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

by

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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.

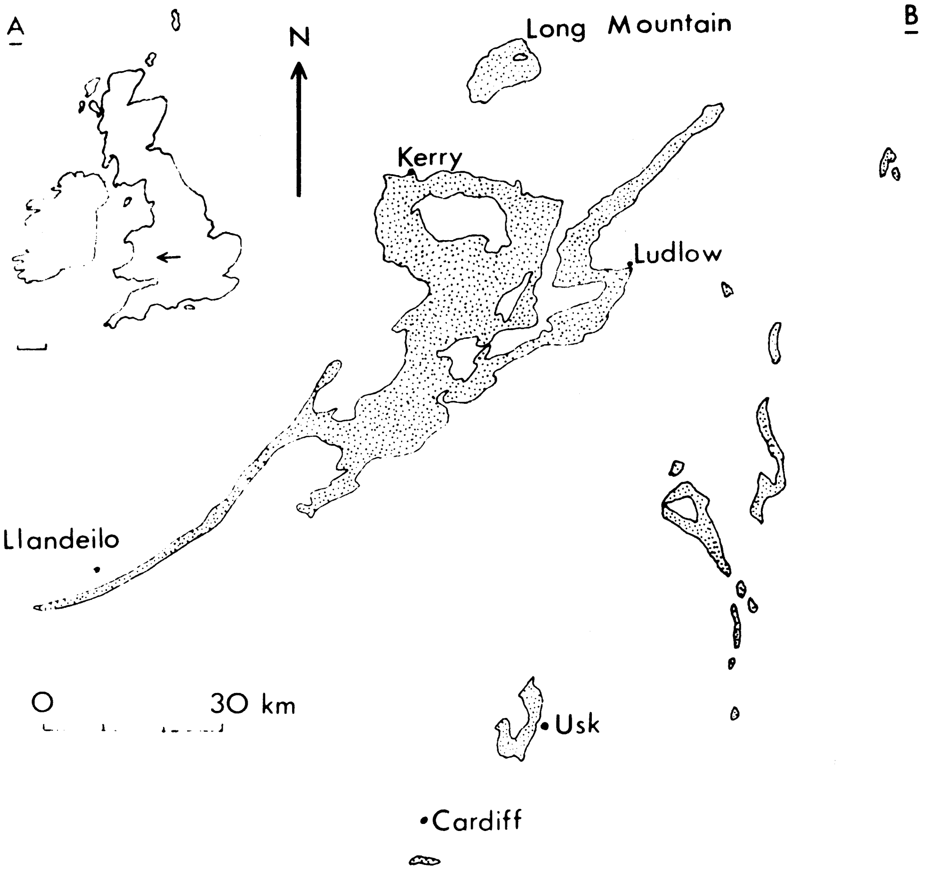
Introduction

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.

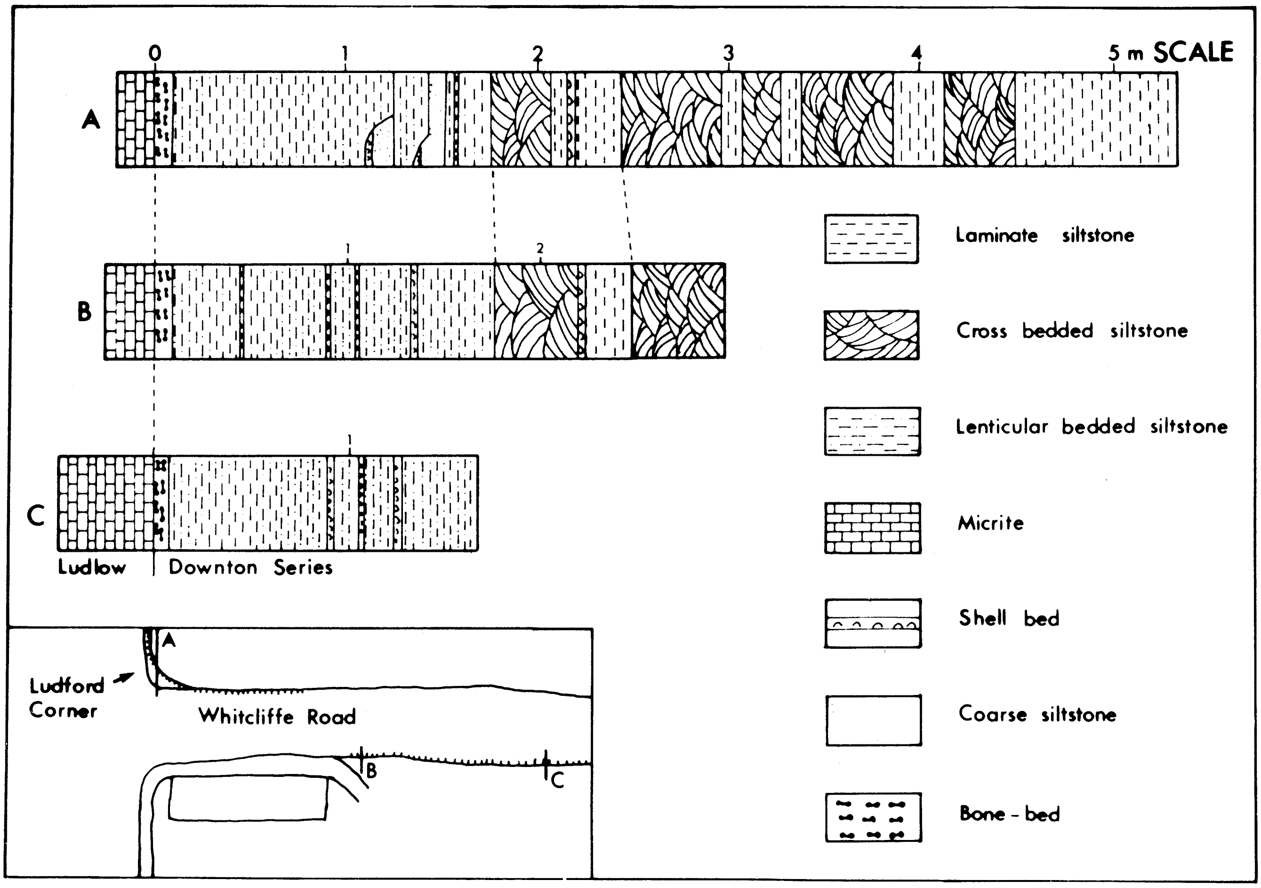


Text-fig. 1: Location map showing the outcrop of Ludlovian sediments in the Welsh Borderlands.

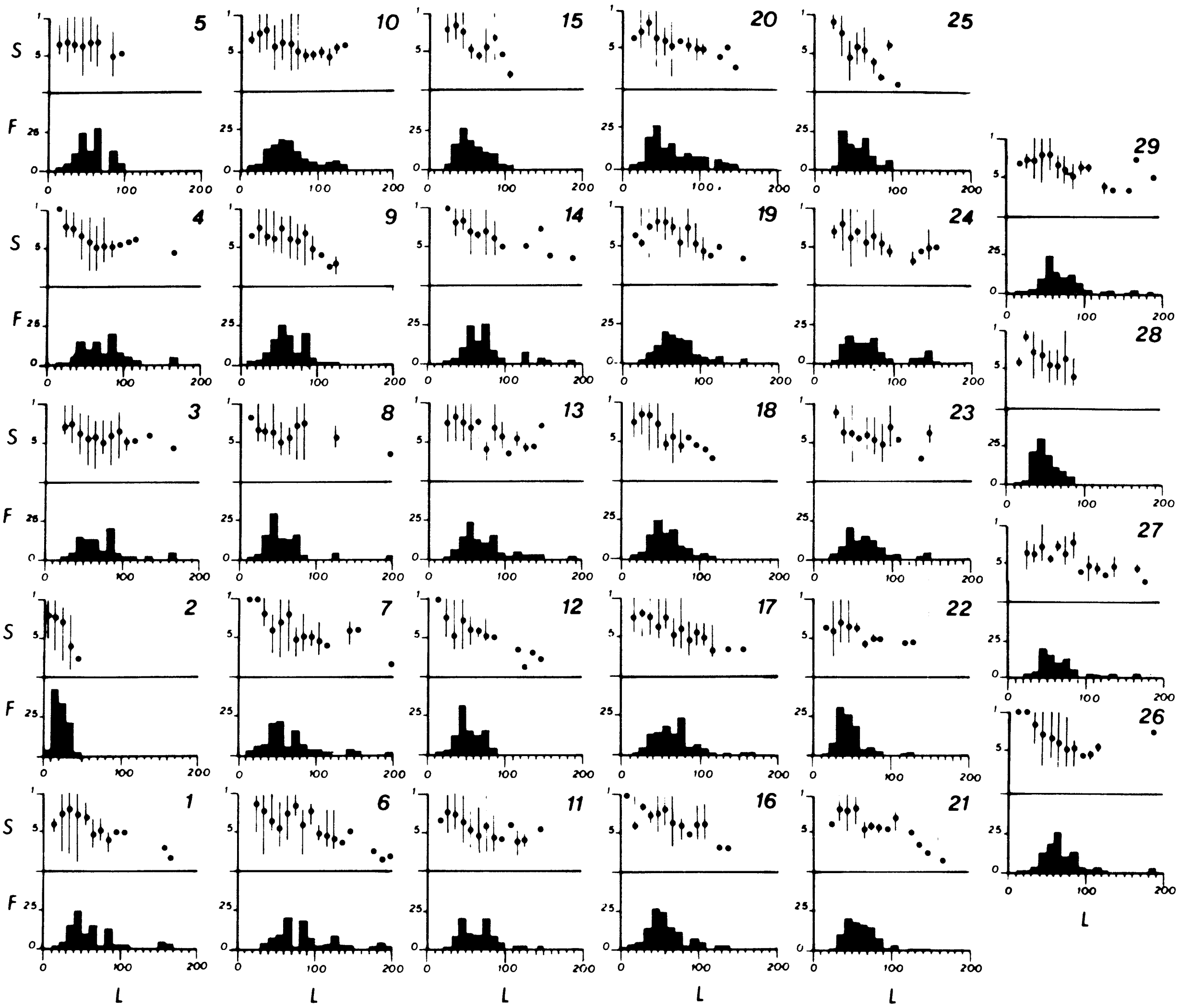
The sediments in the section have been assigned to a number of palaeoenvironments in the past. Initially, the Ludlovian sediments were considered to represent a marine environment and those of the Downtonian a brackish marine environment (e.g. Murchison, 1859; Stamp, 1923). The Downtonian sediments were 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.

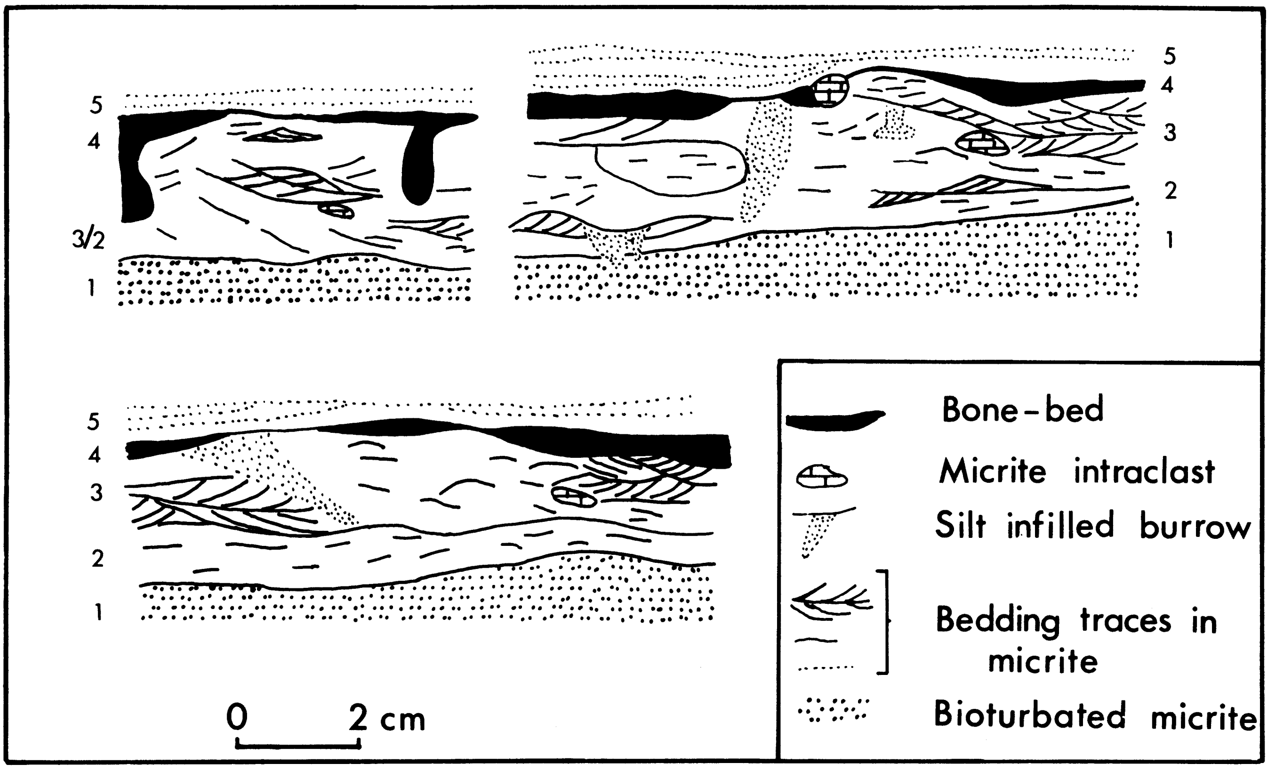
Table 1: Orientations of dead articulated *Cerastoderma edule* shells at Sales Point, Bradwell, Essex.

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.

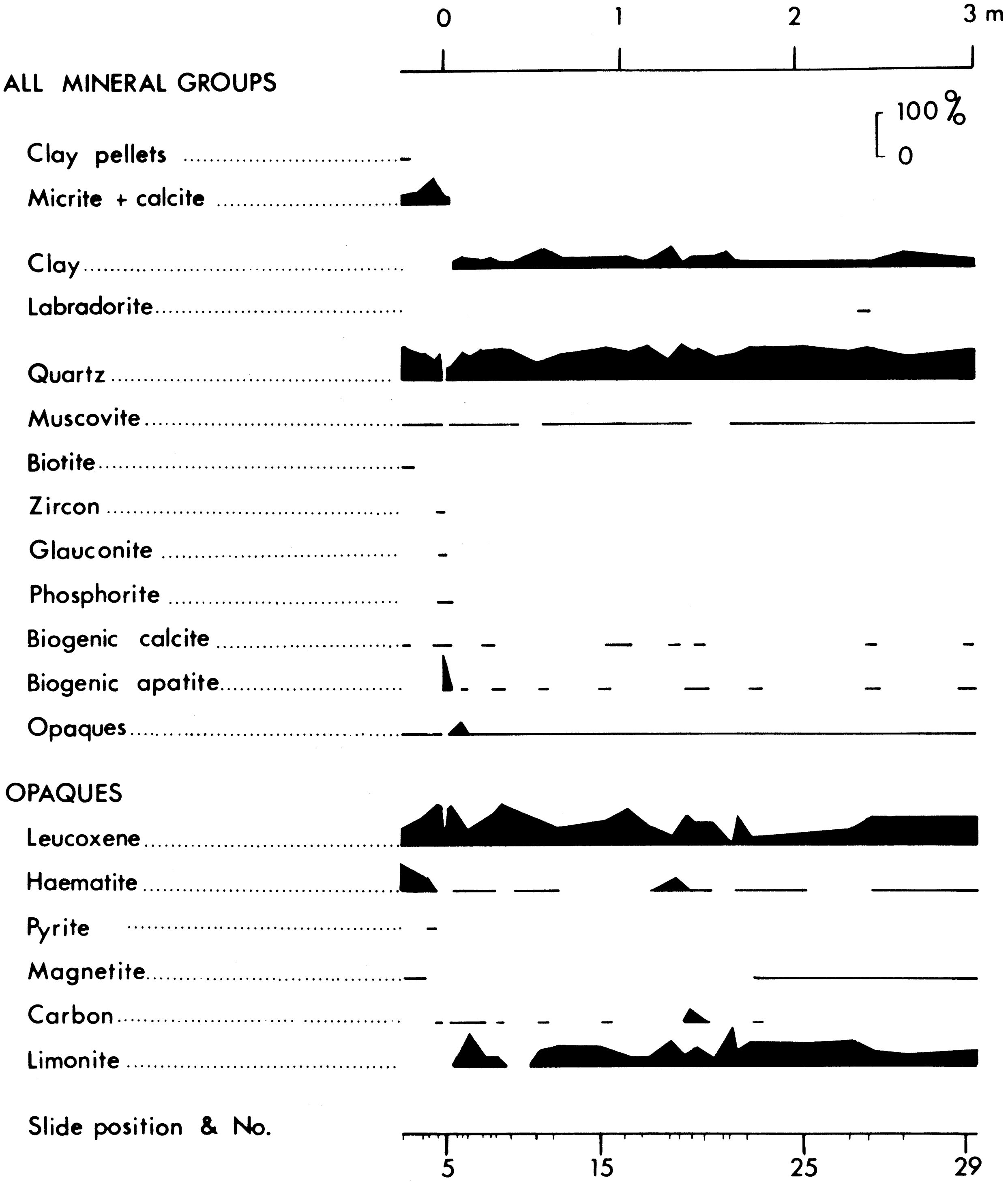
source of the micrite in the sediment is unknown. Among the more probable sources are the diagenetic dissolution and reprecipitation of calcite from shell debris and the reprecipitation of aragonite needles on the sea bed.

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

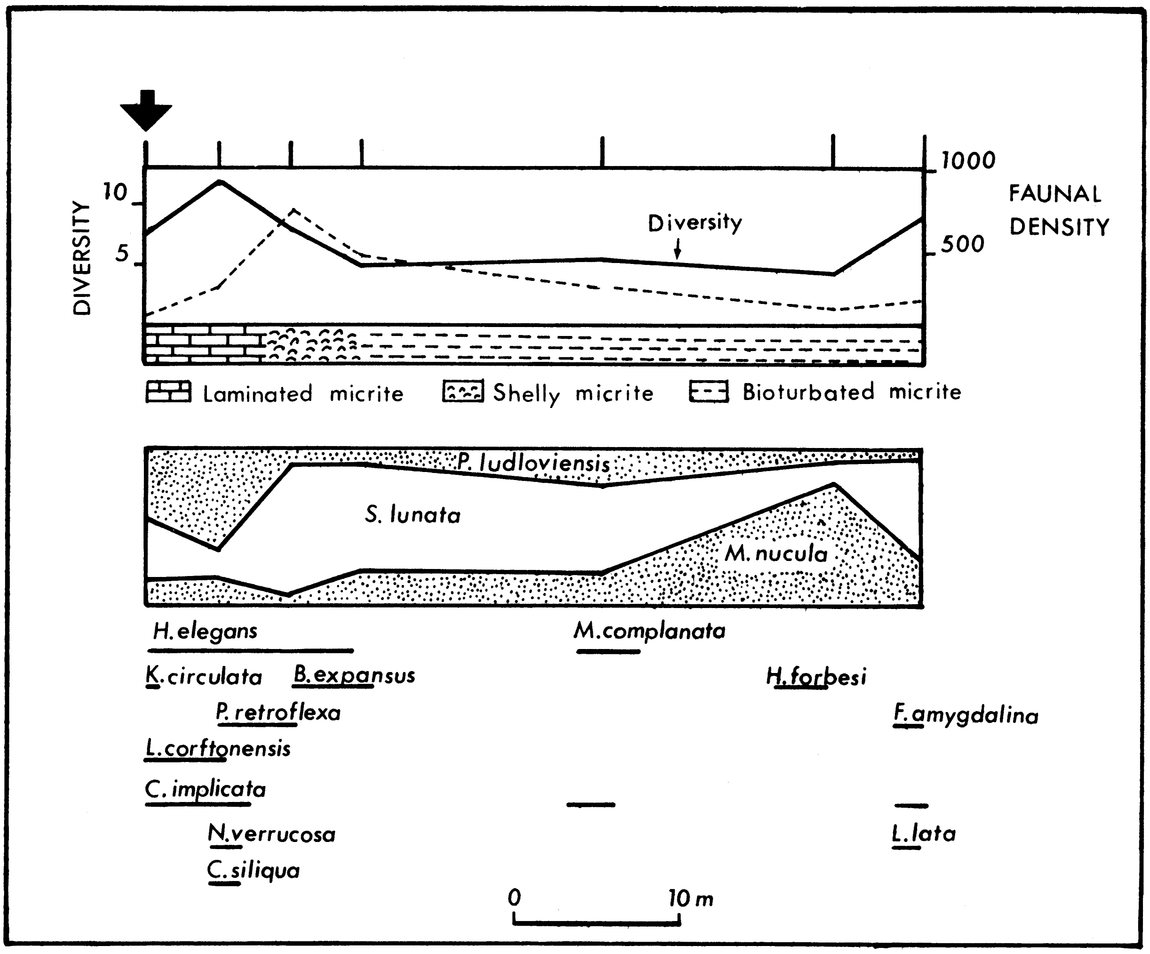
The proportion factor k need not be calculated since Futterer (1978a,c) has demonstrated a direct graphical relationship between the w/F ratio and the settling velocity of molluscan shells (bivalves and gastropods).

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



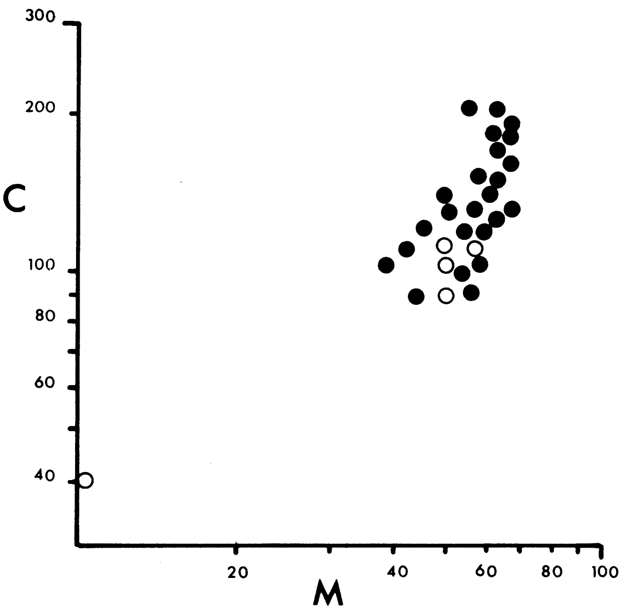
Text-fig. 6: Variation in sediment type, faunal diversity and faunal composition along a bedding plane surface 14 cm below the Ludford Bone-Bed. Arrow indicates Ludford Corner. Transect is along Whitcliffe Road. The raw data used to compile this diagram is presented in Table 2.

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).

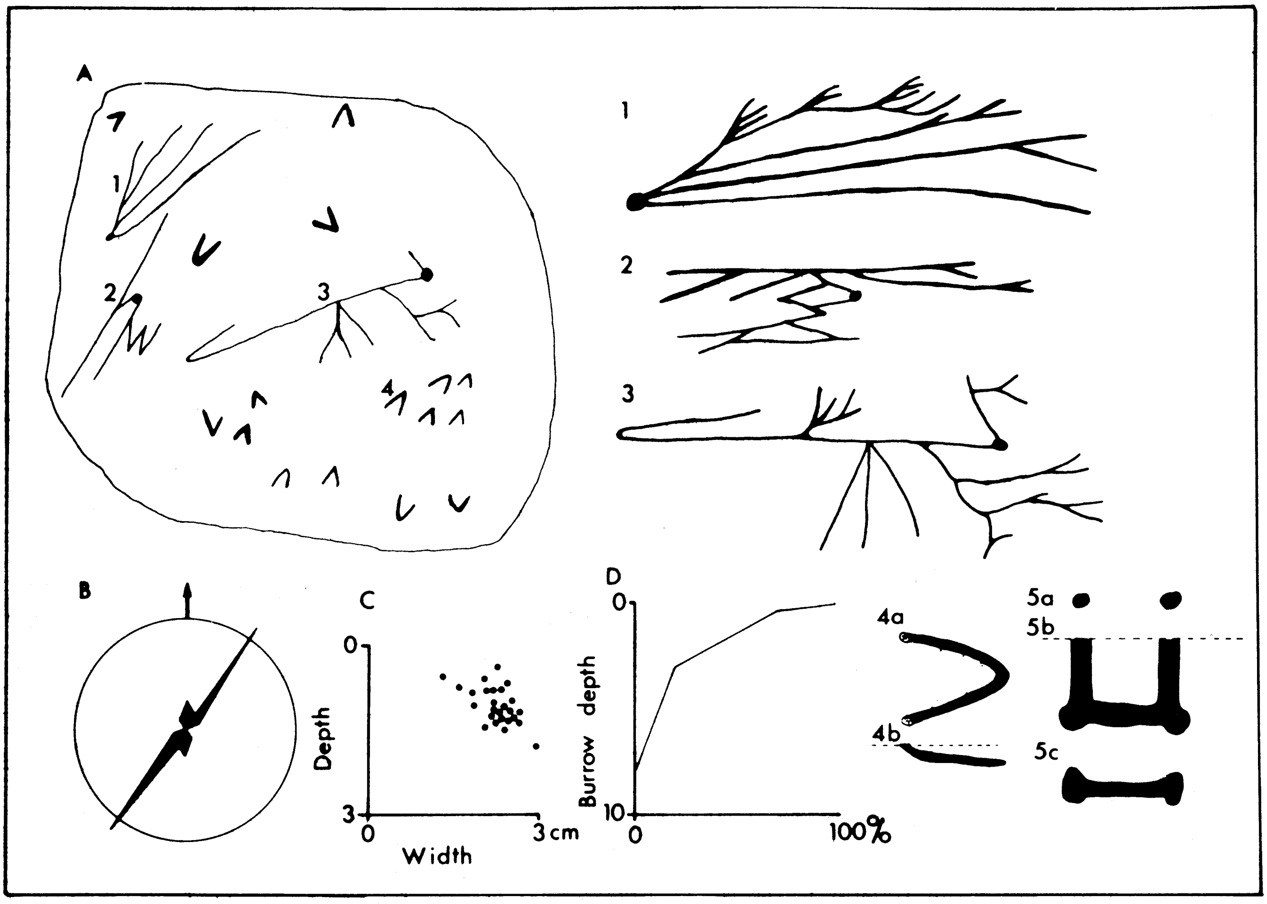


Text-fig. 7: C/M diagram for the Ludford transect. Open circles are Whitcliffian samples. Closed circles are Downtonian samples.

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.



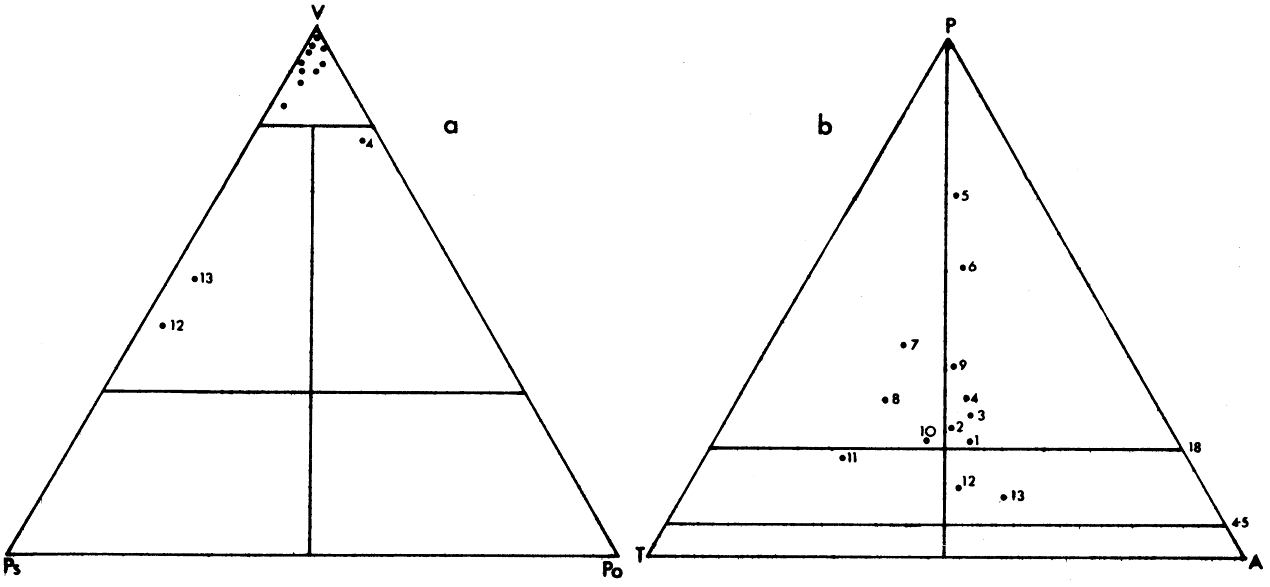
Text-fig. 8: Trace fossils in Facies A:

(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

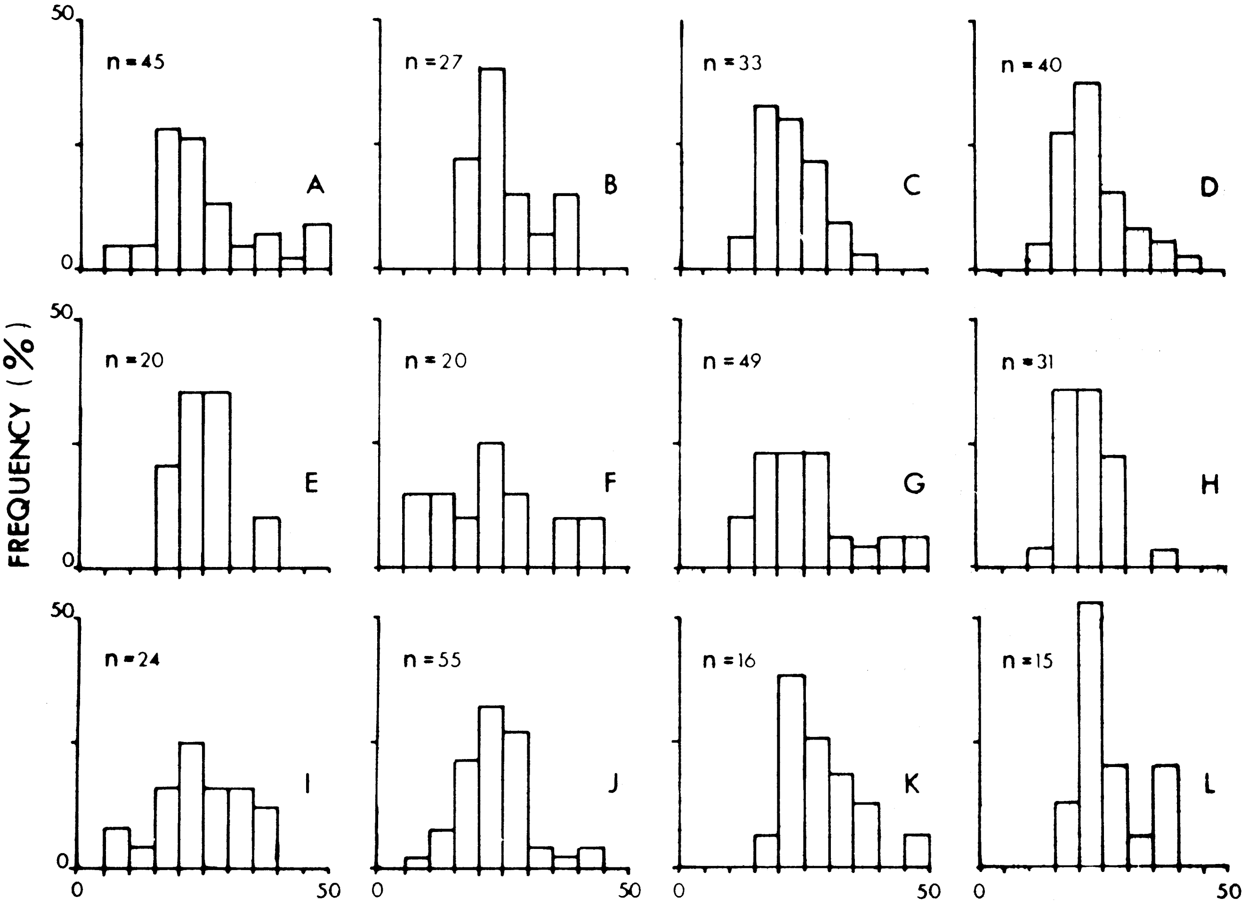
Thelodont grains are usually complete and show little evidence of abrasive rounding. However, chip marks and abrasion scratches are present on their outer surfaces (Antia & Whitaker, 1979). Some grains have been broken in half during deposition. In such cases the break has developed along cracks parallel 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

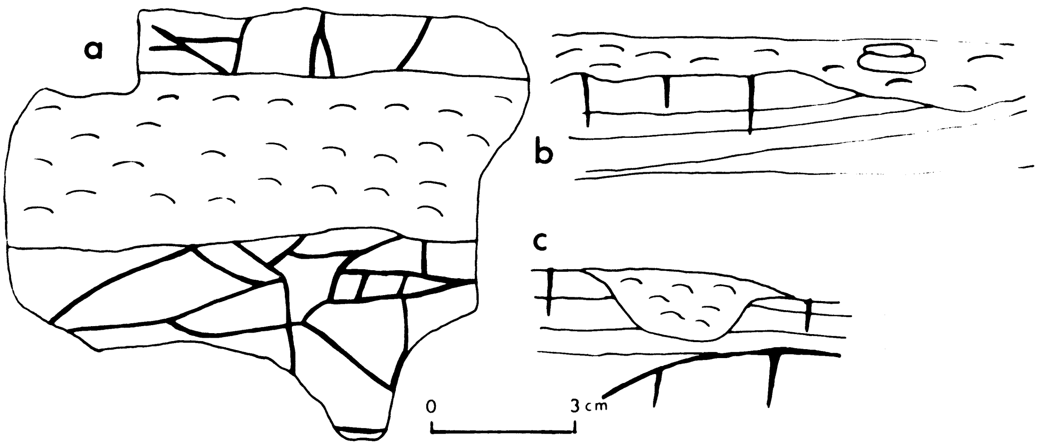
Table 7: Faunas across the Ludlow-Downton Boundary on Whitcliffe Road, Ludford. (Transect C, text-fig. 2) - Vertebrate faunas have been excluded from this layer.

	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 mud-cracked 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.

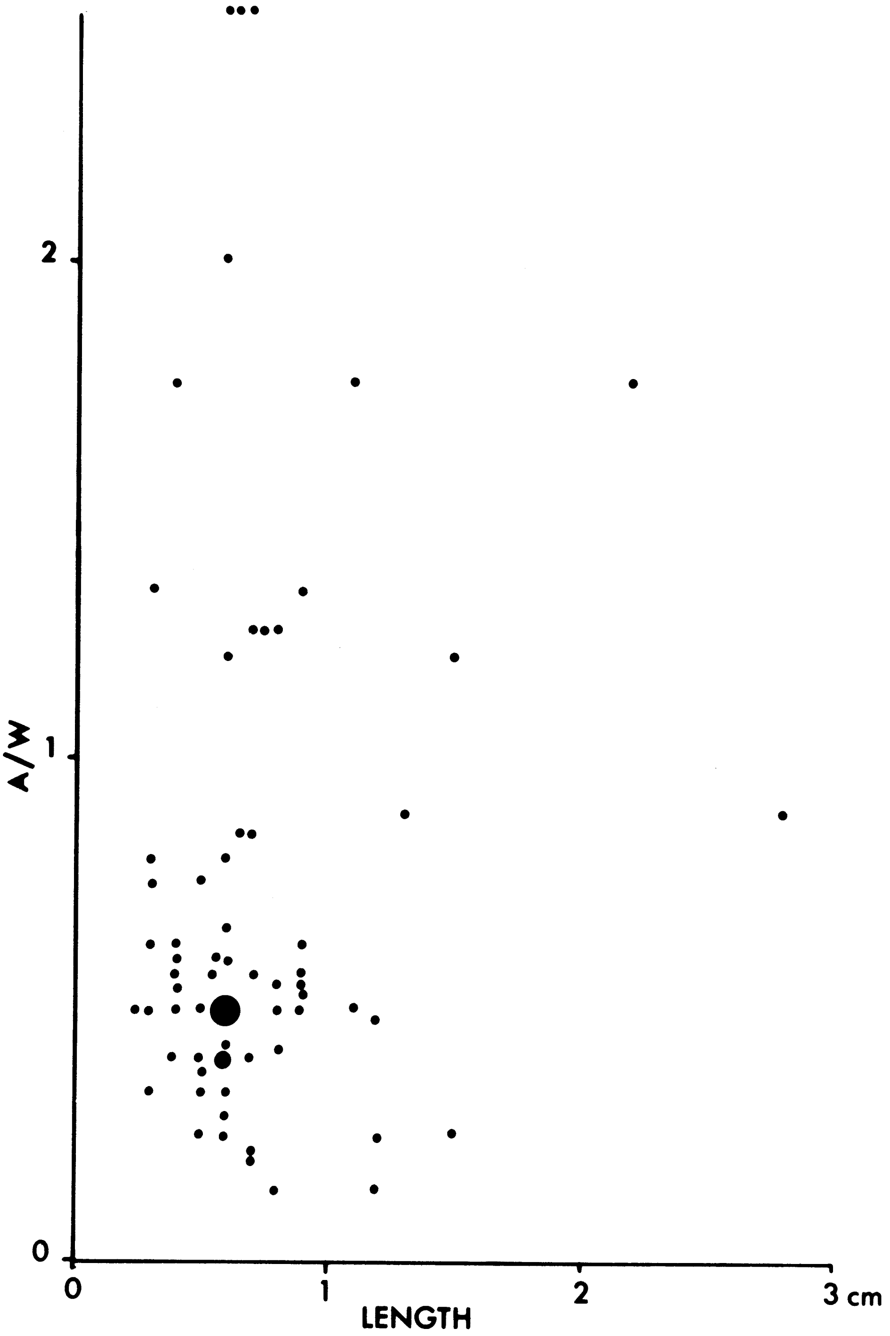
In the mounds, limonite replaced burrows and trails, limonitised and phosphatised complete internal moulds of *Loxonema gregarium* and *Leodispis barrowsi* are present. Mudcracks rarely penetrate to a depth greater than 3 cm and are infilled with coarse silt and fine sand. They have a crack width of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

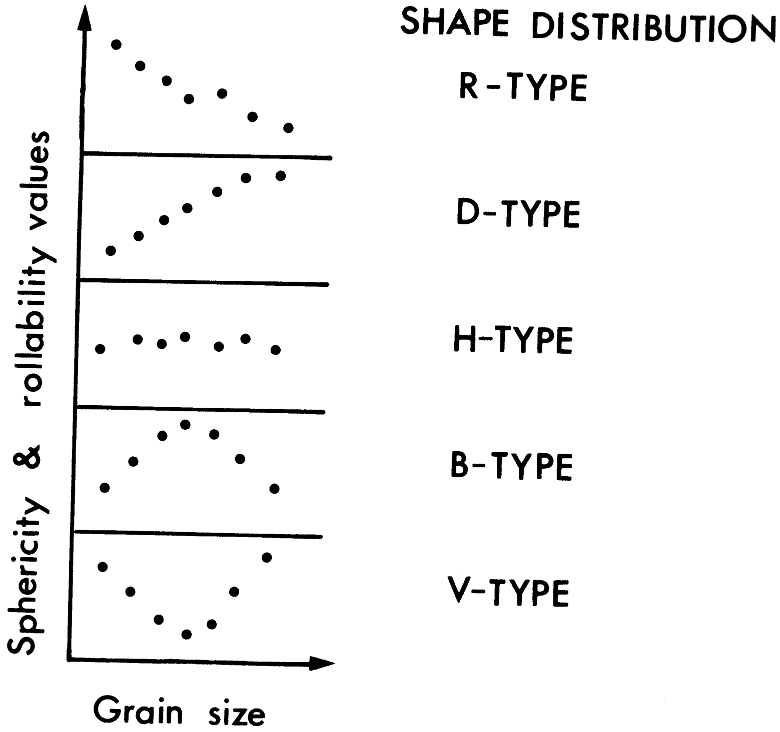
1. R-Type — These curves are characteristic of accreting environments of diminishing energy conditions. They are most commonly encountered in dunes sand/mud flats in tidal regions, beaches and point bar sequences (Winkelmolen, 1969, p.117; 1971, p.709). The beach and sandflat sediments tend to have fairly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

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Corrections

The following corrections have been requested for text-fig. captions in D.D.J. Antia's paper: Sedimentology of the type section of the Upper Silurian Ludlow-Downton Series boundary at Ludlow, Salop, England, contained in Vol. 7, No. 4 of the Mercian Geologist.

p.294, text-fig. 3, correction to read:

Grain size (L) in μm is given on the x axis.

p.306, text-fig. 10, correction to read:

Size measurements in μm.