetrate to a depth greater than 3 cm and are infilled with coarse silt and fine sand. They have a crack width of between 0.5 and 3 mm.

The grain size and shape distributions (text-fig. 3, p.294) of the quartz grains indicate an effective settling velocity of between 10 and 15 cm/sec. The calcareous shell fauna of the environment consists of brachiopods, ostracods and molluscs (tables 5-7, pp.307-311. Shells of the latter two faunal groups tend to have been replaced during diagenesis by limonite. Some of the ostracod carapaces contain internal moulds of gypsum (e.g. *Cytherellina siliqua*).

Facies D

The upper 3 m of the stratotype section consists of an interbedded sequence of micaceous sandstones and micaceous siltstones. The sandstones occur as trough cross-bedded sand wedges (15-35 cm thick), which are locally channelled (Allen, 1974). They merge at their tops into micaceous siltstones containing either well developed parallel lamination or symmetric to asymmetric ripple marks with a wavelength of between 5 and 20 cm. Local erosion surfaces are present at the top and bases of these sand wedges. Allen (1974) has suggested that these sediments may be beach deposits.

Fossils are rare in this facies and occur as fragments of lingulid brachiopods, ostracods, eurypterids and plants. Locally patches (up to 1 m in diameter) of shell or plant debris are common within the siltstones. Trace fossils belonging to two forms ?*Isopodichnus* and ?*Zoophychus* occur infrequently in the siltstones, though locally the latter species occurs in densities which approximate to 800 per m^2 bedding plane surface area. Size and shape measurements for the latter species are given in text-fig. 12.



Text-fig. 12: Plot of ?*Zoophychus* length against posterior width/ anterior width. Large circle = 10 observations, median circle = 5 observations.

Grain size

Grain size and grain shape are useful parameters which can aid the interpretation of palaeoenvironments. Grain size as measured directly from slides is useless for comparative purposes with more modern grain size studies which deal in grain weight or volume. In order to make the slide measurements comparable with modern studies, the mean grain sphericity was calculated for each size frequency unit considered. Where grain sphericity (GS) is calculated as follows:

$$GS = S/L$$

where S = shortest axis of grain

L = longest axis of grain

Then for each size interval the mean grain sphericity (MGS) was multiplied by both grain frequency (GF) within the unit and the unit's median size (UMS) to give an effective volumetric frequency (VS).

i.e. $VG = MGS \times UMS \times VS$

The effective volumetric frequencies for each unit (i) were converted to their present volumetric frequencies (PVS).

i.e. $PVS = (VS_i / \sum_{i=1}^{n} VS) \times 100$

These percentage volumetric frequencies are presented in text-fig. 3 (p.294) and may be considered to represent the volumetric distribution of quartz grains of different size frequency elements within the section. The mean grain sphericity and grain sphericity range for each unit is also indicated in text-fig. 3.

The latter sphericity points and their variation with grain size within a sample are directly proportional to the equivalent variation in rollability (Winkelmolen, pers. comm. 1979). Consequently a plot of mean sphericity against grain size should produce similar patterns to a plot of rollability against grain size (text-fig. 13). Winkelmolen (1969, p.76-79, 1971, p.708-709) has distinguished five such distribution curves which are illustrated in text-fig. 13 and may be interpreted as follows:

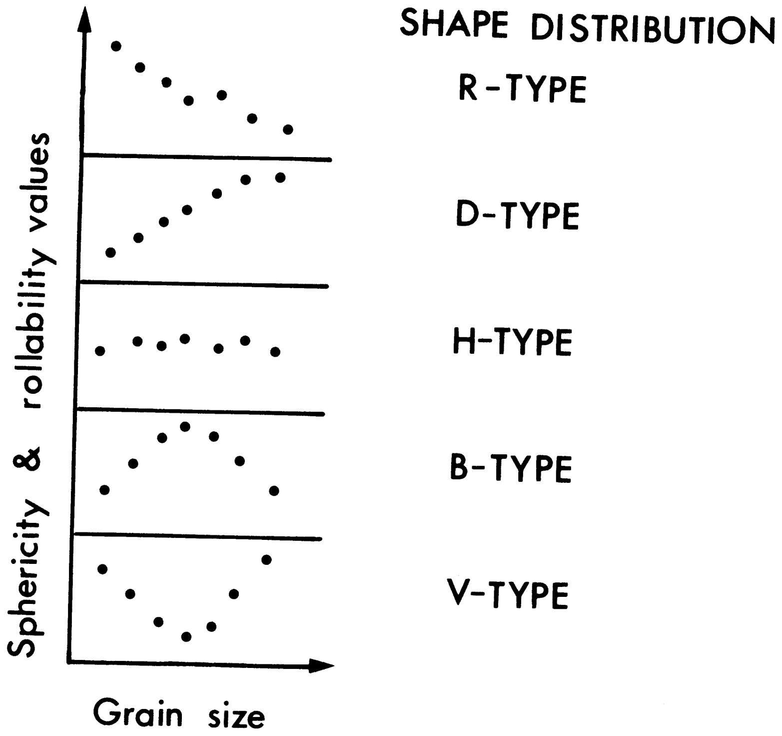
1. R-Type — These curves are characteristic of accreting environments of diminishing energy conditions. They are most commonly encountered in dunes sand/mud flats in tidal regions, beaches and point bar sequences (Winkelmolen, 1969, p.117; 1971, p.709). The beach and sandflat sediments tend to have fairly flat curves, while tidal sediments bordering channels and point bar sediments tend to have steep curves.

2. D-Type — curves characterise a lag deposit (Winkelmolen, 1971, p.709) formed in the tidal channels and in a shallow offshore zone, where sand is gradually moved towards a beach by wave action.

3. H-Type — curves indicate that the deposit has been derived from a local source that already contained lag characteristics inherited from earlier depositional events (Winkelmolen, 1969, p.79). This type of curve occurs most commonly in offshore sediments (Winkelmolen, 1969, p.117).

4. B-Type — curves are most characteristic of river channel deposits (Winkelmolen, 1971, p.709).

5. V-Type — curves are indicative of hybrid sediments which arise when there is a difference in strength or duration between alternating tidal currents. The sediment on the curves coarser side usually represents a relict lag deposit (Winkelmolen, 1969, p.80; 1971, p.709).



Text-fig. 13: Shape distribution curves for sphericity and rollability values, (modified after Winklemolen, 1969).

The sphericity distributions in text-fig. 3 of Whitcliffian and Downtonian sediments in the section show R-type curves in most of the section (e.g. text-fig. 3 - slides 1, 2, 9, 12, 14 to 21, 24, 25, 27, 28, 29), suggesting that the sediments were deposited in an accreting environment of diminishing energy conditions, e.g., a mud flat (cf. Winkelmolen, 1969; 1971). The Ludlow Bone-Bed (text-fig. 3 - slide 5) has an H-type curve suggesting that it formed as a lag deposit (cf. Winkelmolen, 1969). Composite H-type or very gently dipping R-type curves are present in the remainder of the section (text-fig. 3 - slides 3, 4, 6, 7, 8, 10, 11, 13, 15, 22, 23, 26). Many of these curves have V-type curves superimposed on an original R-type curve (e.g. text-fig. 3 - slides 4, 6, 7, 15). Such composite curves provide evidence that the Upper Silurian sediments were deposited in a region in which alternating tidal currents varied in strength and duration (cf. Winkelmolen, 1969; 1971).

The gradual diminution of the slope of the R-type curves from Facies A to Facies D (text-fig. 3) supports (Winkelmolen, 1969) the suggestion (Allen, 1979) that the transition from Facies A-B-C-D represents a regressive intertidal situation in which Facies D may have formed a beach and Facies A an offshore environment.

Palaeoenvironments

The lenticular bedded strata present in Facies A, B and C suggest that they were deposited in a region of tidal flow (cf. Reineck & Singh, 1973). The presence of mud cracks in the upper part of Facies C suggests that it was deposited or formed a temporary erosion surface in the upper part of the intertidal zone (cf. Greensmith & Tucker, 1967; 1976). The sphericity shape curves (text-fig. 3) suggest that the sediments were deposited in an accreting environment of diminishing energy conditions, e.g., a mud flat.

The distinctive change in mineralogy (table 4, text-fig. 5) at the boundary between Facies A and B is interesting because it implies a geochemical depositional change in the nature of the environment. It suggests that the sediments on the substrate in Facies A contained oxygenated carbonate rich geochemical microenvironments, while the presence of pyrite framboids (Antia, 1979) and pyrite deformed spores and acritarchs (Dorning, 1977, personal communication) in Facies B suggests that the depositional subsurface substrates (down to about 40 cm depth below the sediment water interface) in this facies were anoxic and reducing in nature (cf. Berner, 1970; Greensmith & Tucker, 1976). This is in part confirmed by the presence of silicified and phosphatised fungal filaments on the quartz and phosphate grains in this facies (Antia & Whitaker, 1979; Antia, 1979), because it is unusual for fungi to live on grains buried at a depth of greater than 20 cm below the sediment water interface in an intertidal or a subtidal marine environment (Meadows & Anderson, 1966, 1968). It is probable that the phosphatisation and silicification of the filaments occurred shortly after the deposition of the sediments (Antia & Whitaker, 1979) since studies of marine shelf sediments (e.g. Berner, 1970; Baturin, 1971; Burnett, 1977; Elverhøi, 1977, Muller, 1979) have shown that precipitation of pyrite, phosphate and silica can take place within 20 cm of a substrate surface.

Similar silica and phosphate precipitates are absent from Facies C sediments. Quartz grains when present are frequently well rounded and have a frosted exterior showing solution features similar to those present on the rare but well rounded quartz grains of the bone-bed facies, perhaps indicating a lateral transport of sediment from a region of Facies C deposition to a region of Facies B deposition. In both Facies C and D authigenic limonite is present. In C authigenic limonite and phosphate nodules are also present indicating reducing conditions of formation (Greensmith & Tucker, 1976).

The presence of both a geochemical and a sedimentological change at the Facies A - Facies B junction may indicate a major environmental change. Since the overlying Facies C contains mudcracks and Facies B contains intertidal abrasion marks on its quartz grains, it is possible that the bone-bed facies was deposited at a point low in the intertidal zone and that the Facies A - Facies B transition represents an intertidal-subtidal transition.

This interpretation confirms that of Richardson & Lister (1969) who recorded a chitinozoan-acritarch flora (indicating marine conditions) from Facies A, and a rare acritarch flora and an abundant spore flora from Facies B and C (indicating intertidal or terrestrial deposition).

Thus the Silurian sea represented by the Ludlovian-Downtonian transition Facies A, B and C may be envisaged as a carbonate rich oxygenated shelf sea containing rippled muds and silts, which merged landward at around the intertidal-subtidal junction into a series of rippled muds and silts containing discontinuous patches (up to 30 m in diameter) of coarse clean vertebrate sand. The remainder of the lower half of the intertidal zone may be seen as a series of rippled mud flats merging landwards into a series of runnelled muds (with individual runnels cutting down into previously deposited intertidal mud flat deposits) indicating local changes in the slope of the shoreface from 1 - 2° to 5 - 6° caused by tectonic tilting, sea level oscillations or the effect of a severe storm on the coast line (cf. Greensmith & Tucker, 1967). Since a good mud mound topography is unlikely to be preserved because of its erosive nature, it is probable that the runnel channels observed in the upper part of Facies C constituted the seaward end of a mud mound type complex, where they were more likely to be buried by landward encroachments of the rippled mud facies. The absence of a well developed mud mound topography immediately underlying the beach sands in the section (Facies D interpretation after Allen (1974)), probably results from the temporary nature of a mud mound facies (cf. Greensmith & Tucker, 1975), since it is only developed in order to re-establish a lower angle equilibrium slope on the shoreface. Once this angle has been achieved, the mud mound topography disappears. Such topographies can disappear within 20 years of formation (cf. Davis, 1964; Greensmith & Tucker, 1975).

The uppermost part of the intertidal zone (Facies D) probably consisted of beach sands. Many of the sedimentary structures present in these sands are described and illustrated by Allen (1974). They probably arose from the effect of wash on the beach. The siltstones containing trace fossils may have represented backbeach silt deposition areas. The recurrence of both facies types several times may indicate that the encroachment of the land into the sea was both gradual and oscillatory.

Conclusions

This study has examined the sediments (text-fig. 2) and faunas (tables 3,5,6,7) of the holostratotype section of the Ludlovian-Downtonian series boundary and has:

(1) verified (Elles & Slater's, 1906) observation that the Ludlow Bone-Bed marks the junction between a Ludlovian and a Downtonian fauna. However, some Ludlovian faunal elements (e.g., *Protochonetes ludloviensis*) have been shown (table 7) to continue into the Downtonian;

(2) shown that Ludlow-Downton Boundary marks a mineralogical change carbonate/micrite rich sediments to limonite/clay-rich sediments (text-fig. 5, table 2);

(3) shown that grain size modal peaks throughout the section are in the order of 40-80 mm (text-fig. 3);

(4) suggested that the grain sphericity curves for the section (text-fig. 3) indicate that its sediments were deposited in an accreting environment of diminishing energy conditions, in which alternating tidal currents varied in strength and duration. In some layers (e.g., the Ludlow Bone-Bed) the sphericity curves indicate that sediment was deposited as a lag concentrate;

(5) confirmed Allen's (1974) suggestion that the section can be divided into four sedimentary/environmental facies. The environmental interpretations of each facies are as follows:

  (a) Facies A - subtidal shallow carbonate mud environment

  (b) Facies B - low intertidal/very shallow subtidal mud/silt flat environment containing vertebrate debris sand patches

  (c) Facies C - intertidal mud flat deposits

  (d) Facies D - high intertidal silt or beach deposits

(6) shown that most of the quartz grains in the section were deposited out of suspension (text-fig. 7);

(7) shown that both sediment type and the composition of invertebrate faunas in Facies A are variable along a bedding plane (text-fig. 6);

(8) noted that the Ludlow Bone-Bed rests conformably on the underlying Whitcliffe Beds (text-fig. 4); and

(9) provided size measurements for three trace fossil species.

The faunal and sedimentary data presented here appears to support the suggestion that the Ludlow Bone-Bed formed as a lag concentrate during a marine regression in a tidal environment. However, it may have been deposited in the littoral or sub-littoral zone.

Acknowledgements

I wish to thank N.E.R.C. for financial support; Dr. J.D. Lawson for reading the draft manuscript; Mr. J. Norton for discussion and for the use of museum facilities at Ludlow, and Professor B.E. Leake for research facilities at the Dept. of Geology, Glasgow University.

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David D. J. Antia,
Geological Division,
BP Petroleum Development, Norway, U.A.
P.O. Box 3077
Mariero
4001 Stavanger
Norway

Exploration Dept.
BP Petroleum Development Ltd. &
Farburn Industrial Estate
Dyce
Aberdeen
AB2 OPB, U.K.

BOOK REVIEW

CLARKSON, E.N.K. *Invertebrate Palaeontology and Evolution*
Allen & Unwin, 1979, paperback, 323 pages, illustrated, index. £7.95

Members of the East Midlands Geological Society will recall with pleasure Dr. Ewart Clarkson who has organised a Scottish field excursion for the Society and visited Nottingham to lecture on trilobites. We have been awaiting the publication of his book with anticipation. As a general text on palaeontology intended for undergraduates the book will compete with R.M. Black's *Elements of Palaeontology.*

The book is divided by the author into two parts not as the title might suggest, but into a short section (46pp.) on general principles of palaeontology, theory of evolution and on the origin of the metazoa - best considered as an extended introduction. Part 2 is the main section on the invertebrate phyla. The emphasis of evolution in the title is no doubt intended to waylay fears of a dry text on morphology. In fact the book deals in about equal detail on morphology, ontogeny, evolution, taxonomy and palaeoecology of the various groups. The book is well written and easily understood. The information given is up-to-date and in this respect is clearly an improvement on other palaeontological texts. There is sufficient description of soft morphology in order that assumptions on skeletal and shell morphology can be appreciated. As with R.M. Black's book, the detail in the morphological sections could be increased if aiming for the undergraduate students. I would have expected from a trilobite expert a little more on trilobite facial sutures. Is the *Peltura* and *Crassifimbria* saga too contentous to be included?

One can always find points of disagreement and errors in other people's books. The following are not intended to detract in any way from the value of the book from the scientific point of view but to aid the author during the inevitable reprint edition and to continue with the overall description of the book. The sections on classification generally follow accepted practice but not every specialist will accept the format given in every case. There is presumably a restriction on space and little room for protracted discussion of debatable points - for example the inclusion of the Heliolitiidae within the order Tabulata and not as a separate order. In the classification of the Bivalvia two genera (*Lithophaga* & *Pholas*) appear in two different subclasses - presumably a printing error. The range of the Heterodonta (p.151) is given Trias - Recent but on the next page it is stated that the Lucinacea (subclass Heterodonta) occur in the Palaeozoic. The order Phychopariida (p.287) is obviously Ptychopariida. It is good to see detail on life history of many groups included, and one expects the faithful diagram on septal insertion in corals to be reproduced, but here only showing part of the story. Surely the text p.68 doesn't agree with fig. 5.4. Metasepta are developed in the vicinity of the cardinal septa. In a review it is to be expected that the reviewer will pick up items as above but they represent a very small fraction of the wealth of information given - a drop on the page (p.52, fig. 4.12).

I am sure that this book will be useful for teaching A-level and first year undergraduate courses and for general reading and information for members of the EMGS.

F.M. Taylor

Index for Volume 7, 1979-1980

THE MERCIAN GEOLOGIST

Journal of the East Midlands Geological Society

The journal first appeared in December 1964 and since that time 27 parts, comprising 7 volumes have been issued; the last, Vol.7, No.3, in November, 1979. The Mercian Geologist published articles especially on the geology of the Midlands of England, but other articles have been published which are of current interest to geology generally. Contents include original papers, review articles, biography, bibliographies, excursion reports, book reviews and the Secretary's report on Society activities.

For Contributors:

Authors intending to submit manuscripts of papers for publication in the Mercian Geologist are asked to follow the format of papers included in a recent number of the journal, and if possible to provide two copies. As the journal is read by Members with a wide spectrum of geological interest and ability, authors are asked to ensure adequate introductions for their papers, particularly, if the subject has not been reviewed in the journal over the last few years. The paper should be complete in itself, without the need of the reader to refer to specialist journals not easily available to the average Member of this Society. It follows that the length of the paper may be greater than that published by some other journals but authors are asked to be as lucid and concise as possible and to avoid repetition.

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

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