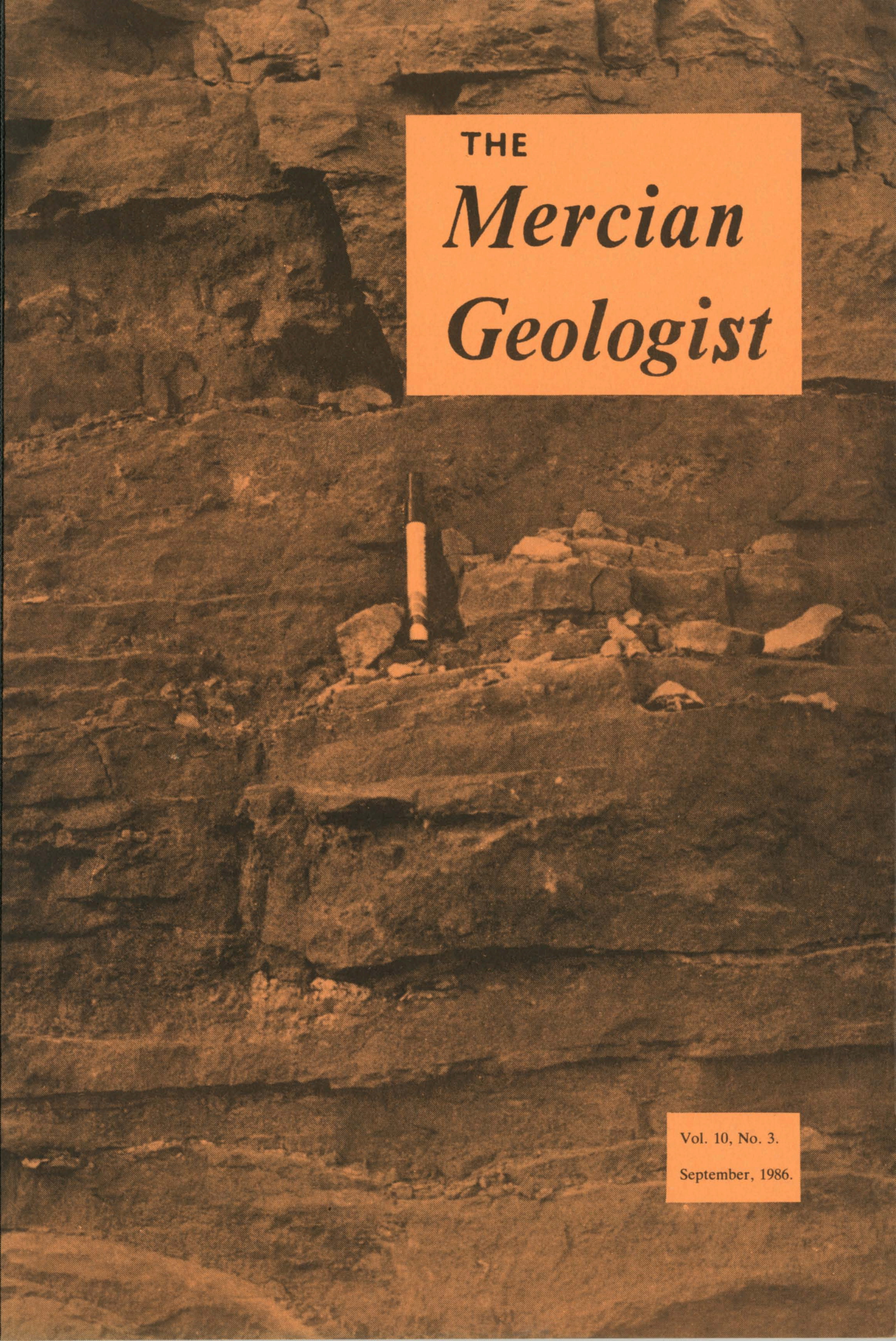
THE Mercian Geologist

Vol. 10, No. 3.
September, 1986.



EAST MIDLANDS GEOLOGICAL SOCIETY

THE MERCIAN GEOLOGIST

Editor: R.J. Firman.

Volume 10

Number 3

September 1986

CONTENTS

Excursion Report

Reviews

Errata

Secretary's Report

Mercian Geologist, vol. 10, no. 3,
September, 1986, pp. 151–234,
plates 9–14.

THE EAST MIDLANDS GEOLOGICAL SOCIETY

Address for Correspondence,

General information, membership details:
The Secretary,
East Midlands Geological Society,
311 Mansfield Road,
Redhill,
Arnold,
Nottingham NG5 8JL

Tel. No. (0602) 267442

ISSN 0025 990X

Printed by the Nottingham University Press

Front Cover: Hummocky cross-stratification in the Cadeby Formation exposed at a quarry in Bulwell (SK 538438). A well developed hummock occurs at the level of the marker pen (horizon B; fig. 2). The hummocky bed shows a wave rippled top and contains concentrations of shell moulds at its base. Pen 14cm long.

INTERSTADIAL DEPOSITS WITH CHELFORD AFFINITIES FROM BURLAND, CHESHIRE

by

A.P. Bonny, S.J. Mathers and E.Y. Haworth

Summary

A borehole drilled in 1959 near Nantwich, Cheshire proved an organic sequence beneath thick Devensian and possibly older glacigenic deposits. However, palaeontological work on this sequence was made difficult by poor core recovery.

A second borehole has since been drilled at the site and provides a detailed lithological sequence and data on the distribution of pollen and diatoms. The organic deposits are thought to have accumulated in either an abandoned river channel or a lake, possibly during the Chelford Interstadial.

Introduction

In 1959 the Geological Survey drilled a borehole adjacent to Burland Farm, [NGR SJ 6018 5333] west of Nantwich, Cheshire as part of a regional investigation of Triassic stratigraphy. A thick Quaternary sequence including substantial organic deposits, was encountered overlying the Triassic bedrock.

The organic deposits were proved from 27.4 to 37.5 m in the borehole beneath a thick glacial sequence. Samples from these organic layers were examined by P. Osborne and D. Bartley who wrote short reports on the Coleoptera and flora. The fragmentary material at their disposal did not provide any conclusive evidence regarding the age of the deposits. The work remained unpublished.

In 1980 a second borehole was drilled at the original site using a cable-percussion (shell and auger) rig. This has resulted in an improved lithological log of the sequence and in the recovery of enough organic material for further studies of its palaeoenvironmental significance and likely age. This paper describes the lithostratigraphy of the Quaternary sequence, and details the results of diatom and pollen analysis of the organic deposits. Also included are preliminary comments on the organic chemistry (Dr P. Cranwell) and the Coleoptera (Dr R. Coope and Dr B.J. Taylor) of the organic layers: more extensive accounts will be published elsewhere.

The upper part of the Burland pollen profile may be provisionally correlated with the sequence recorded at the Chelford Interstadial type site. Radiocarbon dating, which provides a minimum age › 47 000 aBP for the Burland organic deposits, tends to support this correlation.

Lithostratigraphy

The log of the original Burland borehole is given in the Nantwich (Sheet 122) Memoir (Poole and Whiteman 1966, pp. 106–107). It records a Quaternary sequence 38.1 m thick resting on Upper Keuper Saliferous Beds (Triassic). The limited recovery of core, especially from the organic parts of the sequence, resulted in the original log being rather brief. The redrilling of the borehole has enabled the construction of a more detailed lithological sequence (Fig. 1) despite the limitations of the shell and auger technique. In the new borehole the Quaternary sequence is 37.5 m thick and can be sub-divided into four units for purposes of description.

Mercian Geologist, vol. 10, no. 3,
1986, pp. 151–160, 2 figs.

1. **Basal Diamicton** (36.6-37.5 m)

A stiff pebbly clay, 0.9 m thick, occurs between 36.6 and 37.5 metres (Fig. 1) resting on Triassic bedrock. The matrix of the deposit is moderate reddish brown (10 R 4/6) and was largely derived from the underlying red mudstones of the Upper Keuper Saliferous Beds. The lithology of the pebbles which occur throughout the deposit is given in Table 1; flint and quartzose pebbles are the dominant constituents. The quartzose pebbles derive from Carboniferous sandstone and Triassic pebble-bed outcrops marginal and adjacent to the Shropshire-Cheshire Basin. Such pebbles are abundant within the Quaternary deposits of this area. The origin of the flint is more problematical. Flint is a minor constituent of many of the tills in the West Midlands. The small outcrop of chalk in Northern Ireland is a possible source.

Although this diamicton could be interpreted as having been produced by fluvial reworking of the Triassic bedrock, the origin of the pebbles argues rather for a glacial derivation. We therefore interpret this layer as a till. The suggested correlation of the overlying organic deposits with the Chelford Interstadial (see below) suggests that this basal diamicton at Burland may correlate with the thin tills and other glacigenic deposits that occur beneath the interstadial Chelford Sand Formation at Oakwood Quarry near Chelford (Worsley *et al.* 1983). The age of these glacial deposits is uncertain although they were tentatively assigned to the Wolstonian by Evans and Arthurton in Mitchell *et al.* (1973).

Table 1 Percentage Composition of gravel-sized pebbles
(+ 4–64 mm) in samples from the Burland borehole

Sample No.	Depth(m)	n	T. Slt	T. Sd	Lst	Arg	Aren	Ign	Fl	Qtz	Qtzt	Others
BUR 8	3.7- 5.0	104	36	6	9	17	4	15	1	6	4	2
BUR 12	8.8-11.0	193	40	4	3	15	17	1	4	11	2	3
BUR 13	11.0-14.2	176	27	11	6	18	11	2	7	12	1	5
BUR 15	14.2-18.0	177	40	14	2	8	12	4	4	11	1	4
BUR 42	36.6-37.5	48	-	-	-	-	19		20	42	19	-

Abbreviations

T. Slt = Triassic siltstone, T. Sd = Triassic sandstone, Lst = limestones, Arg = other argillaceous rocks, Aren = other arenaceous rocks, Ign = igneous, Fl = flint, Qtz = quartz, Qtzt = quartzites.

2. **Organic-rich Deposits** (27.7-36.6 m)

These deposits comprise a thick (8.9 m) sequence of organic silts and clays within which a thin peat layer occurs. The pebbles in the basal coarse gravel are probably derived from the underlying diamicton. Overlying this gravel are sandy silts which fine rapidly upwards into clayey silts. These silt-rich deposits contain pieces of wood and layers of comminuted shell. The deposits are olive grey (5Y 3/2) in colour.

The shell and auger drilling of these silts, which lay beneath the water table, destroyed any sedimentary structures that may have been present. However, short lengths of core from the original rotary-drilled borehole showed that the silts and clays contain numerous clasts of red mudstone and gypsum crystals up to 20 mm in diameter, including a high detrital input of material from local Triassic strata. Faint horizontal bands up to a few centimetres thick are present at several levels, reflecting subtle variations in the ratio of silt to clay. Ripple cross-lamination is also present within some of the more silty layers indicating the effect of weak currents.

A 1-m layer of peat (base at 30.5 m) is overlain by a sequence of greenish black (5GY 2/1) clays and silty clays between 27.77-29.5 m. These clays contain thin sand layers, wood and rarely, finely comminuted shell fragments. Clasts of red mudstone derived from the local Triassic bedrock and sporadic pebbles, including flint and quartzite, are also present.

Boreholes within five kilometres radius of the Burland borehole are sparse and do not enable the detailed form of the bedrock surface to be determined. However, the exceptionally thick (37.5 m) Quaternary deposits at Burland suggest that the lower parts of the sequence may fill a depression or channel. Remains of aquatic biota suggest that the organic sequence was deposited in a small lake or in a fluvial system.

3. **Proglacial Deposits** (18.9-27.7 m)

These deposits are 8.8 m thick and comprise a variable sequence of sands, silts and clays. The lower part of this sequence consists of rhythmically laminated deposits of overall greenish grey (5G 6/1) colour. From 27.2 to 27.7 m they comprise faintly laminated silty clay in layers 1-5 mm thick. From 26.0-27.2. m the deposit contains

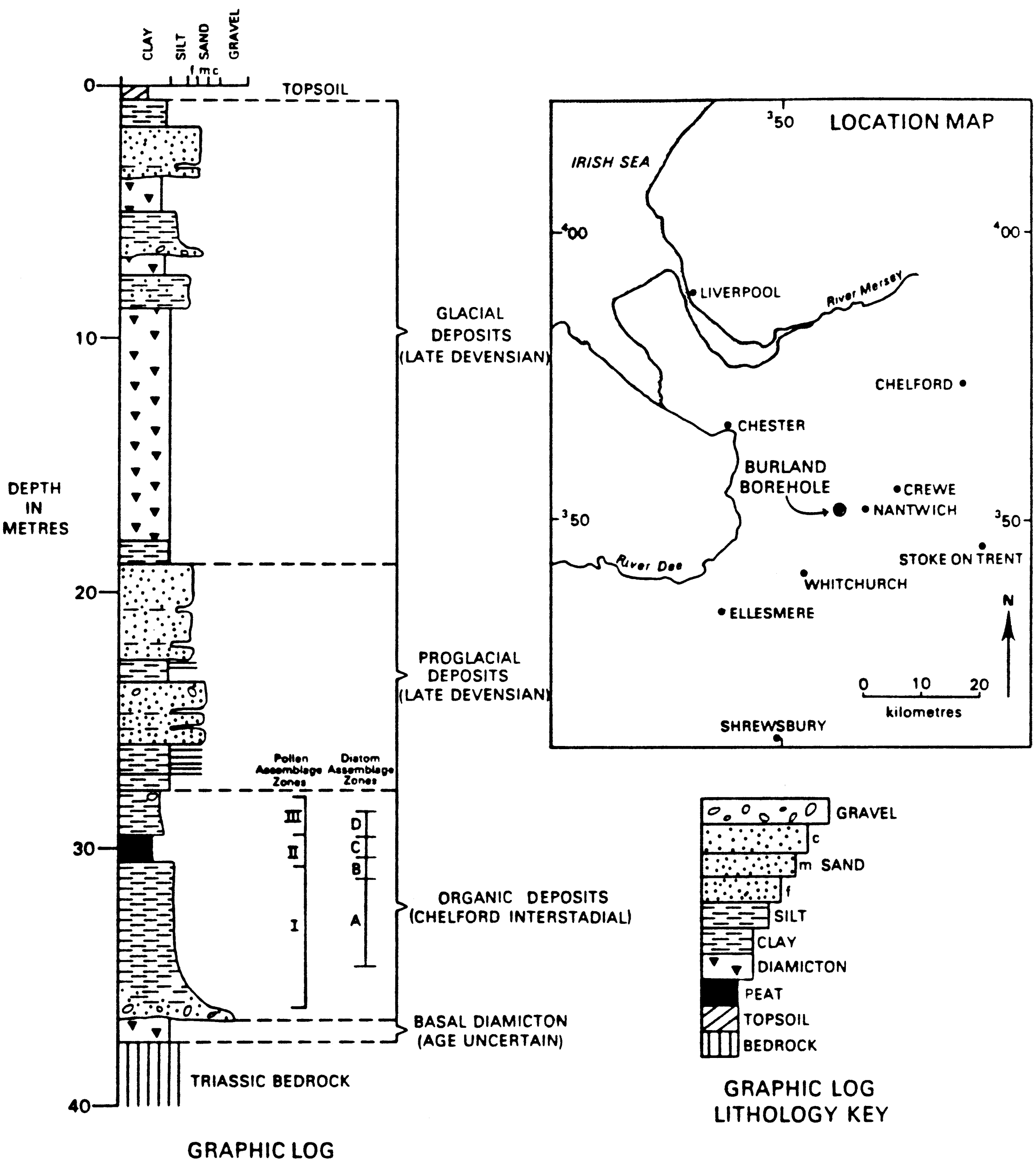


Fig. 1. Location map and lithostratigraphy of the Burland borehole.

numerous distinct clay-silt couplets each with a basal layer of sand commonly one grain thick. Many of the couplets have an upper darker clay layer sharply overlying lighter coloured silts; some resemble the "Case 7" varves of Sturm (1979). Individual rhythmites are commonly 1-3 mm thick, although some appear composite and larger units occur. If the individual units are annual varves, then about 600 years would have been required to form these lacustrine deposits.

The upper part of the proglacial deposits comprise sands with subordinate thin layers of silt and clay, some of which are massive and contained pebbles whilst others are pebble-free and finely laminated. The sands are commonly clayey and poorly sorted, containing thin seams of pebble and rare abraded shell fragments. Shell material has been reported from Devensian glacial deposits by Thompson and Worsley (1966) and interpreted as a derived marine fauna. Overall the sands are moderate brown (5YR 4/4) in colour, generally medium to fine-grained and comprise rounded quartz grains with numerous fragments of grey and red Triassic siltstone, fine sandstone, gypsum and aggregates of quartz grains cemented by pyrite. The more clayey and cohesive parts of the sands display small-scale cross bedding. The sediments are interpreted as proglacial, glacifluvial and glacilacustrine deposits, laid down ahead of the advancing Late Devensian ice-sheet.

4. **Glacial Deposits** (0.3-18.9 m)

Between 18.0 and 18.9 m the borehole encountered a silty clay in which sand laminae 1-3 mm thick picked out small-scale folding and faulting. The silty clay is moderate brown (5YR 3/4) in overall colour and characterised by numerous slickensided and sometimes striated surfaces interpreted as shear planes. Initially the deposit, which is over-consolidated was probably a glacilacustrine rhythmite, subsequently sheared and deformed, probably by an overriding ice-sheet. It may be termed a deformation till after Elson (1961); such subglacial sediment deformation has been observed by Boulton (1979).

A 10.5 m-thick uniform massive over-consolidated stony diamicton overlies the deformed beds between 8.5 and 19.0 m. This deposit is a moderate brown (5YR 3/4) calcareous sandy clay studded with numerous pebbles. It contains rare lenses of sand and silt up to 20 mm thick. The composition of the pebbles for three diamicton samples (BUR 12, 13 and 15) shows abundant material of non-local origin (Table 1); the deposit is regarded as a lodgement till.

The upper-most part of the glacial deposits (0.3-8.8 m) is a sequence of stratified clayey sands and silts interbedded with diamicton layers (Fig. 1). The stratified sediments are commonly poorly sorted and, where clayey, are commonly calcareous and contain small shell fragments. The matrix of the diamicton layers and their pebble composition (Table 1-BUR 8) appears to be lithologically similar to those of the thick underlying diamicton and so are also regarded as tills. We regard this sequence as the product of ice-sheet stagnation and supraglacial sedimentation.

In the absence of any data to the contrary, it is assumed that these glacial deposits were laid down by the Late Devensian ice-sheet that covered the Shropshire-Cheshire basin between 25 and 14 Ka (Worsley, 1985).

Diatom Analysis

Fifteen samples from between 25.2 and 35.5 m were analysed for diatoms and other siliceous remains. The results are summarised in Table 2.

Table 2 Diatom Assemblage Zones of the Burland Borehole

Diatom Assemblage Zone	No. of Samples	Depth (m)	Observations
-	6	25.2-29.5	No diatoms recorded
D	3	29.5-30.5	Many diatom fragments, occasionally identifiable, chrysophyte spores and grass silica present between 29.7 m and 30.3 m.
C	2	30.5-31.3	Many identifiable diatoms and fragments; occasional freshwater sponge spicules and chrysophyte cysts.
B	2	31.3-32.1	Few diatoms; sponge spicules present
A	2	32.2-35.5	Very few diatom fragments; sponge spicules present between 34.0 and 35.5 m

Interpretation and discussion

An abrupt transition, from peat containing diatoms below 29.5 m to clay devoid of diatoms above, indicates a distinct change in sediment source. Diatoms in all samples from below this horizon are eroded in appearance and there is a high proportion of fragmented specimens. Their generally poor condition suggests that much of the material may have been transported. Organic geochemical analysis of a sample from the silty clay (31.3—31.6 m) also indicates that this sediment was derived from both terrestrial and aquatic sources (having relative proportions characteristic of a mesotrophic lake), but few marker compounds indicative of aquatic biota were found in a peat sample from 30.0–30.3 m depth. (Dr P. Cranwell, pers. comm.).

All the samples that contain diatoms appear to represent essentially the same assemblage, which is diluted by clay minerals in the sections above 30.5 m and below 31.3 m depth. Two adjacent samples from between these depths, ie. one from the uppermost part of the silty clay and one from the transition to peat, contain enough diatoms for an assemblage analysis to be made from each. Taxa occurring at a frequency of 1% or more are listed in Table 3. Although the samples are similar in composition, the chief difference is that the upper one is dominated by *Fragilaria elliptica*, a tiny form (Haworth, 1975) that is not at all conspicuous in other samples. This diatom is common in early post-glacial sediments and is either a planktonic form or benthic among aquatic weeds in lakes. The predominant diatoms in both samples are those of shallow waters: *Cocconeis, Epithemia* and *Rhoicosphenia* spp. are typically epiphytic on littoral water weeds (algae, mosses or higher plants). *Fragilaria* spp. abound both amongst weed and on sediments, and are dominant in the minerogenic environments typical of the early Flandrian (Haworth, 1975). *Navicula* and *Gyrosigma* spp. are benthic dwellers that glide on the sediment surface. Only a few specimens of a planktonic form, *Cyclotella comta*, were seen: lack of planktonic forms is typical of the interstadial deposits of the Late Devensian, even in deep lakes. Possibly other planktonic algae which do not leave remains in sediment may have dominated the flora. Although chrysophyte cysts occur in many samples, no scales were observed.

Table 3 Percentage composition of diatom assemblage in two samples from DAZ 3 in Burland borehole

	30.5–30.8 m	30.8–31.3 m
Achanthes lanceolata (Bréb.) Grun.	+	1
A. minutissima Kütz.	1	-
A. cf. *peragalli* Brun	1	-
Amphora ovalis var. *libyca* (Ehr.) Cleve	2	2
A. ovalis var. *pediculus* (Kütz.) Van Heurck	2	3
Caloneis bacillum (Grun.) Mereschkowsky	-	1
C. fasciata var. *fonticola* (Grun.) Petersen	-	2
Cocconeis placentula Ehr.	11	18
C. placentula var. *euglypta* (Ehr.) Grun.	7	16
Cyclotella comta (Ehr.) Kütz.	+	2
Epithemia turgida (Ehr.) Kütz.	1	4
E. zebra (Ehr.) Kütz.	1	3
Eunotia lunaris (Ehr.) Grun.	-	2
Eunotia pectinalis (Kütz.) Rabh.	-	3
Fragilaria brevistriata Grun.	1	-
F. construens var. *binodis* (Ehr.) Grun.	2	-
F. construens var. *venter* (Ehr.) Grun.	+	2
F. elliptica Schumann	52	7
F. pinnata (Ehr.)	8	-
Gomphonema angustatum (Kütz.) Rabh.	+	2
G. gracile Ehr.	+	1
Gyrosigma acuminatum (Kütz.) Rabh.	+	3
Navicula lanceolata (Agardh) Ehr.	+	2
N. radiosa Kütz.	+	2
Nitzschia spp.	1	4
Rhoicosphenia curvata (Kütz.) Grun.	1	2
Synedra cf. *ulna* (Nitzsch) Ehr.	1	4
Other	6	14

The presence of freshwater sponge spicules in samples from the silty clay suggests that the site of deposition was either a shallow lake or a slow-moving river. The diatom assemblage consists, in the main, of taxa found more commonly in alkaline than in acid water, although more *Eunotia* and *Pinnularia* spp., typical of the acidic waters of, for example, Sphagnum peat pools, were found in the topmost peat sample. Occasional specimens of *Anomoeoneis sphaerophora* (Kütz) Pfitzer and *Nitzschia opiculata* (Gregory) Grunow *sensu* Hunstedt (1930), which are more usual in water of high salinity or conductivity, were found in DAZ3 and were presumably derived from habitats affected by local salt deposits.

Pollen Analysis

Samples of the organic-rich deposits between 27.7 and 36.2 m in the borehole contained countable pollen. The resulting profile (Fig. 2) can be divided into three distinct Pollen Assemblage Zones (see Fig. 1), the main characteristics of which are as follows:-

Pollen Assemblage Zone Burland I (PAZ Bu I). A pine-birch zone (30.8–36.2 m) is characterized by high values for *Pinus* 39–62% Arboreal Pollen (AP) and *Betula* (37–61% AP), and by the virtual absence of other tree pollen taxa. Herbaceous pollen makes up between 16% and 38% TDP (Total Determinable Pollen).

PAZ Bu II. A pine-birch-spruce zone (29.5–30.8m) is characterized by maximum values for *Picea* (up to 21% AP) and *Pinus* (up to 70% AP). Percentages of *Betula* are lower than in Zone I, reaching a minimum of 16% AP for the profile. Percentages of Gramineae and Cyperaceae are higher than in Zone I, as is total herbaceous pollen (between 21% and 54% TDP).

PAZ Bu III. A birch-pine-alder-juniper zone (27.7–29.5 m) is characterized by maximum percentages of *Betula* (up to 80% AP) and by declining values for *Pinus* and *Picea*. *Alnus* reaches a maximum (10% AP), as do values for *Juniperus*, ericaceous taxa, Cyperaceae and the spores of Polypodiaceae and *Sphagnum*. Total herbaceous pollen comprises 40–46% TDP.

Interpretation and Discussion

The biogenic profile begins after the establishment of pine-birch forest: there is no evidence of earlier, pioneer vegetation of 'late-glacial' type.

Many of the herbaceous taxa recorded from PAZ Bu I are likely to have formed tall herb communities around the open water in which the aquatic taxa recorded were living. There is little evidence of plants of open ground in the pollen record, so vegetation cover was probably fairly complete. *Picea* appears to have become established at the expense of *Betula*, since percentages of the latter decrease as those of *Picea* increase in PAZ Bu II. The transition between PAZ Bu I/II is abrupt and is marked by peaks in percentages of Gramineae and Cyperaceae pollen. Conditions at the site of deposition may have been responsible for these features since changes in water level, for example, could have favoured the expansion of such plants as *Phragmites* and reedswamp sedges. The high proportion of degraded pollen at this horizon also suggests that some alteration occurred in the deposition and/or preservation of pollen.

The transition between PAZ Bu II and III is even more abrupt: percentages of *Pinus* and *Picea* decrease and those of *Alnus*, *Corylus*, Ericaceae, Compositae, *Succisa*, Polypodiaceae and *Sphagnum* rise immediately at the zone boundary to maxima for the profile. It is unlikely that this rapid shift in pollen spectra is wholly a reflection of vegetational change. More probably, the PAZ Bu II/III boundary (which coincides with a sharp stratigraphical change from peat below to clay above) marks the level in the profile at which recruitment to the deposition site of chiefly local and contemporary pollen became augmented by significant proportions of pollen derived from soils and drift in the area. Many of the taxa that peak just above the PAZ Bu II/III boundary are those with relatively thick exines which resist destruction and are often preserved preferentially in minerogenic deposits from which more fragile pollen taxa have disappeared. An increased contribution of allochthonous material would also account for the high proportions of degraded pollen and pre-Quaternary spores found in these samples. The upper limit of PAZ Bu III is drawn arbitrarily at the level above which samples were too poor in pollen to count.

Some aspects of the PAZ Bu III pollen spectra may indicate real vegetational change, for example the increasing curve for Cyperaceae pollen and the high percentage of *Juniperus* found in the topmost countable sample. Neither of these taxa is notably resistant to destruction (in comparison with those mentioned above), so it may be that there was a temporary response by herbs and light-demanding shrubs like juniper to an environmental change that reduced tree cover. Possibly, fire terminated the local development of boreal forest around this site, since the samples from 28.3 to 29.5m contain many small black fragments which may be charcoal. There is stronger evidence, however, that the environmental change manifested at the PAZ Bu II/III boundary was predominantly climatic, since samples from above this horizon are from clays which become laminated above 27.7 m depth: these are thought to be the sediments laid down in a proglacial lake. No countable pollen was found in the laminated clay. The most likely explanation for the sequence of events above the PAZ Bu II/III boundary is that climatic deterioration ended the dominance of boreal forest, brought about an increase in the erosion rate of the local land surface, and provided open conditions which could be exploited, temporarily, by non-tree vegetation until its eventual extinction by the onset of glacial conditions.

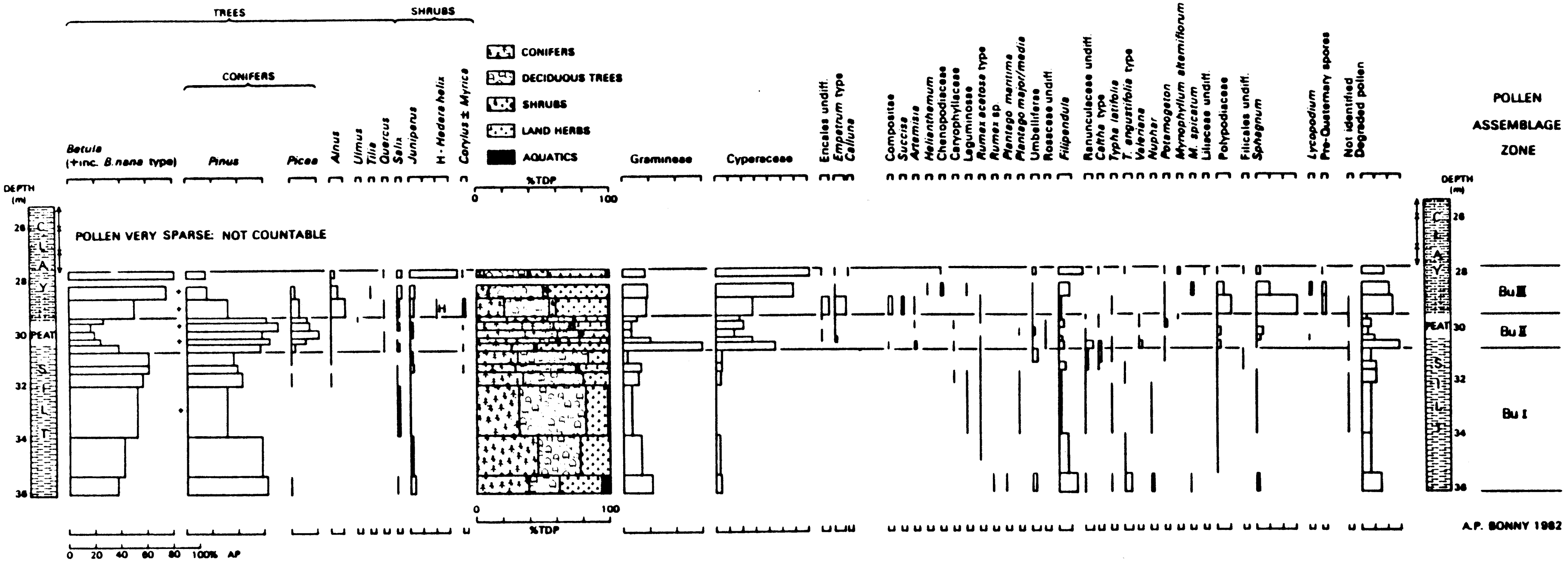


Fig. 2. Pollen diagram from Burland borehole. Individual pollen and spore taxa are plotted as percentages of total Arboreal Pollen. Summary diagram included shows groups of taxa plotted as percentages of Total Determinable Pollen.

Correlation of Pollen Profile

The pollen profile from Burland is incomplete since it lacks evidence of pioneer vegetation and passes upwards into minerogenic sediments which contain an admixture of derived palynomorphs. However, it shows clearly the development of boreal forest with an accompanying ground flora of predominantly damp and aquatic habitats.

The chief feature of the diagram (Fig. 2) is the rise of the curve for *Picea* pollen during the period when *Pinus* pollen percentages are at a maximum. This circumstance has not been recorded from interglacial successions, but is found in the interstadial profile from Chelford (Simpson & West 1958), which the diagram from Burland (only 30 km distant) resembles in many respects. The diagram from Chelford does not include the pre-*Picea* phase shown at Burland (PAZ Bu I), neither nor does it include problematical pollen spectra of the type that characterise PAZ Bu III. The whole of the Chelford profile can be correlated most readily with PAZ Bu II, representing the period when *Pinus-Betula-Picea* forest was the dominant vegetation, although *Picea* pollen percentages are higher at Burland (up to 21% AP) than at Chelford (up to 8% AP).

Other similarities between the sites in respect of tree pollen are the occurrence in low frequencies of *B. nana* pollen as a proportion of total *Betula* throughout the *Pinus-Betula-Picea* phase, and the occasional presence of the pollen of thermophilous trees, ie. *Alnus*, *Ulmus*, *Carpinus*, *Quercus* and *Corylus*, presumably recruited by long-distance transport. Diagrams of both sites indicate the presence of the herbaceous vegetation of conifer forest (eg. *Empetrum*—although the incidence of Ericaceae is higher at Chelford), of damp habitats (eg. *Filipendula* cf. *ulmaria* and *Valeriana*, probably *V. dioica*) and of forest pools (eg. *Caltha* type, *Myriophyllum* and *Typha*). Neither site shows much evidence of the local presence of open ground, although such taxa as *Artemisia* and *Helianthemum* occur in low frequencies.

Simpson & West (1958) considered that the geographical affinities of the vegetation represented at Chelford lie with the northern conifer-birch region, more specifically with the type of forest found between 63° N and 60°N in Finland, north of the limit for deciduous thermophilus trees, but south of the northern pine forest limit. Certainly, modern pollen spectra from lake sediments in this region (eg. Prentice 1978) resemble in many respects those from Chelford and from PAZ Bu II at Burland. The latter correspond best with spectra from the northern subregion of Finnish boreal forest, although percentages of *Betula* are rather lower at Burland. Pollen assemblages of PAZ Bu I (not represented at Chelford) show reasonably good agreement with spectra from lakes farther north in Finland where birch forest is dominant. Both PAZ Bu I and Bu II have higher proportions of Non Arboreal Pollen (NAP) than are evident at the Finnish sites which they most resemble, and some different taxa are present. This is perhaps a reflection of local pollen recruitment at Burland, where the NAP is composed largely of taxa from damp habitats likely to have been close to the site of deposition.

From the present distribution of the flora and vegetation recorded, Simpson & West (1958) deduced that climatic conditions during the boreal forest phase represented in the Chelford profile were similar to those of central Finland today. The present distribution of the Coleoptera found as fossils at this site (Coope 1959, 1977) also suggest this: a continental climate with average July temperatures around 15 °C is indicated, being slightly cooler than the Cheshire Plain at the present day. Similar conditions are likely to have been obtained during the period of *Pinus-Betula-Picea* forest at Burland (PAZ Bu II) since the Coleoptera present in the peat layer show definite affinities with the Chelford assemblage (Dr R Coope, pers. comm.). The analogy between the pollen spectra of PAZ Bu I and those of northern birch forest in Finland suggests, however, that the preceding pine-birch phase at Burland was characterized by an even cooler regime.

Another site in the West Midlands, Four Ashes (Staffordshire), shows similarities with the profile from Chelford (and so with that from Burland) in respect of the assemblages of pollen and Coleoptera recovered from two detrital mud lenses at the base of gravels assumed to be of Early Devensian age (Morgan 1973; Andrew & West 1977). A third British deposit with possible affinity to Chelford and Burland has been described by West *et al.* (1974) from Wretton, Norfolk. Here, a pollen spectrum with high percentages of *Betula*, *Pinus* and *Picea*, but with very little NAP was thought to provide evidence of the local presence of boreal forest of the type represented at Chelford. However, Coleoptera from this site indicate a harsh climate of arctic severity and an extremely barren landscape with scant vegetation cover (Coope, 1975). It now seems that the Wretton pollen spectra resulted from the long-distance transport of tree pollen to a site where local pollen was extremely low. Lacustrine sandy muds and peat containing a *Pinus-Betula-Picea* dominated pollen assemblage, from Roosting Hill, Beetley, Norfolk have also been tentatively correlated with the Chelford Interstadial by Phillips (1976).

Of the continental European sites at which there is palynological evidence of interstadial conditions, that most likely to be correlated with Chelford (and so with Four Ashes and Burland) is the Brørup Interstadial of Jutland, Denmark, although in the view of Andersen (1961), this remains to be proved.

Radiocarbon Dating

Radiocarbon dating was attempted on four samples from the organic deposits in the Burland borehole. The results are as follows:-

Sample			Depth	Date (yrs. B.P.)
SRR 2117	A	Peat	29.5–29.7	30,780 + 360 −340
SRR 2118	B	Wood fragments	34.0–36.8	24,930 + 280 −280
SRR 2371	C	Peat	30.0–30.3	40,110 + 880 −790
SRR 2371	D	Peat	30.3–30.5	›47,200

Samples A and B, submitted first, gave ages in reversed stratigraphical order although there was no reason to suppose that the samples had been affected either by contamination with modern material or by any kind of hard-water error which could have increased the apparent age of the peat relative to that of the wood fragments. Furthermore, while both dates indicate that the organic layers formed before the maximum extension of the Devensian ice-sheet, neither was as old as might have been expected from the close resemblance between the pollen assemblages from Burland (PAZ Bu II) and Chelford, where the oldest finite 14C age from the Interstadial sediments has been dated at c. 60 Ka. In view of these uncertainties, the submission of two further samples was invited. These (C and D) were rather small, but yielded significantly older dates which are best regarded as an indication of the minimum age of the deposits (Dr D. Harkness, pers. comm.). Hence it is possible that the organic layers at Burland may have been formed during the Chelford Interstadial (Worsley, 1980).

The 'true' age of the type Chelford Interstadial deposits is likely to be older than 65 Ka and a pre-Devensian age for these deposits still cannot be completely discounted (Worsley, 1985).

Conclusions

The 37.5-m sequence of Quaternary deposits proved in the re-drilled Burland borehole is interpreted as follows:

Above the Triassic bedrock, the thin layer of stony clay which contains clasts of non-local origin is thought to be a till, probably of pre-Devensian age. Overlying it is a thick sequence of organic deposits—silty clays and a thin peat layer—which represent the infill sediments of a lake or an abandoned river channel that supported a varied aquatic biota. The pollen record from this section shows evidence for local pine-birch forest into which spruce migrated. The pine-spruce-birch character of the profile indicates a possible correlation with the record from Chelford, and 14C-dating results from the Burland deposits are not inconsistent with this interpretation.

Organic silts and clays of mainly terrigenous origin, containing much reworked and degraded pollen, overlie the peat. These are interpreted as the result of increasing soil erosion attendant upon climatic deterioration. The sequence passes upwards into laminated clay-silt sediments that were probably formed in a proglacial lake. There are no diatom deposits associated with this water body. The overlying sands, which contain thin layers of silt and clay, are interpreted as proglacial outwash deposits.

The outwash deposits are overlain by over-consolidated glacilacustrine sediments, much sheared and deformed, which are interpreted as a deformation till produced by an over-riding ice-sheet. This deposit is overlain by a massive, stony diamicton (also over-consolidated), interpreted as a lodgement till. The upper-most part of the glacial deposits is a sequence of stratified clayey sands and silts interbedded with diamicton layers: this is regarded as a product of suraglacial sedimentation in association with the stagnation of the Late Devensian ice-sheet.

Acknowledgements

The authors thank Professor P. Worsley, for improving an earlier draft of this manuscript and Dr D. Harkness for helpful discussions on the interpretation of the radiocarbon dates.

This paper is published with the permission of the Director of the British Geological Survey (NERC).

References

Andersen, S. Th. 1961. Vegetation and its environment in Denmark in the Early Weichselian Glacial (Last Glacial). *Danm. Geol. Unders.* II, 75—175.

Andrew, R. and West, R.G., 1977. Flora and Fauna: Early and Middle Devensian flora and vegetation. *Phil. Trans. R. Soc. B* 280, 299-346.

Boulton, G.S., 1979. Processes of glacier erosion on different substrata. *J. Glaciol.* 22 15-38.

Coope, G.R., 1959. A Late Pleistocene insect fauna from Chelford, Cheshire. *Phil. Trans. R. Soc. B.* 151, 70-86.

Coope, G.R., 1975. Climatic fluctuations in northwest Europe since the Last Interglacial, indicated by fossil assemblages of Coleoptera. In *Ice Ages: ancient and modern* (eds. Wright, A.E. and Moseley, F.). *Geol. J. Spec. Issue* 6. Liverpool.

Coope, G.R., 1977. Fossil coleopteran assemblages as sensitive indicators of climatic changes during the Devensian (Last) Cold Stage. *Phil. Trans. R. Soc. B* 280, 313-340.

Elson, J.A., 1961. The geology of tills. *Proc. 14th Can. Soil Mech. Conf. Tech. Mem.* 69, 7-13.

Haworth, E.Y., 1975. A scanning electron microscope study of some different frustule forms of the genus *Fragilaria* found in Scottish late-glacial sediments. *Br. phycol. J.* 10, 73-80.

Hustedt, F. 1930. Bacillariophyta (Diatomeae). In: *Susswasser-flora von Mitteleuropas (ed. A. Pascher)*, part 10, 466pp. Jena.

Mitchell, G.F., Penny, L.F., Shotton, F.W. & West, R.G., 1973. A correlation of Quaternary deposits in the British Isles. *Geol. Soc. Lond., Special Report No. 4*, 99pp.

Morgan, A., 1973. Late Pleistocene environmental changes indicated by fossil insect faunas of the English Midlands. *Boreas* 2, 173-212.

Philips, L., 1976. Pleistocene vegetational history and geology in Norfolk. *Phil. Trans. R. Soc. B* 275, 215-286.

Poole, E.G. & Whiteman, A.J., 1966. Geology of the country around Nantwich, (Sheet 122). *Mem. Geol. Surv. GB.*

Prentice, I.C., 1978. Modern pollen spectra from lake sediments in Finland and Finnmark, north Norway. *Boreas* 7, 131-153.

Simpson, I.M. & West, R.G., 1958. On the stratigraphy and palaeobotany of a late-Pleistocene organic deposit at Chelford, Cheshire. *New Phytol.* 57, 239-250.

Sturm, M., 1979. Origin and composition of clastic varves In *Moraines and Varves* (Ed. C. Schluchter) A.A. Balkema, Rotterdam, 281-285.

Thompson, D.B. and Worsley, P., 1966. A late Pleistocene marine molluscan fauna from the drifts of the Cheshire Plain. *Geol. J.* 5, 197-207.

West, R.G., Dickson, C.A., Catt, J.A., Weir, A.H. & Sparks, B.W., 1974. Late Pleistocene deposits at Wretton, Norfolk. II. Devensian deposits. *Phil. Trans. R. Soc. B* 267, 337-420.

Worsley, P., 1980. Problems in radiocarbon dating the Chelford Interstadial of England. In *Cullingford, R.A., Davidson, D.A. and Lewin, J. (Eds.) Timescales in geomorphology.*

Worsley, P., Coope, G.R., Good, T.R., Holyoak, D.T. and Robinson, J.E., 1983. A Pleistocene succession from beneath Chelford Sands at Oakwood Quarry, Chelford, Cheshire. *Geol. J.* 18, 307-324.

Worsley, P., 1985. Pleistocene history of the Cheshire-Shropshire Plain. In *Johnson, R.H., (ed.). The Geomorphology of north-west England.* Manchester University Press, Manchester 200-201.

Dr. A.P. Bonny,
2 Jersey Close,
Chertsey,
Surrey, KT 9PA.

Mr. S.J. Mathers,
British Geological Survey,
Keyworth,
Nottingham, NG12 5GG.

Dr. E.Y. Haworth,
Freshwater Biological Association,
The Ferry House,
Far Sawrey,
Ambleside,
Cumbria, LA22 OLP.

THE STRATIGRAPHIC DISTRIBUTION AND PRESERVATION OF FOSSIL VERTEBRATES IN THE OXFORD CLAY OF ENGLAND

by

D.M. Martill

Summary

Vertebrate fossils are abundant in the basal beds of the Oxford Clay of the East Midlands. Large brick pits in the Peterborough district still yield large reptile skeletons as well as an abundant micro-vertebrate fauna. Preservational styles vary with changes in lithology and there is a correlation between vertebrate abundance and organic carbon content. Vertebrate carcases are subjected to a number of taphonomical processes which coupled with a variety of sedimentological and diagenetic processes acting on the exposed skeletons produce a spectrum of preservational types.

Introduction

Fossil marine vertebrates are frequently found in bituminous shales and, in some formations, can be a major part of the nekton. Most palaeontologists are familiar with the often beautifully preserved marine reptiles from European Jurassic bituminous shale formations, such as the Lower Lias of Dorset, and Upper Lias of Yorkshire, both in England, and the Posidonia Shales of Holzmaden, West Germany. Such specimens occur infrequently compared to the large number of fragmentary skeletons and isolated bones and teeth that are also found at these localities.

The Oxford Clay of Central England is in part bituminous, especially in the lower parts of the sequence, and yields an abundant and diverse vertebrate fauna, which although consisting largely of marine vertebrates, also contains a few terrestrial elements.

The Lower Oxford Clay has long been famous for the beautiful preservation of some of its vertebrate remains, and because of the abundance of fresh material, it is a suitable formation on which to base a study of marine vertebrate taphonomy and preservation.

A detailed examination of vertebrate remains from the Callovian transgressive episode, represented in Central England by the Upper Cornbrash, Kellaways beds, Lower and Middle Oxford Clay (Callovian, Middle Jurassic) and Upper Oxford Clay (Oxfordian, Upper Jurassic) shows that a broad spectrum of preservational styles can be recognised, which are in part lithologically dependent. Changes in abundance and diversity are also recognised through the succession. Each of the preservational styles is controlled by a variety of taphonomic, sedimentological and diagenetic factors.

Kauffman (1981) has shown that taphonomic studies on marine vertebrates can yield important palaeoecological and sedimentological data. He examined the fish and marine reptiles of the West German Posidonia Shales (Lower Jurassic, Toarcian) and drew conclusions about the level of oxygenation at the sediment/water interface. Unfortunately the material examined occurs on large slabs of indurated shale which have been prepared from below, prohibiting examination of the upper surface of the specimen, a surface which is crucial to learn about the activities of epibionts and the degree of weathering of bones that took place on the sea floor.

In the Lower Oxford Clay it is usually possible to free the fossils completely from the matrix simply by washing, thereby being able to examine the specimen from all aspects.

Mercian Geologist, vol. 10, no. 3,
1986, pp. 161–186, 17 figs.,
plates 9, 10 and 11.

Localities

The main part of the field work was undertaken in the extensive brick pits (described below) in the Peterborough and Whittlesey districts (Fig. 1). Six brick pits were in operation at the commencement of the project, with the pit at Dogsthorpe (National Grid Reference TF 219 019) being the most important locality. Pits at Yaxley (TL 178 932), Norman Cross (TL 173 916), Orton (TL 165 937), and two pits at Whittlesey (TL 252 976 and TL 250 976) supplemented the collecting.

The pit at Norman Cross was exhausted by October 1982 and fell into disuse. This pit is now partly flooded and has been designated a nature reserve. The remaining pits are all in full production, are highly mechanised and can be dangerous. It is necessary to obtain permission from the London Brick plc before entering these sites.

Other localities which expose the Lower Oxford Clay and have been examined are:- The borrow pit at Farcet (TL 200 958), and Gravel pits at Maxey (TF 135 075 at the time of study). Gravel pits in this district are often temporary, and fresh exposures are continually appearing and disappearing. Gravel pits at Baston (TF 110 130) were yielding Lower Oxford Clay vertebrates in 1978, but have not been examined in recent years by the author.

Pits exposing Middle and Upper Oxford Clay have been examined at Warboys, Cambridgeshire (TL 308 818), and Stewartby, Bedfordshire (SP 010 420). No systematic work has been carried out in these beds, as all visits to these localities were unproductive.

The Lower Oxford Clay was examined in brick pits at Calvert, and Bletchley, Buckinghamshire (SP 670 230 and SP 850 320 respectively), to observe the lithologies associated with specimens from these localities, that have accurately documented stratigraphic information, and are deposited in the collection of University of Leicester, Department of Geology.

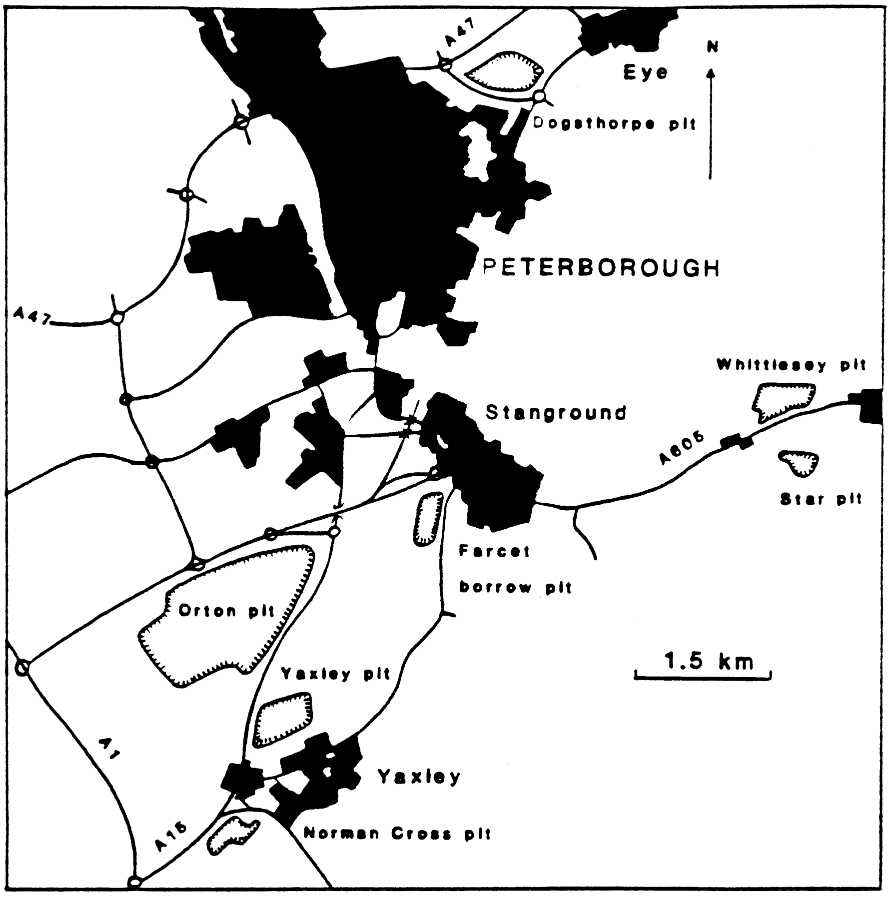


Fig. 1. Map of Peterborough district showing the main vertebrate bearing localities.

During this study, the chance discovery of an ichthyosaur by a site workman at a reservoir construction site near Milton Keynes, Buckinghamshire (SP 892 352), was brought to my attention. A systematic excavation of the skeleton was undertaken, and the results included within the scope of this project.

Visits to classic fossil marine vertebrate sites were undertaken for comparative purposes. These were:- Holzmaden, Baden Wurttemburg, West Germany, and Monte San Giorgio, near the sleepy village of Meride, Tessin, Switzerland. Collections from these sites were also examined in the Museum of the Department of Geology, University of Tubingen and the Natural History Museum, Zurich.

Methods

Although extensive collections of vertebrates from the Oxford Clay, especially the Lower Oxford Clay, can be found in museums all over the world, this type of study requires the examination of *in-situ* specimens. It was therefore necessary to undertake extensive field work to collect fresh material.

Vertebrate remains can usually be found on any visit to a pit in the Lower Oxford Clay, but are rare in the Middle and Upper Oxford Clay. (A visit to a pit in the Middle or Upper Oxford Clay will probably not bring forth any fossil vertebrate material, except perhaps for isolated fish teeth).

Material has been obtained by occasional visits before 1982, almost daily visits during the summers of 1982, 83 and 84, and visits at monthly intervals during other seasons to the brick pits near Peterborough. This ensured that all newly exposed parts of the pits could be examined before being covered by overburden.

Methods used to extract the clay from the pits, the nature of the overburden, and also economic factors can bias sampling. It has not been possible to assess how much effect these had on collecting, but it is assumed that the increased abundance of macro-vertebrates in the basal beds of the Lower Oxford Clay may be partly due to the greater amount of exposure of these beds.

Of the pits examined in the Peterborough area, six are operated for brick production, one for gravel extraction, and the other was a borrow pit for a road construction programme, and is to be used for refuse disposal. Each pit has its own advantages and disadvantages for the collector of fossil vertebrates as outlined below:-

1. Gravel Pits

To the north of Peterborough extensive excavations for river gravels expose the Oxford Clay floor of the flat lying Fens. Due to severe drainage problems, it is often necessary for the operators to dig large sumps and drainage ditches in the base of the workings. These sumps frequently create fresh exposures of the Kellaways beds and the Oxford Clay. Gravel pits towards the eastern edge of the fens sometimes expose the vertebrate bearing horizons of the Lower Oxford Clay, and Kellaways Sand. Unfortunately these workings flood easily, and during winter and in wet summer the pit floor may be inaccessible.

2. Farcet Borrow Pit

During construction of the Peterborough inner ring road, a large borrow pit was excavated to obtain material for the construction of road embankments. The pit is to be used for refuse disposal now that construction of the highway is complete. The pit has exposed part of a glacial channel filled with boulder clay, cutting down to the base of the Lower Oxford Clay, much of which is heavily cryoturbated at the contact. Beneath the channel, the pit extends into undisturbed Kellaways beds and exposed the top of the Upper Cornbrash. The excavation was made by large earth scrapers which left comparatively gentle gradients to the sides of the pit allowing easy access to beds that are normally only rarely exposed in the drainage ditches of the large brick pits. This pit has been one of the most productive over a short space of time. Disposal of refuse was due to start during the summer of 1985.

3. Brick pits at Dogsthorpe, Orton, and Yaxley

These pits are all operated by London Brick plc, using large dragline excavators which stand on top of the workable beds and dig the clay beneath. At Dogsthorpe and Yaxley the overburden is stripped off by earth scrapers, leaving a clean surface of unweathered Lower Oxford Clay. At Orton the overburden is also removed by a dragline.

This method exposes a wide strip of basal Lower Oxford Clay, usually beds 10 to 12 (bed numbers after Callomon 1968, see below) along the foot of the working face. The width of this exposure is dependent on the length, usually about 20m, of the jib of the dragline. At Orton the overburden is dumped on the pit floor in advance of the dragline working the brick clay, and consequently buries the strip exposed by the previous cut.

The length of time the freshly exposed basal beds remain accessible depends on two factors. 1) The length and height of the pit face. 2) Demand for bricks. During the economic recession of the late 1970's and early 1980's no night shifts operated in the brick fields, and as a consequence the newly exposed beds remained accessible for longer than normal. This also meant that the amount of newly exposed material was limited, but the advantage was that weathering was allowed to continue for a longer period. This resulted in many specimens being washed out of the clays.

At Dogsthorpe the overburden excavated during 1983 was sold for the construction of the Peterborough ring road, and as a result no overburden was dumped on the pit floor, except for that from the tidying up of the top and bottom of the working face which produced small rows of conical spoil tips parallel to the pit face. These spoil tips consist of a mixture of basal and top beds with broken bricks previously used to build temporary roads for the dragline. The spoil dumps are allowed to weather, often for several years, before being bulldozed during land reclamation. This results in large numbers of vertebrate remains being weathered out, and it is sometimes possible to assess whether the bones were derived from the basal beds or top beds by the presence or absence of broken bricks in the spoil.

Large concretions are frequently dropped on these spoil dumps, especially if the dragline accidentally excavates too deeply and also during the construction of drainage ditches and sumps. At Dogsthorpe and Yaxley the concretions are all from bed 10 and at Orton they come from beds 7/8 and 10. In all pits concretions can yield vertebrate remains. It is possible to determine the derivation of the concretions at Orton by their shape and the degree of brecciation.

4. Brick pits at Whittlesey

These pits are also operated by the London Brick Company, but are worked by "shale planers" which stand on the pit floor. This method breaks the clay into small pieces, and leaves no spoil. The floor of the pit is covered with "brick bats" (roads for the machinery, constructed from broken and mis-fired bricks) which hide the freshly exposed basal beds. There is very little overburden in this area and, what there is, is dumped in an old pit which is now becoming very overgrown. As a consequence the pits at Whittlesey are less productive for the fossil collector, although isolated bones are commonly picked up by the pit workmen. Here the workmen, unlike the workmen at Dogsthorpe, Orton and Yaxley, work in the pit bottom, and are only two or three metres from the face. The amount of material picked up by these men suggests that vertebrate remains might be fairly numerous hereabouts. Several visits to these pits have resulted in the discovery of a large caturid fish, shark fin spines, ichthyosuar and crocodilian remains. Before 1975 a large pit at Kings Dyke, (TL 237 970) was worked by dragline in the same fashion as the Yaxley and Dogsthorpe pits. It yielded the remains of a number of reptiles and fish. Historical accounts also suggest that the Whittlesey area was highly productive for vertebrate fossils (Leeds 1956, Porter 1861).

Stratigraphy

The Oxford Clay forms an almost continuous outcrop from Weymouth, Dorset, to Scarborough, Yorkshire (Fig. 2). Its widest outcrop is in the East Midlands, where it floors the Fens of Cambridgeshire and Lincolnshire. On the wider parts of the outcrop extensive brick manufacturing operations have developed on the Lower Oxford Clay, especially around Peterborough and Bedford, and to a lesser degree at Calvert and Bletchley. A small brick field was developed at Chickerill, near Weymouth, but there are no longer any active pits in this area.

The large brick pits are the only sizeable exposures of the Oxford Clay inland. Coastal exposures occur east and west of Weymouth, and to the south of Scarborough, but there are no good coastal exposures of the Lower Oxford Clay.

The transgressive episode of the Callovian, with the return of ammonite bearing facies to the East Midlands, can be divided into five lithological units (Fig. 3). A lower rubbly limestone, the Cornbrash, is a coarse shelly limestone, often ferruginous, up to 2 m thick, with a rich fauna including bivalves, brachiopods, echinoderms and serpulids. Many of the fossils are worn and encrusted. Hardgrounds covered with *Lopha marshii* are commonly developed.

This is followed by the Kellaways Clay, which in places lies with sharp contact on the Cornbrash, but may pass from shelly limestone to a shelly clay and into normal clay without a sharp boundary. This unit is around 2 m thick, but it is not often seen and little is known about lateral thickness variations. The unit consists of uniform grey clay with occasional calcerous concretions and some pyrite. Fossils are usually poorly preserved, being restricted to internal moulds of ammonite body chambers and rare pockets of bivalves.

Upwards the Kellaways Clay becomes silty and passes into the Kellaways Rock or Sand. Both the base and the top of this unit are difficult to define due to the gradational nature of its boundaries, but again 2 m is about the maximum in the Peterborough district. The Kellaways Rock is a fine sand or silt with an appreciable clay content. In some areas it is cemented into a hard sandstone, but this is never continuous laterally for more than 2 or 3 m. The fauna includes a variety of ammonites and belemnites in super-abundance towards the top, along with small oysters transitional between *Catinula* and *Gryphaea*. Other bivalves occur sporadically, including *Pinna* and *Oxytoma*.

The fourth, and economically most important unit, is the Lower Oxford Clay. Up to 12 m of bituminous clays, shales and paper shales, are punctuated by shell beds composed of *Gryphaea* at the base and *Nuculaceans* and *Grammatodon* towards the top. The Lower Oxford Clay is highly fossiliferous with abundant ammonites, belemnites, bivalves, serpulids and wood. Rare crustaceans and echinoderms also occur. At the base it is possible to find vertebrates without too much difficulty. For a list of Lower Oxford Clay fossils see Duff (1975).

Traditionally the clays above the Lower Oxford Clay are divided into two units, the Middle Oxford Clay, followed by the Upper Oxford Clay. This division is based on faunal elements and it is not possible to distinguish Middle and Upper Oxford Clay on lithological grounds. I prefer to consider them as a single unit, the total thickness of which has never been seen. It is difficult to establish its boundaries in boreholes but a thickness of about 50 m seems probable. The unit consists of grey/green, slightly calcareous clays with low organic carbon content. The fauna includes abundant ammonites preserved as internal moulds in pyrite (Hudson, 1982), bivalves and brachipods. The upper part of this unit (Upper Oxford Clay) is of Lower Oxfordian age.

The transgressive episode, of which the Oxford Clay is the major lithology, began in the late Bathonian in the East Midlands. Deposition of the Lower Cornbrash brought a return of marine sediments with ammonitic facies after the lagoonal limestones and paralic sands and clays of the Bajocian and Bathonian. Although the marine transgression began in late Bathonian times, clay deposition did not begin until the Lower Callovian. Initially the sheltered limestone lagoons of the Bathonian gave way to a current swept limestone sea with the deposition of the Cornbrash, followed by the Kellaways beds.

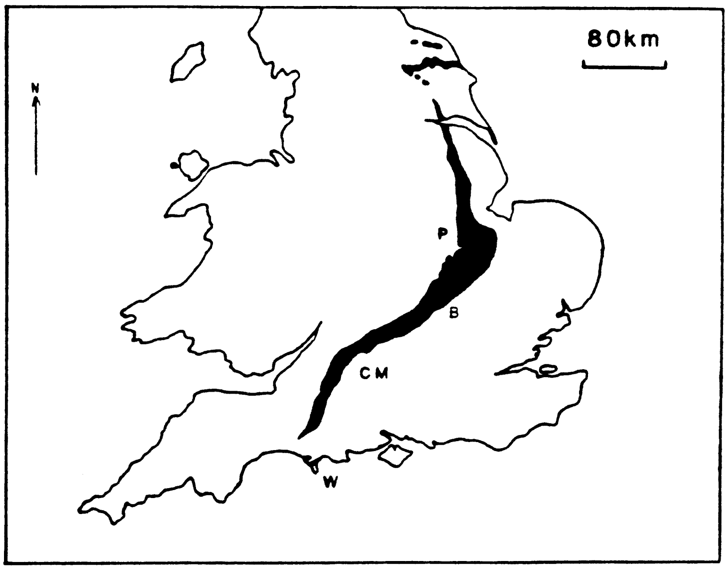


Fig. 2. Onshore outcrop of the Lower Oxford Clay in the British Isles, showing the main vertebrate bearing localities. Based on Duff (1975). B. Bedford, CM. Christian Malford, P. Peterborough, W. Weymouth.

There is a gradual increase in the clay content of the Kellaways Sand upwards as it passes gradationally into the Lower Oxford Clay. This boundary is diachronous over the country (Callomon, 1968), but in the Peterborough and Whittlesey areas it corresponds with the base of the Enodatum Subzone. The top of the Lower Oxford Clay is probably also diachronous with the overlying Middle Oxford Clay as defined lithologically. At Peterborough the upper boundary lies somewhere within the Lower Athleta Zone.

The total thickness of the Lower Oxford Clay in the Peterborough area is around 12m. In Buckinghamshire and Bedfordshire it is around 15m thick. Most of the thinning at Peterborough occurs in the Jason Zone, and this affects the abundance of fossil vertebrate material. Good sections through the Jason and Coronatum Zones occur around Peterborough and lower beds down to the Kellaways Sand are usually accessible in dry summers in pit drainage ditches.

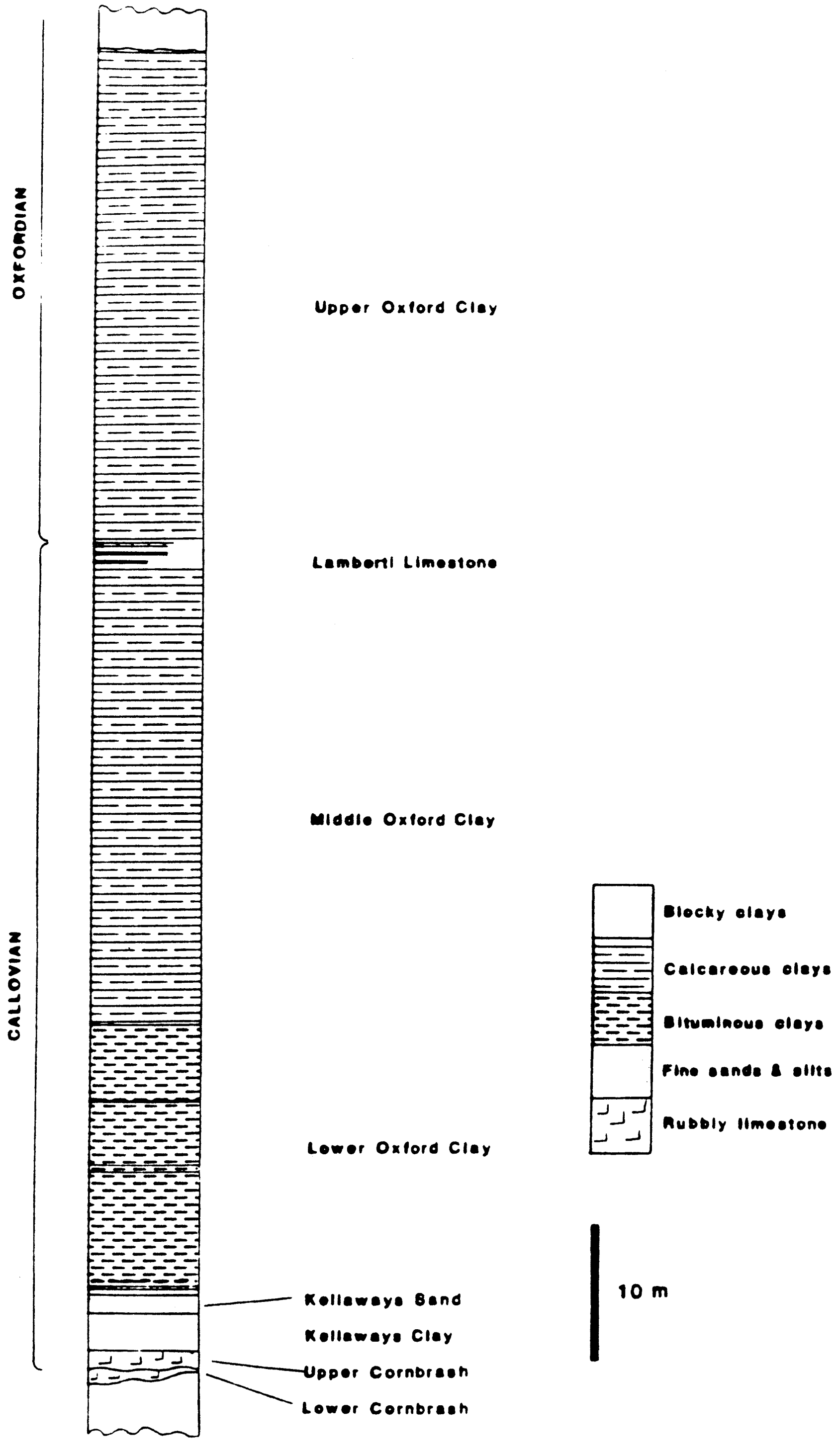


Fig. 3. Simplified stratigraphic log of formations within the Callovian transgressive episode in the East Midlands.

Only the pits at Yaxley and Whittlesey expose the junction with the Middle Oxford Clay, and at Whittlesey access is difficult due to the steepness of the face.

The Middle Oxford Clay is a slightly calcareous, non bituminous clay, and is not generally used for brick production, consequently exposures are rare. A rather weathered face at Norman Cross exposes several metres of clays with large septaria and yields abundant pyritised ammonites of the genera *Kosmoceras* and *Peltoceras*. Older pits that used to work these clays are now flooded as at Eye (TF 231 034), or have been filled in.

The only exposure of the Upper Oxford Clay is at Warboys, Cambridgeshire, where the clay had been worked for extruded pipe production until 1984.

Middle and Upper Oxford Clay vertebrate fossils are not as abundant as those from the Lower Oxford Clay, but sites at Eye, Warboys, Woodham and Weymouth have yielded small quantities of material.

Fig. 3 shows a generalised succession through the Callovian and Lower Oxfordian strata of East England. Details of the vertebrate bearing parts of the Lower Oxford Clay are shown in Fig. 4. Stratigraphical ranges visible in the Peterborough area are shown on Fig. 5.

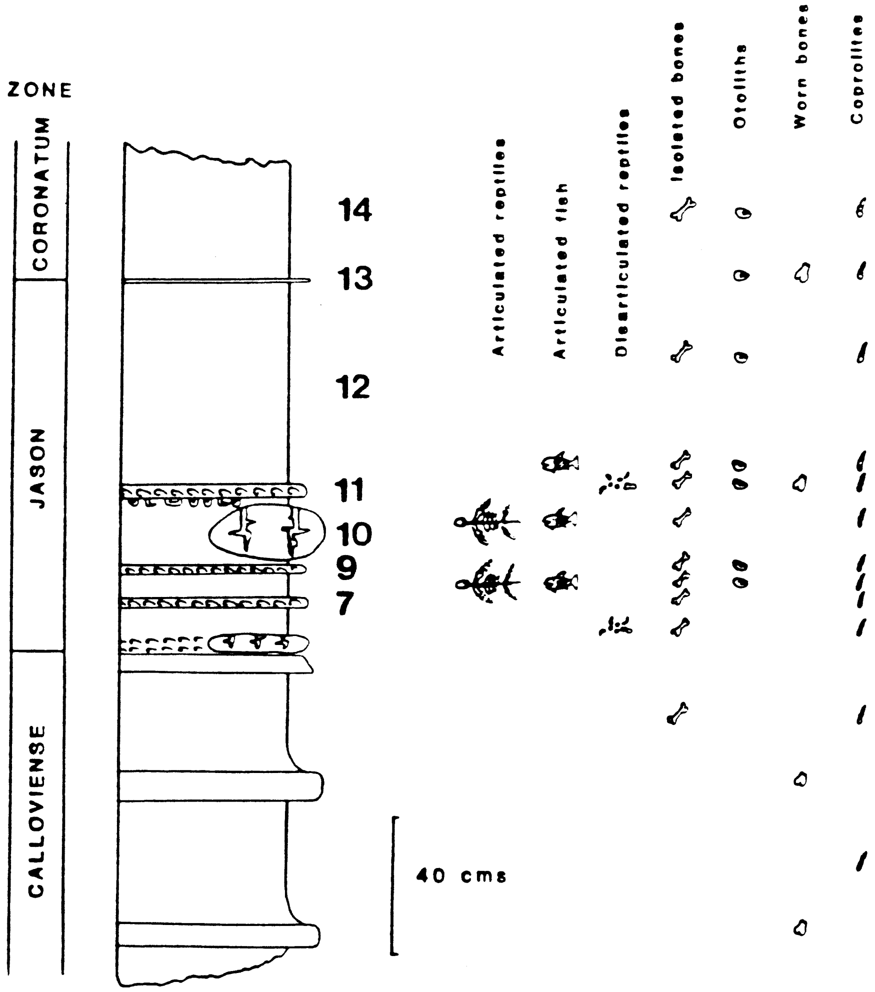


Fig. 4. Distribution of vertebrate preservational types in the basal Lower Oxford Clay of the Peterborough area. Bold bed numbers after Callomon (1968, p. 279).

Historical

Vertebrate remains have been recorded from exposures over most of the outcrop of the Lower Oxford Clay, and a number of sites have become famous for the beautiful collections of fossil fish and reptiles they have provided. The most notable of these being the old brick pits to the south of Peterborough, Cambridgeshire, (Leeds 1956, gives a map of the localities opposite p. 16), and Christian Malford, Wiltshire (ST 957 774).

Little is known about the stratigraphy of the Christian Malford sites, which were borrow pits dug for the construction of the Great Western Railway. Collections of beautifully preserved Christian Malford fishes exist in the British Museum (Natural History), Bristol City Museum, Devizes Museum, and a few other provincial museums. The locality is also well known for its beautifully preserved cephalopods, some of which display the tentacles and ink sac.

A large crocodilian, *Steneosaurus* sp. in Bath Museum is also recorded as coming from this locality, (Bath Museum, no number).

The sites at Peterborough which yielded material for the famous Leeds collection of fossil reptiles, and the lesser known collections of Swales, in Leicester Museum and Art Gallery, and of P.J. Phillips in the City Museum, Peterborough, are now flooded or filled with fly ash. However, as outlined above, the brick industry at Peterborough is very active, and furnishes many square miles of exposure of the vertebrate bearing beds from which the old collection were obtained.

Prior to the development of the Fletton brick making process, many small brick pits were in operation over the outcrop of the Oxford Clay. A few of these in the Lower Oxford Clay yielded vertebrate fossils.

A number of these historical sites in the Lower Oxford Clay have been identified from the literature, (Porter 1861; Judd, 1875; Jukes-Brown 1885, and Leeds, 1956) but these sites are now overgrown, flooded or inaccessible (Fig. 2).

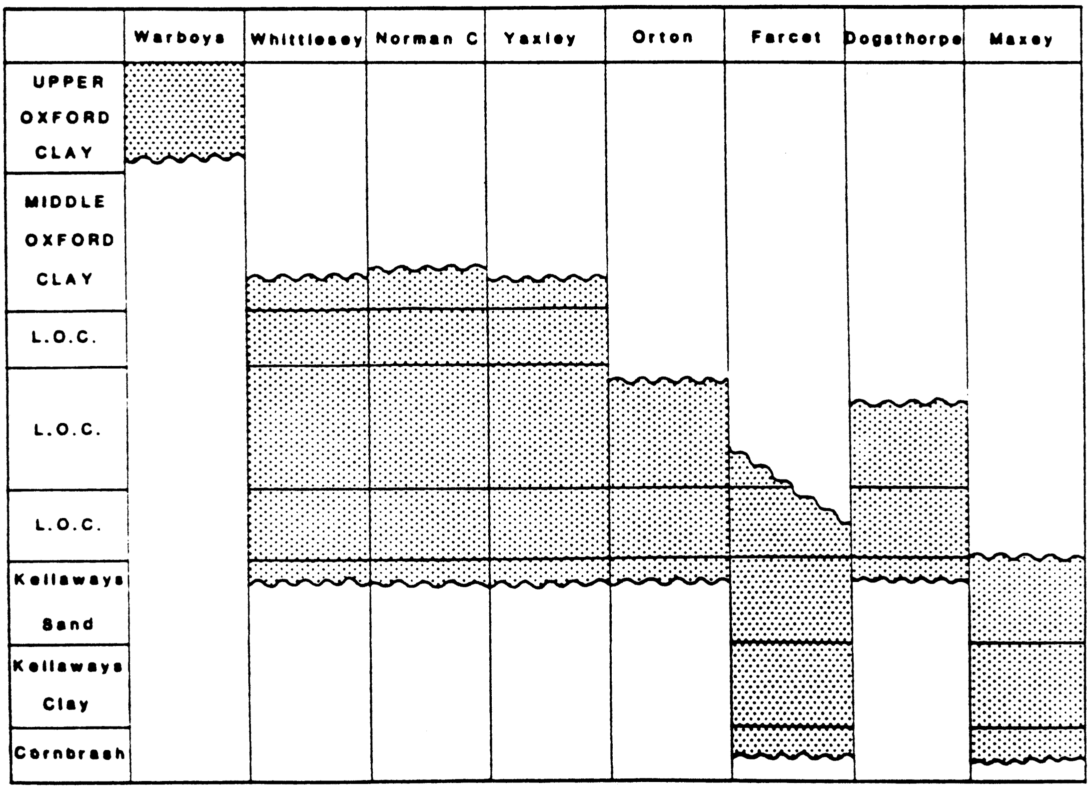


Fig. 5. Diagram showing the stratigraphical range of the Oxford Clay visible at various localities in the Peterborough area.

Museum collections

To supplement the field data, material in the following museums has been examined. British Museum (Natural History), London, BM(NH)., Sedgwick Museum, Cambridge, SMC., Oxford University Museum, OUM., Leicestershire Museums and Art Gallery, LCM., Peterborough City Museum and Art Gallery, PCM., Buckinghamshire County Museum, Aylesbury, BCM., Dorset County Museum, Dorchester, DCM., and the collection of the department of Geology, University of Leicester, LEIUG..

Numerical records of Oxford Clay vertebrates in a number of other collections have been used to assess the abundance of taxa, but none of these specimens are referred to individually.

Vertebrates have been recorded from the Lower Oxford Clay for well over one hundred years. The fauna is diverse, consisting mainly of marine reptiles and fishes, although a poorly represented but nevertheless diverse terrestrial fauna of dinosaurs is known. There are also a few records of pterosaur remains from the Lower and Middle Oxford Clays. (Lydekker, 1890; Leeds, 1956).

The marine reptiles are the most abundant and are now very well known, due largely to the industrious collecting efforts of Mr Alfred Leeds at the turn of the century, which led to descriptions in a two part monograph by Andrews (1910, 1913). This has formed the basis for all of the more recent reviews of the fauna. (Appleby, 1956; Tarlo, 1960; and Brown, 1981). The dinosaur fauna was described by Seeley in 1889, and Woodward in 1905, but reviews have appeared more recently (Charig, 1980; Galton, 1980).

The fish fauna is less well known, and was mainly described at the turn of the century (Woodward 1897). Thies (1983) discovered several new species of neoselachian sharks based on teeth collected from shell beds in the Lower Oxford Clay of Bedfordshire. Fieldwork undertaken for this study has resulted in the discovery of several new fossil fish, including a new palaeoniscid and a giant pachycormid.

Stratigraphic distribution of vertebrates

Upper Cornbrash

Vertebrates have been recorded from the Upper Cornbrash (Lyddeker 1889) at Stilton, Cambridgeshire (TL 170 890) but the exact locality is in some doubt. Most of this material appears to be of a fragmentary nature. More recently Upper Cornbrash vertebrates have been found in the top of the formation from the gravel pit at Maxey, where isolated bones, usually worn, are found in association with *Lopha marshii* and *Macrocephalites* sp..

Kellaways Clay

No certain records exist of vertebrate remains coming from the Kellaways Clays of the East Midlands. Old brick pits in Northamptonshire, around Thrapston, and elsewhere in the Nene valley have yielded saurian remains (Judd 1875), some of which may have come from the Kellaways Clay, but there are no longer any exposures at these sites.

Existing exposures of Kellaways Clay at Thrapston, (SP 990 780) at Maxey gravel pit, at a refuse disposal tip at Fletton, (TL 180 956) and the borrow pit at Farcet, failed to yield any vertebrate remains during this project.

Kellaways Sand

Macro-vertebrate remains occur frequently in the Kellaways sand of Cambridgeshire and Lincolnshire, despite most of the exposures being drainage ditches in pit floors. The remains are usually isolated and worn bones, sometimes encrusted with epibionts. Most of the material encountered appears to be sauropterygian, but some ichthyosaur material is known. An uncertain record of a sauropod dinosaur from this horizon is reported by Seeley (1889).

Lower Oxford Clay, Beds 1–6

The basal beds of the Lower Oxford Clay are probably quite rich in macro-vertebrate remains, but I have not found any substantial quantities of material *in-situ*.

Lower Oxford Clay, Bed 7

Bed 7 is a *Gryphaea* and ammonite coquina in a greenish clay matrix. Despite the limited amount of exposure (bed 7 is only well exposed at Farcet) a number of scattered vertebrate remains have been discovered. Material collected includes the remains of three crocodilians and some scattered ichthyosaurian bones.

At Orton a concretion horizon is developed at this level. The concretions can be up to 1.5 m long, 0.5 m wide, and as much as 20 cm thick. They are frequently highly brecciated, and re-cemented with coarse white calcite. Bones are commonly found within these concretions after they have been exposed in sumps in the pit floor. The concretion horizon is not developed at this horizon elsewhere, except perhaps at Maxey, although the correlation is a little tenuous.

The borrow pit at Farcett has good exposures through this shell bed, and has yielded the remains of at least two crocodilians. All the specimens consist of scattered elements, some of which display weathered fractured surfaces. These features must have occurred on the sea floor. (See ischium of PCM R. 248). The crocodilian LEIUG 88450, was associated with a large quartzite pebble encrusted with oysters, possibly a gastrolith, swallowed for bouyancy regulation (Taylor, 1981 and pers. comm.). Unfortunately this is of little value for determining the source area.

Lower Oxford Clay, Bed 8

Fissile shales of bed 8 have yielded few vertebrates, there being only a single specimen believed to have come from this horizon. A perfectly preserved, complete specimen of *Cryptoclidus eurymerus* was reported by Charig and Horrell, (1971), from the base of the large brick pit at Orton (Pit LB 2/4 in their paper). They did not record the exact horizon, but commented that it was from the Jason Zone. Personal discussions with a number of workmen who helped at the discovery site suggested that the specimen lay some eighteen inches below the working face of the pit. When discovered, Orton pit was being excavated by a face shovel standing on a firm floor provided by bed 10. This suggests that the *Cryptoclidus* must have come from bed 8 since this is approximately eighteen inches below the top of bed 10. This is the only non-shell bed lithology that lies within the Jason Zone below the main concretion horizon of bed 10.

Lower Oxford Clay, Bed 9

This *Gryphaea* shell bed has yielded only a single macro-vertebrate during my field season. The specimen is a fish fin ray 3 m long from the giant pachycormid fish *Leedsichthys*. It was found in the borrow pit at Farcet, during December, 1984, but because the bones of the fin are so fine, I decided not to collect the specimen.

Lower Oxford Clay, Bed 10

Several complete or partially complete vertebrate skeletons have been collected from this horizon. Bed 10 is a highly bituminous (up to 10% organic carbon, Fisher, 1983) fissile shale with large septarian concretions whose formation was discussed in detail by Hudson (1978). Invertebrate fossils are abundant and include benthic and pelagic forms. The infauna is restricted, but certain infaunal and semi-infaunal elements are common. Vertebrates occur in both the fissile shales and in the concretions, where the shape of the concretion may be influenced by the shape of the vertebrate skeleton.

A recently collected suite of specimens from this horizon has been deposited in the collections of the Department of Geology, University of Leicester, by Mr P. Schultz, formerly of Towcester, Northamptonshire. This collection is well documented, with accurate location and stratigraphic data. Most of the material is enclosed in large concretions, although some is from the shale. Nearly all of the specimens were collected from the large pit at Orton.

Several fish and reptile specimens from this horizon were collected by the author from the pit at Dogsthorpe.

Lower Oxford Clay, Bed 11

Bed 11 is a *Gryphaea* and ammonite coquina in a green clay matrix, containing a diverse invertebrate fauna dominated by cephalopods and bivalves. Burrows in the top of Bed 10 below are filled with the finer shell debris and clay matrix of bed 11.

Both macro and micro-vertebrates are common. The pit at Dogsthorpe has been the most productive for larger marine reptiles (e.g. Fig. 6) but this is due to the operator of the dragline, who leaves much of the shell bed intact in the floor of the pit. In the Orton and Yaxley pits this bed is removed and bed 10 is left as the floor of the pit. During this study the pit at Dogsthorpe produced on average three skeletons from bed 11 each time the dragline completed a cut along the face, (each cut takes six months, but this is dependent on economic factors). Many more skeletons have occurred since several were destroyed by the dragline leaving scrappy fragments lying around the pit floor.

Lower Oxford Clay, Bed 12

Bed 12 is a dark grey clay which is fissile in its lower part. Large patches of this bed have been exposed in the pit at Dogsthorpe, and have yielded the remains of a large pachycormid fish, and a number of other smaller fish. A gigantic fish fin, (Fig. 8) was found at an unknown level, thought to be within bed 12, at Farcet borrow pit.

Lower Oxford Clay, Bed 13

This bed, although only 2–3 cm thick, yields abundant vertebrate remains. The bed consists of a coquina of nuculacean bivalves and broken ammonites, with masses of small belemnites, coprolites and worn fragments of wood. It is highly pyritised and is conspicuous on weathered pit faces as a thin orange band, usually about 1 m above the floor of the large brick pits. At Farcet borrow pit it is present in a few places where the glacial channel has not cut too deeply.

All of the macro-vertebrates obtained from this level are isolated bones and teeth and only rarely are associated elements found. Usually the bones are broken, worn, encrusted with epibionts and have a thin coating of pyrite. Microvertebrates are also common at this level, particularly otoliths, most of which are slightly etched (Plate 9D).

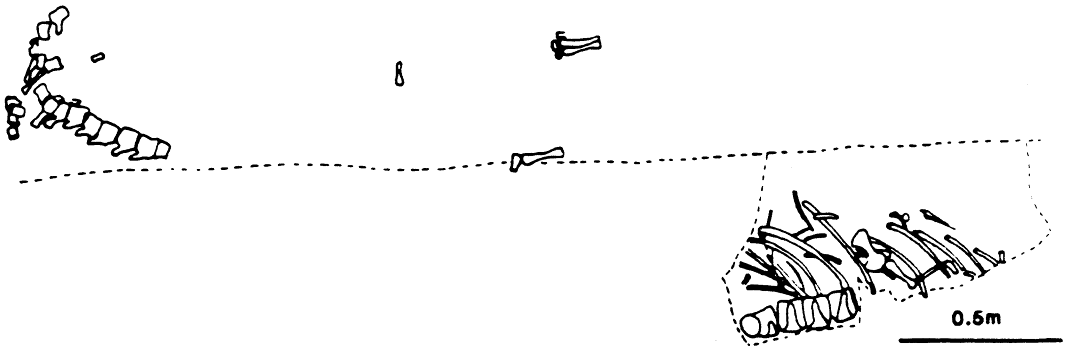


Fig. 6. Plan of in-situ skeleton of *Metriorhynchus* sp. LEIUG 90985. Lower Oxford Clay. Bed 10 and 11, Dogsthorpe, Peterborough.

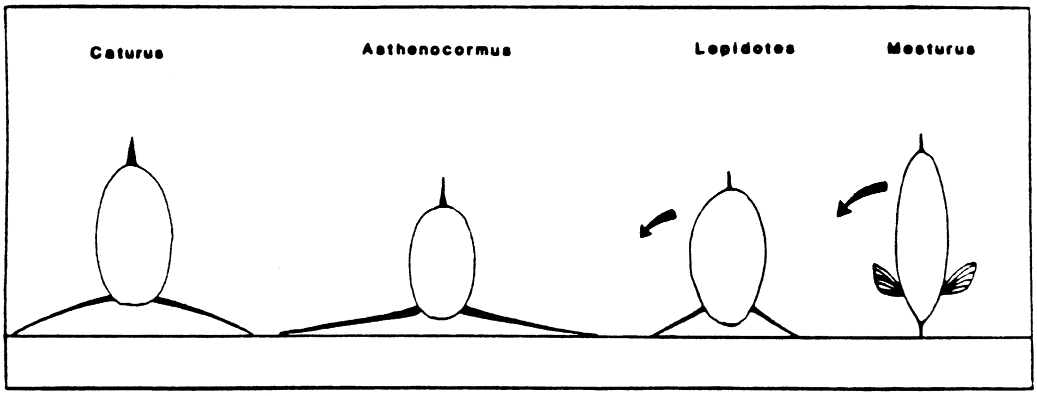


Fig. 7. Cross sections of fishes to show how body shape and pectoral fin morphology can influence the attitude of a fish carcase on the sea floor.

Lower Oxford Clay, Bed 14

During ths study only micro-vertebrate material was found in this bed. This bed is the thickest unit within the Lower Oxford Clay. Fossils are less abundant than in some of the other horizons. The bed is made up of almost featureless bituminous shale, which is blocky when fresh, becoming slightly fissile after weathering.

Lower Oxford Clay, Bed 15

This is a nuculacean shell bed in which micro-vertebrate material is common. Only two associated ichthyosaur centra were collected from this level.

Lower Oxford Clay, Bed 16

This highly bituminous shale forms a useful marker horizon in the Peterborough brick pits, which stands out as a dark band on the pit face between two prominent shell beds.

During 1972 Mr P. Schultz discovered an almost complete, fully articulated, mature adult specimen of *Ophthalmosaurus* sp. from this level at the Orton pit. LEIUG 90986, which was excavated by Dr R. Clements of Leicester University (Fig. 9). This specimen is perhaps the most complete *Ophthalmosaurus* sp. to be collected from these pits in recent times.

Lower Oxford Clay, Bed 17

This nuculacean shell bed is well exposed in the abandoned pit at Norman Cross, where, in 1983, it was possible to walk along one of the pit faces at this level. Several unidentifiable fragments of very worn reptilian bone were found. Micro-vertebrates are also common at this level.

Lower Oxford Clay, Beds 18 to Top

Because of the limited amount of exposure, and inaccessibility of these higher beds, no macro-vertebrate material was found above bed 17 in the Peterborough district. Samples taken at these higher levels for microvertebrates all yielded fish teeth and otoliths.

Clays above the Lower Oxford Clay "Middle Oxford Clay"

Although historical records exist of vertebrates from the Middle Oxford Clay (Leeds, 1956, Lyddeker, 1889) several visits to exposures of these beds at Norman Cross, Cambridgeshire and Stewartby, Bedfordshire, failed to reveal any vertebrate specimens.

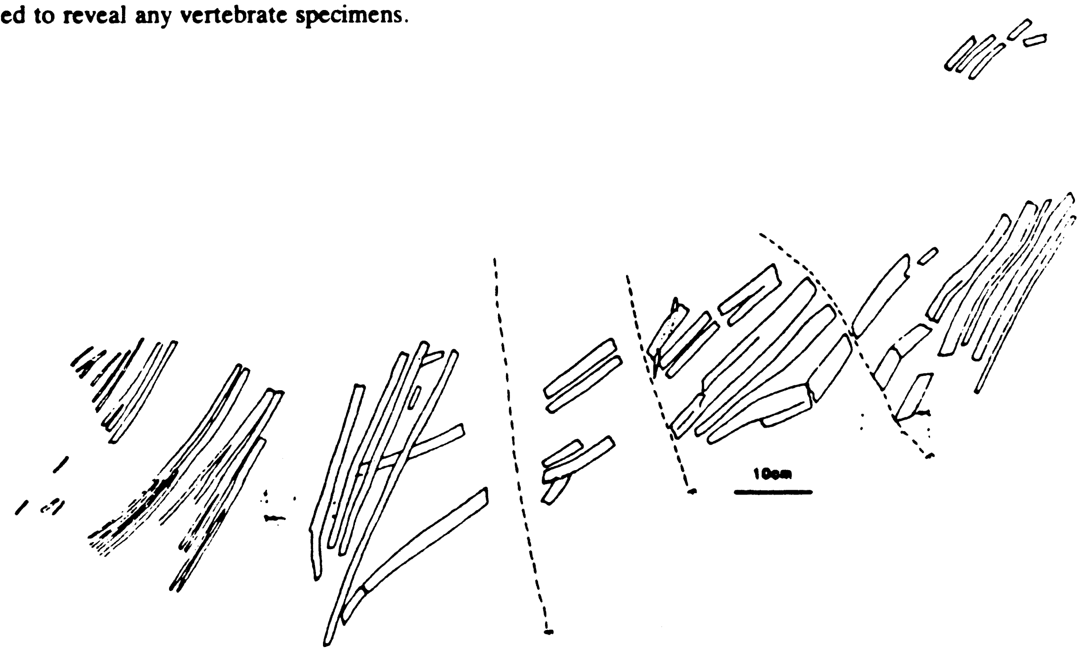


Fig. 8. Portion of fin of *Leedsichthys* sp. Lower Oxford Clay, Bed 12 or 14.

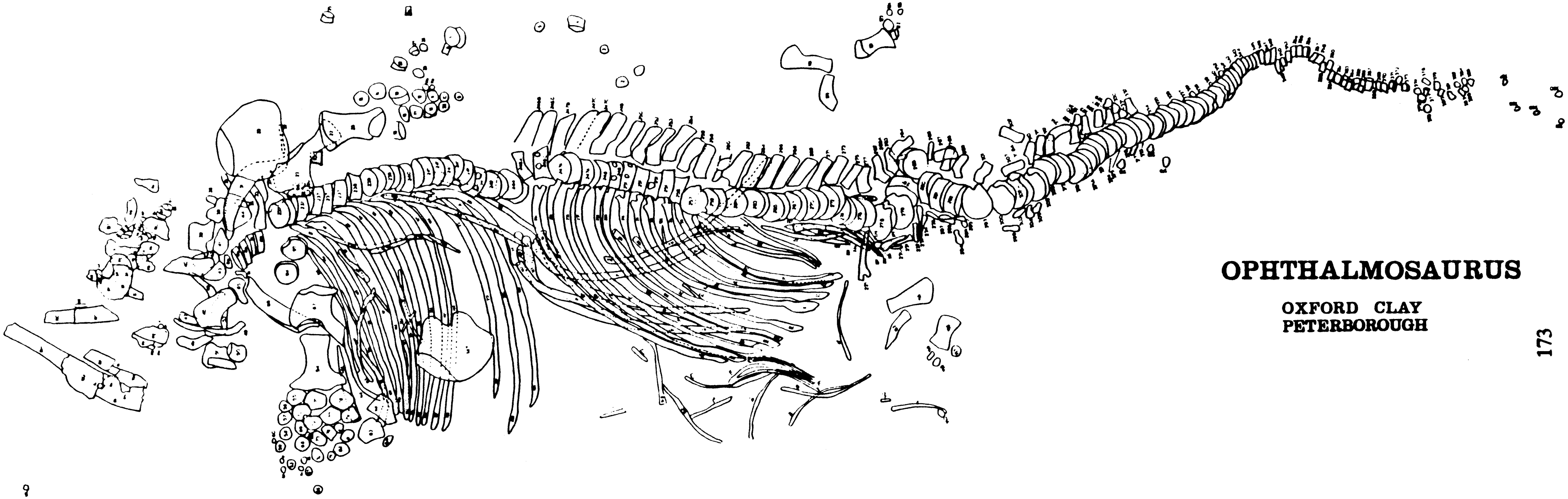


Fig. 9. An almost complete, fully articulated, adult specimen of *Ophthalmosaurus* sp. from the Lower Oxford Clay (Coronation Zone) of Orton Pit. Discovered in 1972 by P. Shultz and excavated by Dr R.G. Clements of Leicester University. Cat. no. LEIUG 90986. Ribs of the right side omitted for clarity.

Lamberti Limestones

No records of vertebrates from this level exist, and no certain exposures of this bed are known today. A downfaulted block of Middle Oxford Clay at Stewartby shows a series of thin muddy limestones which might represent the Lamberti Limestone.

Clays above the Lower Oxford Clay "Upper Oxford Clay"

The only large exposure of the Upper Oxford Clay in the East Midlands was that of the now disused brick pit at Warboys, Cambridgeshire (Callomon, 1968). Vertebrates have been recorded from this pit by Forbes (pers. comm.) but recent visits produced only isolated fish teeth. Fig. 10 shows the scattered remains of an ichthyosaurian from the Mariae Zone, of Warboys.

Palaeoecology

Vertebrate skeletons are internal, multi-component systems, dominantly composed of a single mineral phase. Vertebrates are, therefore, useful as palaeoecological indicators, especially when invertebrates are absent due to diagenetic removal.

As the vertebrate skeleton is internal except for teeth and some types of dermal armour, a skeleton cannot be encrusted by epibionts until the animal has died and the bones exposed. Therefore, any epifauna on the surface of a bone must be post-mortem, and indicates the presence of oxygenated sea water at or near the sediment water interface. Vertebrate remains, therefore, conveniently avoid the argument that ensues with encrusted ammonites, as to whether encrusting took place whilst the ammonite was alive or whether encrusting was post-mortem (Seilacher, 1981).

Two mineral phases occur in fish skeletons, hydroxy apatite, and calcium carbonate; bones and teeth being composed of the phosphatic phase, and otoliths of the carbonate phase. These different phases are prone to different diagenetic effects which can affect the preservational potential of certain skeletal elements.

Fig. 10. Partial skeleton of an ichthyosaur, cf. *Ophthalmosaurus* sp. Upper Oxford Clay, Warboys, Cambridgeshire. Excavated by Dr C. Forbes. SMC J.68689.

Vertebrate preservational styles in the Oxford Clay and adjacent strata

Andrews (1910) commented on the often beautiful preservation of some of the fish and reptile specimens, but preservation has until recenty been virtually ignored by most palaeontologists and sedimentologists. Vertebrate palaeontologists have now begun to realise the importance of taphonomic studies on vertebrate remains for palaeoecological interpretations. Increasingly, papers are now appearing in which taphonomy forms at least a part of the discussion. (Camp, 1980; Milner, 1980). Studies on the taphonomy of recent aquatic vertebrates (Schafer, 1972; Wuttke, 1983) have shown that the decomposition and break up of a carcase is a complex process, and requires detailed observation. Attempts to do this with fossil marine reptiles from bituminous shales have been made by Keller (1976), and Brenner, (1976) on ichthyosaurs from the South German Posidonienschiefer.

Vertebrate preservation

Although an examination of museum material can be informative for preservational studies, much data is lost when the specimen is taken from the ground and extracted from its matrix. An examination of museum material cannot show the attitude of the specimen as it lay in the ground, and in most cases, considering the loving care which some of the early amateur collectors of Oxford Clay vertebrates must have put into their work, it is surprising that very little data on stratigraphic occurrence, or on the attitude of the skeletons was recorded.

During the latter part of the last century, there was no established zonal scheme for the Lower Oxford Clay, and the first detailed section through these beds in the Peterborough district did not appear until 1929 (Brinkman, 1929). So, unless the collector had any knowledge of geology it was perhaps not easy to establish where in the sequence a specimen came from. This is unfortunate, in that the abundance of Oxford Clay material, with suites of specimens showing ontogenetic variation, and variation within populations, could have led to some interesting evolutionary interpretation, had detailed stratigraphic information been recorded.

An examination of several *in-situ* sauropterygians, crocodilians, ichthyosaurs and fish reveals that even in a seemingly monotonous sequence of clays, slight perturbations of current activity, oxygen level, firmness of substrate and rate of sedimentation can dramatically affect the style of preservation of the animals. Although the range of preservational styles forms an almost continuous spectrum, it is convenient to recognise five preservational categories based on taphonomic and sedimentological criteria. Fig. 11 shows the five preservational styles recognised in the Lower Oxford Clay.

1. Articulated skeletons

Articulated skeletons are those in which all of the bones of the skeleton are present, and lie in positions showing true bone to bone relationships with adjacent elements of the skeleton. Teeth are usually present within the jaws, and in some cases coprolitic material may be present within the gut region. In exceptional cases there may be evidence of soft part preservation.

Such beautifully preserved specimens are rare, and restricted lithologically to only a few horizons within the Lower Oxford Clay. Most notably they occur within fissile highly bituminous shales of the Jason Zone, at the base of the Peterborough succession. These bituminous shales are interbedded with *Gryphaea* shell beds, which also yield large vertebrates. Within the fissile shales large sauropterygians, BM(NH) R. 8621, (Charig et al 1971), LEIUG 90988, Fig. 12, crocodilians, LEIUG 90987, and LEIUG 90988, Fig. 6, have been found, beautifully articulated, along with a small *Lepidotes macrochierus* Woodward, BM(NH) P. 61398. *Asthenocormus* sp. BM(NH) P. 61563, and *Hypsocormus* sp. BM(NH) P. 61397.

The fish all display perfectly articulated tails, fins and scales, and each specimen contains coprolitic material within the body wall. In the case of BM(NH) P. 61398 only the lower surface of the fish is articulated, the scales of the upper surface (right side of the fish) having been disturbed slightly, probably due to the escape of decomposition gases. The *Asthenocormus* sp. contains fragments of *Leptolepis* in the gut.

2. **Disarticulated skeletons**

The degree of disarticulation between specimens can vary considerably. Skeletons may be completely disarticulated, but with all the bones present and in association, or may be only partially disarticulated with more coherent parts of the skeleton, such as interlocking vertebrae, remaining articulated. Due to the large range covered by this category, there is less restriction lithologically, but there is a positive correlation between grain size and degree of disarticulation.

The *Gryphaea* shell beds within the Jason Zone represent non sequences and reworking events and frequently yield large reptilian skeletons. These are always disarticulated partly as a result of reworking of articulated specimens from the underlying shales, and partly due to storm activity upon specimens deposited during the event. A partly disarticulated *Ophthalmosaurus* sp. LEIUG 90984, and a juvenile plesiosaur of *Cryptoclidus* sp. LEIUG 90983, both from Dogsthorpe brick pit, were found within the same shell bed. Fig. 13 shows the position of the skeleton of *Ophthalmosaurus* sp. LEIUG 90984 and shows that parts of the skeleton, such as the shoulder girdle and a part of the rib cage, are articulated, but detached from the skeleton probably due to scavenging on the sea floor. Due to scavenging and perhaps disturbance by storm activity the juvenile plesiosaur, LEIUG 90983, (Fig. 14) shows no articulation of the skeleton.

Higher within the sequence, the deposit feeder bituminous shales, *sensu* Duff (1975), also yield disarticulated skeletons. The rare occurrences of vertebrates in the slightly calcareous shales of the Middle and Upper Oxford Clays are also usually disarticulated (Leeds, 1956; Forbes, unpublished data). Fig. 15 shows the skeleton outline of a large ichthyosaurian *Ophthalmosaurus* sp. BCM 1001 1983 from the deposit feeder bituminous shales of the Coronatum Zone at Milton Keynes, Buckinghamshire. This specimen is partially articulated, mainly on its left side, and partially disarticulated, especially towards the distal end of the vertebral column, the right side of the rib cage and the limbs. This should be contrasted with LEIUG 90984 in (Fig. 13).

The Milton Keynes specimen BCM 1008, 1983 remained partially articulated because the skeleton sank part the way into the muddy sea floor, the enclosing sediment therefore holding the skeleton together after the integument had decomposed.

Fig. 6, shows part of the skeleton outline of a large *Metriorhynchus* sp. LEIUG 90985, which was discovered lying partly in fissile shales and partly in an overlying *Gryphaea* shell bed. Within the fissile shales; the trunk, proximal part of the tail, shoulder girdle and limbs; remain fully articulated. The body cavity contains abundant cephalopod hooklets, presumably the gut contents. Of the parts of the skeleton found in the overlying shell bed the distal part of the tail was disarticulated, but even these bones were closely associated. This indicates that the carcase or skeleton had been completely buried by the fissile shale sediment, and partly re-exposed by storm activity rather than strong current activity. If current activity had been responsible for the reworking, the smaller elements of the tail (small vertebrae and chevrons) would have been washed some distance from the site of the articulated skeleton. Here it is clear that two specimens lie both in category one and category two, but for different reasons; the first due to a soft substrate and slow sedimentation rate, the second due to partial reworking.

3. **Isolated bones and teeth**

Isolated bones and teeth of fish and reptiles occur frequently throughout the Lower Oxford Clay sequence. Many are perfectly preserved. Isolated bones probably dropped from decomposing carcases floating in the water column (Schafer, 1972), although some may have been derived from carcases on the sea floor by scavengers. The most likely explanation for the occurrence of isolated teeth is that they were simply shed whilst the animal was still alive, as in present day reptiles, or like the isolated bones they may also have dropped from drifting carcases. In the Lower Oxford Clay this category does not appear to be lithologically restricted.

4. **Worn bones**

Worn and eroded bones are common within the *Gryphaea* shell beds, nuculacean shell beds and the fine sand and silts that occur at the Kellaways beds-Lower Oxford Clay transition. These bones have been worn due to attrition by comminuted shell fragments and fine sand. In the fine sands and silts, at the base of the sequence the eroded bones are usually a pale yellow or buff colour on their surfaces, suggesting prolonged exposure on the sea floor. It is possible that some of the erosion may be due to biological activity, as some echinoderms and bacteria are known to feed on fish bone. (Brongersma-Sanders 1949). Echinoid remains have been found in some of the shell beds.

5. Coprocoenosic accumulations

Coprolitic material is abundant throughout the Lower Oxford Clay, but it is concentrated in the shell beds, mainly as irregular, buff coloured phosphatic masses and spindle shaped bodies often several centimetres long. Frequently these coprolites contain small bones and teeth.

The notable occurrence of vast quantities of otoliths in a nuculacean shell bed at the boundary between the Jason and Coronatum Zones at Peterborough (bed 13 of Callomon, 1968) may also be included in this category. Here the number of otoliths occurring in samples prepared for micropalaeontological examination far exceded the number of fish teeth found in the same sample. This is due to the concentration of otolith elements in the guts of marine reptiles and fishes where phosphatic elements of the skeleton are preferentially digested by the gastric juices, and removed from the fossil record, whereas the calcareous otoliths are only slightly etched. (Fitch and Brownell, 1968). Such a process occurs in recent cetaceans and is responsible for concentrating slightly etched sacculiths of a limited number of fish species, often within a very narrow size range. The otoliths found in the nuculacean shell beds are all slightly etched, of a similar size, and there is a greater concentration of drop shaped otoliths compared to thin plate like-otoliths. (Plate 9D).

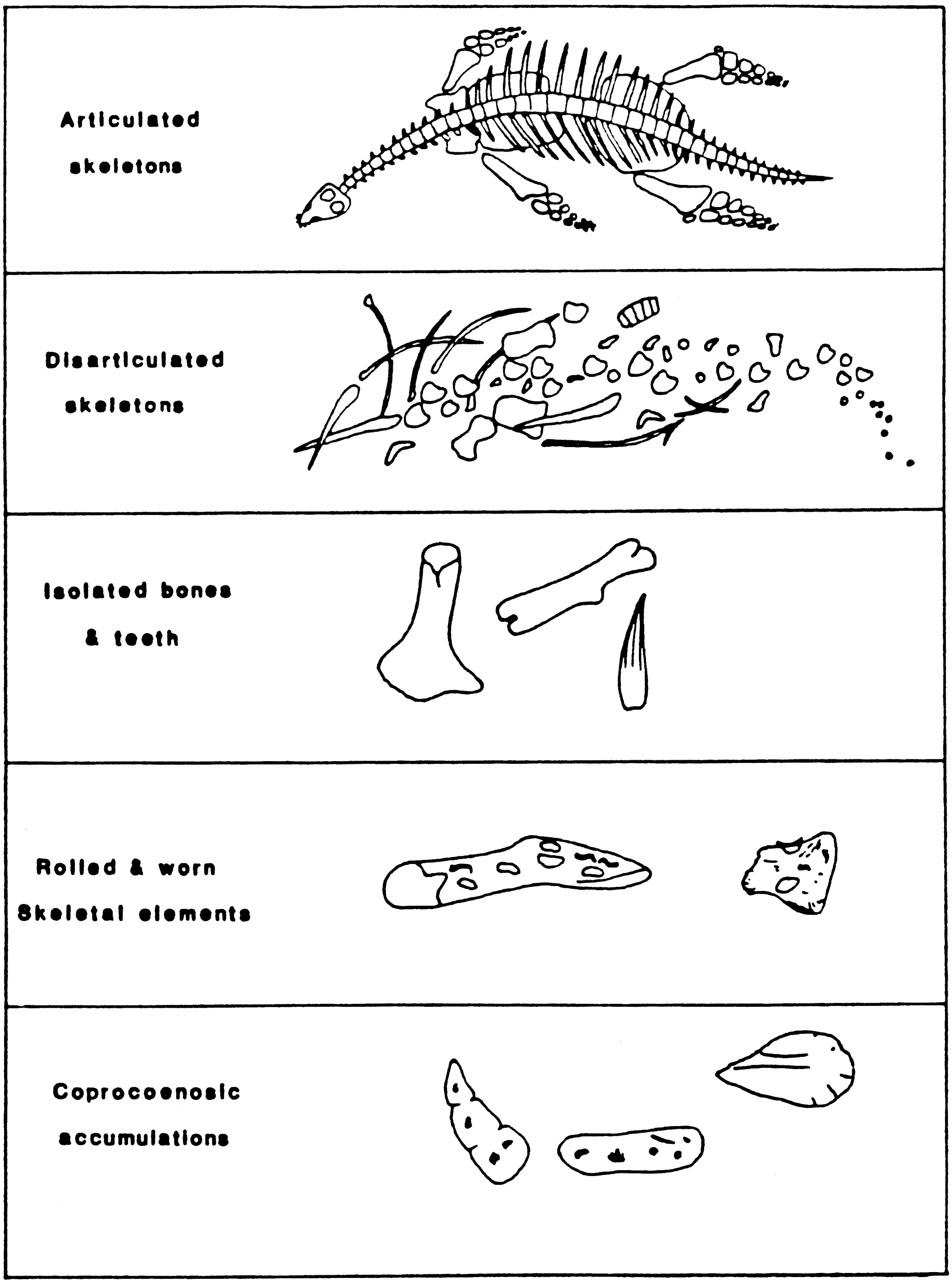


Fig. 11. Vertebrate preservational categories recognisable in the Oxford Clay.

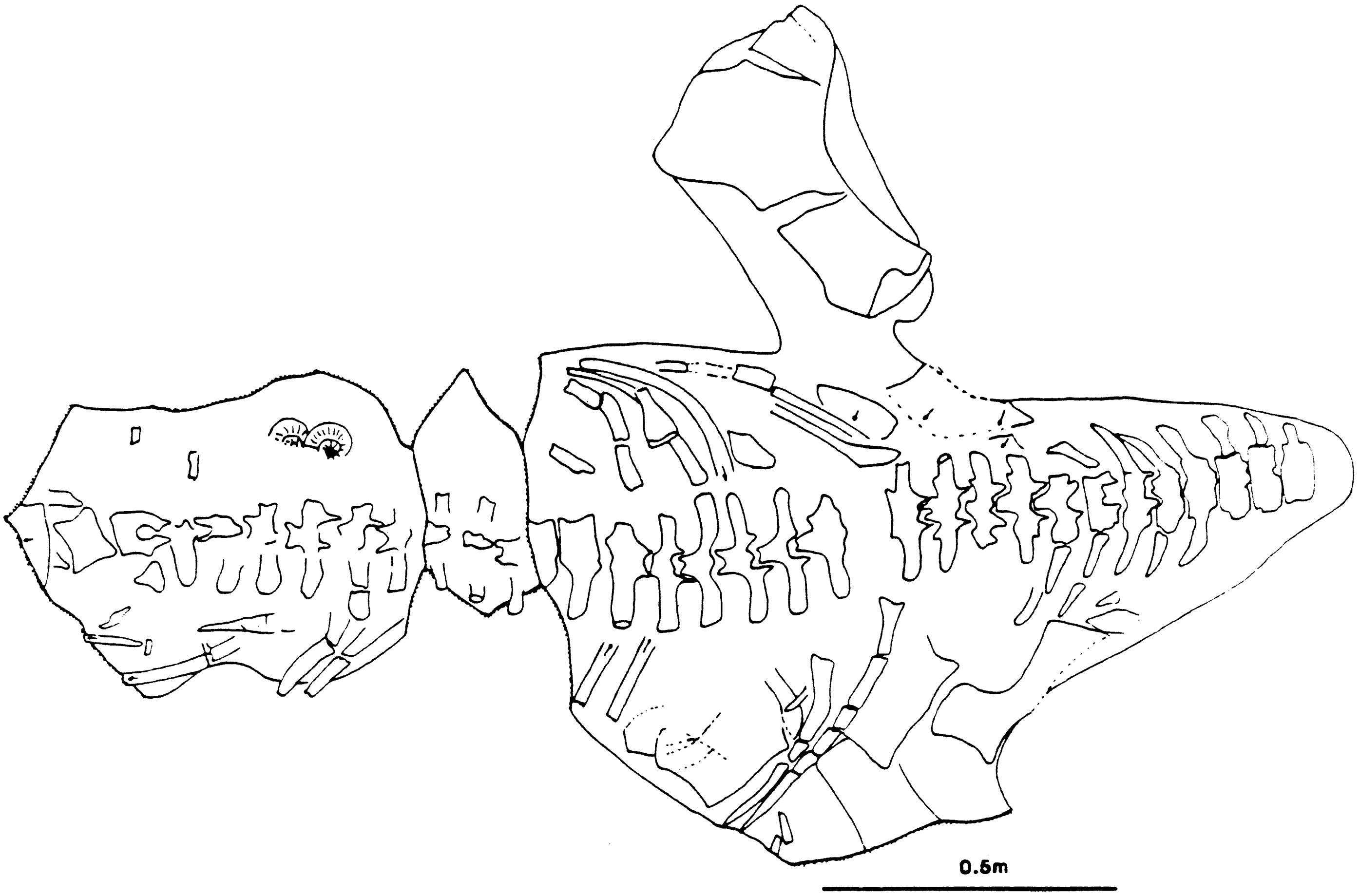


Fig. 12. Skeleton plan of sauropterygian, cf. *Cryptoclidus* sp. LEIUG 90988, enclosed in large septarian concretion. Lower Oxford Clay, bed 10, Orton pit, Peterborough.

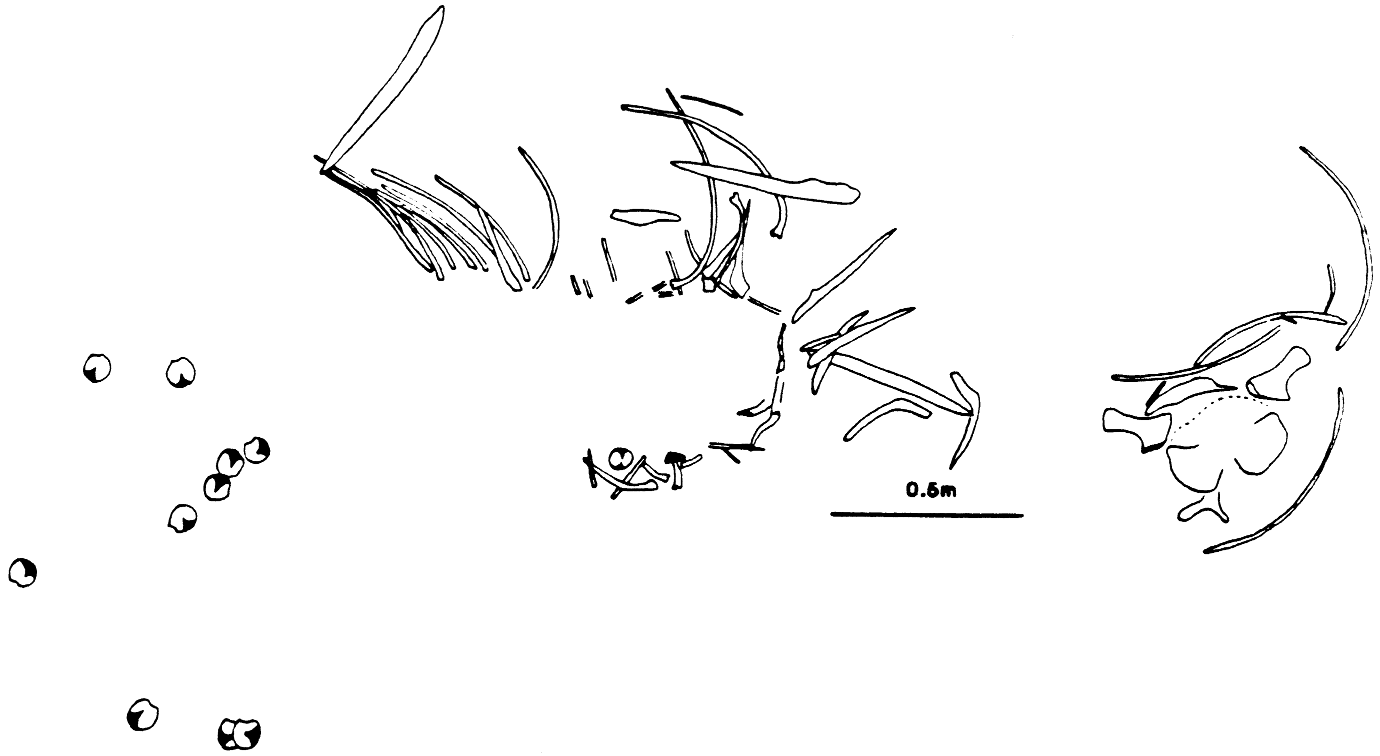


Fig. 13. Skeleton plan of *Ophthalmosaurus* sp. in-situ. Mostly disarticulated but with shoulder girdle still articulated. LEIUG 90984. Bed 11, Lower Oxford Clay, Dogsthorpe, Peterborough.

Taphonomy

The following factors in part control the type of preservation of Oxford Clay vertebrates. They need not occur in the order listed.

1. Death. By old age, predation or disease.
2. Decomposition.
3. Arrival on sea floor.
4. Scavenging.

1. Death

The cause of death is important in determining the state of the animal when it arrives on the sea floor. Three types of death are here invoked for Oxford Clay vertebrates. Death by old age, death by disease, and death by predation. Appleby (1979) has suggested that some ichthyosaurs may have sustained severe injuries to the shoulder girdle through excessive deceleration while swimming rapidly. Such accidents could result in the death of the animal.

Death by disease may result in a complete carcase, as will death by old age. Old age can usually be recognised in specimens by advanced ossification, but it is difficult, if not impossible to show that this was the cause of death. Disease can be recognised if it affected bone development (Delair, 1974), but again it is difficult to show that this was the actual cause of death.

Death by predation is very common, and can often be recognised by scars on bones or by large pieces of the skeleton being missing. Death by predation may involve the mutilation of the corpse and the subsequent detatchment and loss of many parts of the skeleton. Plate 10 shows part of a frontal bone from the giant pachycormid fish *Leedsichthys* PCM F. 1 which was attacked by a crocodile, a tooth of which is embedded in the bone. The fish managed to escape, and the scar healed with new bone growth forming around the crocodile tooth. Obviously no healing takes place if the injury results in the early death of the animal.

Several specimens of *Ophthalmosaurus* sp. notably BCM 1008, 1983 and LEIUG 90986 are old individuals which display expanded ends to the ribs, this bone is diseased, probably arthritic and may have contributed to the death of the animal.

2. Decomposition

Soon after death has taken place the soft tissue begins to decompose. Bacteria within the gut infect the body tissues. Decomposition gasses build up, bloating the carcase which may then float for several days (Schafer, 1972). During this time the body continues to decompose, and parts of the skeleton may be exposed and drop to the sea floor. Scavenging will also take place while the carcase floats, assisting the breakdown of the animal.

3. Arrival on the sea floor

The arrival of the carcase on the sea floor has complex effects. It affects the attiude of the skeleton, and depending on the firmness of the substrate, it affects further decomposition processes.

The attitude of the carcase on the sea floor is largely dependent on the original shape of the animal, and whether the animal arrives on the sea floor intact.

4. Scavenging

Scavengers may be responsible for the complete break up of a carcase whilst it is floating or lying in the sea floor. It is difficult to establish whether missing elements of a skeleton are due to scavenging or predation by the killer. Small teeth of *Hybodus obtusus* associated with large reptile skeletons are probably from a scavenging shark rather than a predatory one.

Ichthyopterygia

Ichthyosaurs usually arrive on the sea floor with their long axis parallel to the main current direction (Brenner, 1976) upside down and with the fore paddles slumped downwards (dorsaly). They then roll over to one side. The upper flipper may point dorsally or ventrally. Often the upper flipper decomposes whilst pointing upwards in the water column, dropping its bones around the carcase.

Due to the extra weight of the skull, many specimens arrive rostrum first on the sea floor, and if the sediment is soft enough the rostrum will penetrate the sediment.

Sauropterygia

All the long necked plesiosaur specimens examined arrived on the sea floor in a dorsal or ventral position, with flippers held out laterally, many have coiled necks, because the weight of the skull and neck vertebrae caused the neck to hang down in the water column while the carcase is floating. The head and neck therefore reach the sea floor before the torso and the neck coils as the body slowly sinks.

Few pliosaurs have been found intact and *in-situ* so little data is available. It is likely that the weight of the large skull is sufficient for it to drop off a floating carcase undergoing decomposition. This might explain the occurrence of pliosaur skulls found without post cranial elements of the skeleton.

Crocodilia

The number of *in-situ* records of crocodile material from the Lower Oxford Clay is negligible. Two specimens were discovered during this study, one, a single fragmentary skull, and the other, a partial skeleton, broken by the dragline, of *Metriorhynchus* sp. LEIUG 90985, lying on its right side (Fig. 6).

Fish

Several articulated fish specimens have been found, and many museum specimens can also be satisfactorily orientated. *Caturus* sp. which appears to be the most common of the articulated fish in collections, is mostly dorso-ventrally flattened, (Plate 9F) as also was a specimen of *Asthenocormus* sp. with only the tail in a lateral position. Specimens of *Lepidotes* sp. and *Hypsocormus* sp. were found lying on their sides. *Caturus* is a fusiform fish with large pectoral fins, it was probably stabilised by these on the sea floor (Fig. 7).

A preservational case study of a partially articulated ichthyosaur

A partially complete skeleton of an ichthyosaur, *Ophthalmosaurus* sp. BCM 1983, 1008, from the Lower Oxford Clay, Coronatum Zone, at Milton Keynes, Buckinghamshire, has been examined in detail whilst still *in-situ* and is now a mounted specimen in Milton Keynes Library.

The specimen was discovered by Mr Les Fitchett, a construction worker employed by French Kier Construction plc. during the excavation of a reservoir at Caldecotte, Buckinghamshire (SP 892 352).

The specimen was a mature adult, approximately 5 m long, which possibly died from old age. There are no visible scars on any of the bones to indicate predation. Fig. 15 shows an outline plan of the skeleton as it lay *in-situ* prior to removal. Some skeletal elements do not appear on the diagram as they were disturbed by the excavating machinery, and cannot be accurately placed. These misplaced elements include part of a coracoid, the right ? ulna, part of the rostrum and numerous digits. Part of the rib cage was also slightly disturbed.

The skeleton was found lying partly within greenish bituminous shale and partly enclosed within a septarian concretion. Two thoracic vertebrae, detached from the main part of the skeleton, were enclosed in a pyrite concretion.

The specimen is an associated, partially articulated *Ophthalmosaurus* sp. Specific identification cannot be determined as the diagnostic coracoids (Appleby, 1956) are not sufficiently well preserved to show the anterior and posterior notches. The articulated parts of the skeleton include the left side of the rib cage and parts of the vertebral column. Some skull elements enclosed within the concretion, and some of those disturbed by the

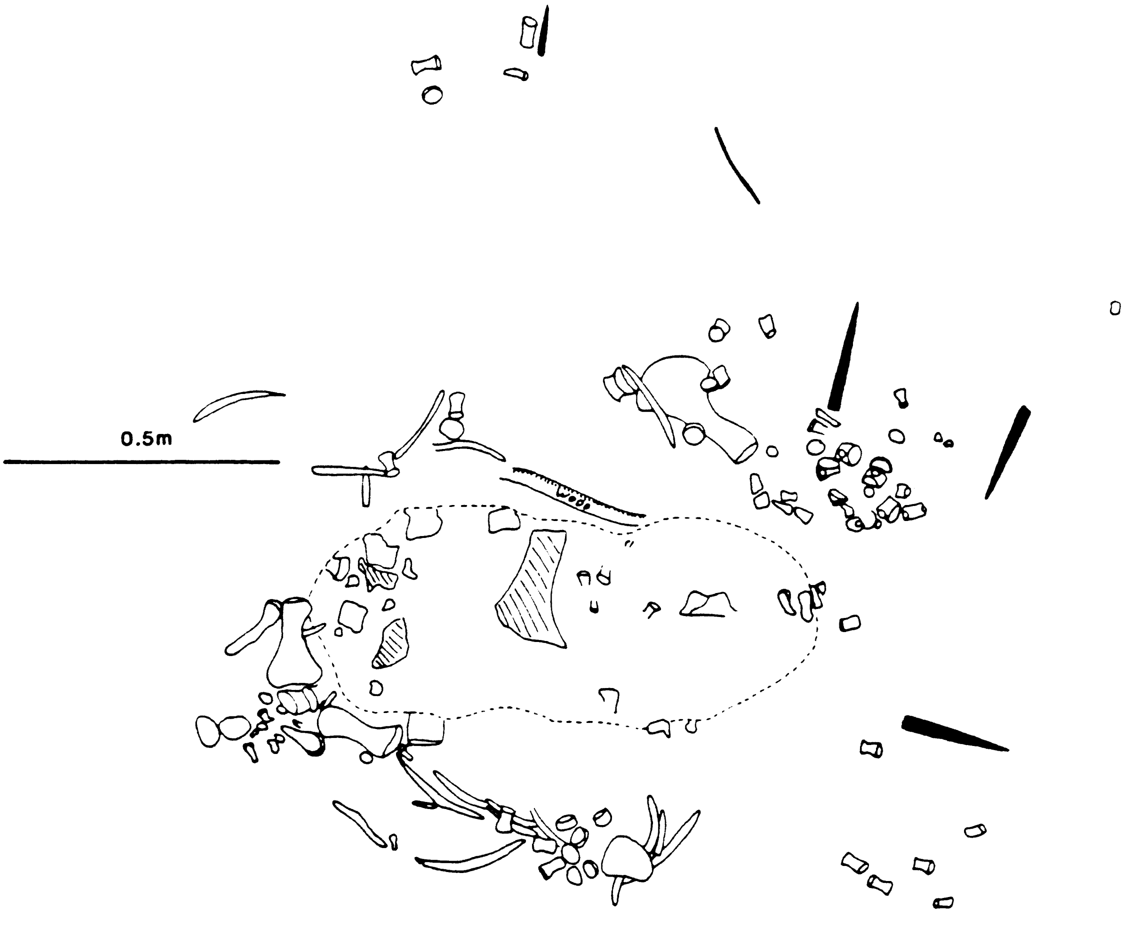


Fig. 14. Completely disarticulated skeleton of juvenile plesiosaurian, LEIUG 90983. Bed 11, Lower Oxford Clay, Dogsthorpe, Peterborough.

Fig. 15. Skeleton plan of *Ophthalmosaurus* sp. The dotted line indicates the part of the skeleton enclosed in a calcareous concretion. BCM 1001, 1983. Lower Oxford Clay, Coronatum Zone, Milton Keynes, Buckinghamshire.

excavator are also articulated. The remainder of the skeleton is disarticulated, but most of the individual bones have not moved from their original positions by more than a few centimetres. Thus the general shape of an ichthyosaur skeleton is maintained. A few elements, notably from the front limbs have been moved several tens of centimetres, suggesting that some scavenging of the carcase took place. Fig. 16 summarises the taphonomic history of the specimen.

The cause of death is hard to establish. None of the bones show teeth marks which are a common feature of predated specimens. Many of the elements of the skeleton indicate the specimen to be an old individual, including its size, and signs of advanced ossification such as fusion of the tibia and fibula of the right hind limb. This particular individual probably died of of old age or disease.

It is difficult to elucidate the history of the specimen between the moment of death and its arrival on the sea floor, but the post-mortem drifting phase was probably short as the affects of scavengers would be more severe, with many of the peripheral elements of the skeleton being absent. The carcase sank to the sea floor and the rostrum penetrated the sediment, indicating that the carcase arrived on the sea floor head first, and with a velocity sufficient for the carcase to sink partially into the sediment.

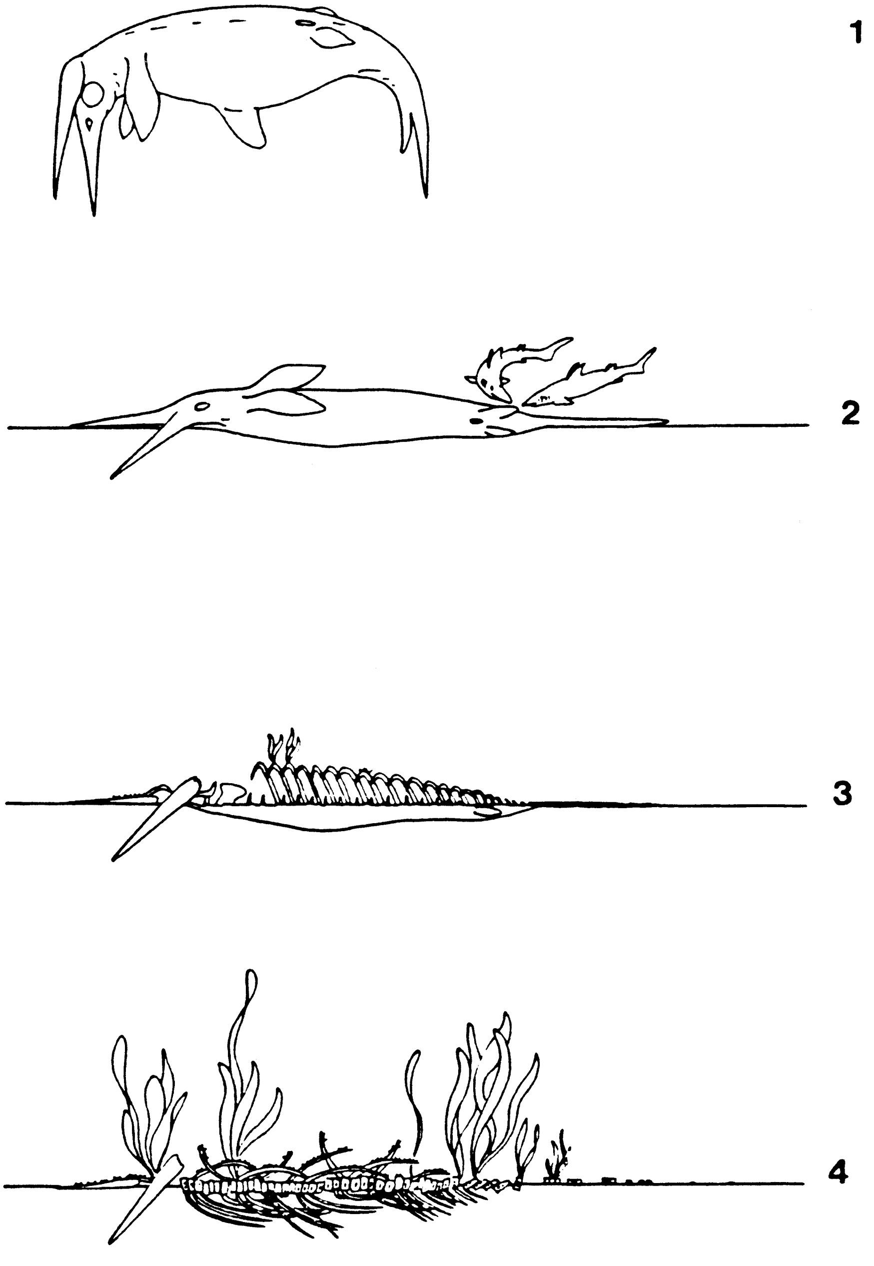


Fig. 16. Taphonomic history of ichthyosaurian BCM 1001, 1983. 1. post mortem drifting in water column. 2. descent to seafloor accompanied by scavenging. 3. rapid decay of integument in oxygenated water, slow decomposition of integument in contact with anoxic pore water. 4. Collapse of skeleton and encrustation by epibionts and seaweed.

Epibionts

Many of the disarticulated elements of the skeleton are a pale buff colour and are frequently encrusted with oysters and serpulid worms. The epibonts are only found encrusting the buff coloured bones, and are restricted to the upper surfaces. No macro-epibionts have been found on the underside of the skeleton, or on the dark brown bones of the articulated portions of the skeleton. The oysters are preserved in dark grey calcite, and frequently reach a length of 4 cm. On flat bones they remain attached continuously during ontogeny; when attached to bones with strongly curving surfaces, e.g. ribs, they are only attached during early onogeny, later stages of shell growth growing away from the bone surface with the oyster becoming curved. On very smooth bone surfaces the oyster may not secrete shell material, but lie in direct contact with the bone (Plate 9A).

Serpulid worms are less common than oysters, and are usually small, being generally less than one centimetre long. They are preserved as white aragonite conical tubes, approximately 2–3 mm diameter at the anterior end. No geotropism or phototropism has been established, but the distribution pattern on the skeleton is the same as that of the oysters.

The undersides of the articulated parts of the skeleton are dark brown, and lack epibionts. A black coating adheres to the underside of the articulated vertebrae that lie within the mudstone, and also to the underside of some of the ribs from the left side of the rib cage. The black coating, overlain by a slightly shiny white/buff coating was also found on a portion of the pre-maxilla.

These coatings are restricted to the dark brown bones. These bones have no encrustations suggesting that they were in contact with and partly buried in the sediment. The black and white coatings may be by-products of a decomposing integument (Fig. 17).

Scanning electron microscopy of the black coating from the underside of the vertebral column shows it to be composed of an amorphous mass, underneath which are numerous ovoids approximately 1 um long, and about 0.5 um diameter. These ovoids are interpreted as lithified bacteria, as have been reported from soft part outlines of Eocene Anura and Chiroptera by Wuttke (1983).

The light buff coloured bones encrusted with oysters have powdery surfaces that are very soft and easily scratched with a finger nail. These bones have been altered due to prolonged exposure on the sea floor. Encrusting oysters were able to grow to 2–4 cm diameter. This shows that sedimentation was slow, and that bottom waters were well oxygenated. An infauna of small scaphopods and foraminifera suggests that the pore water of the top 2–3 cm of the sediment was also oxygenated, although the low diversity of the infauna reflects lower than normal oxygen levels.

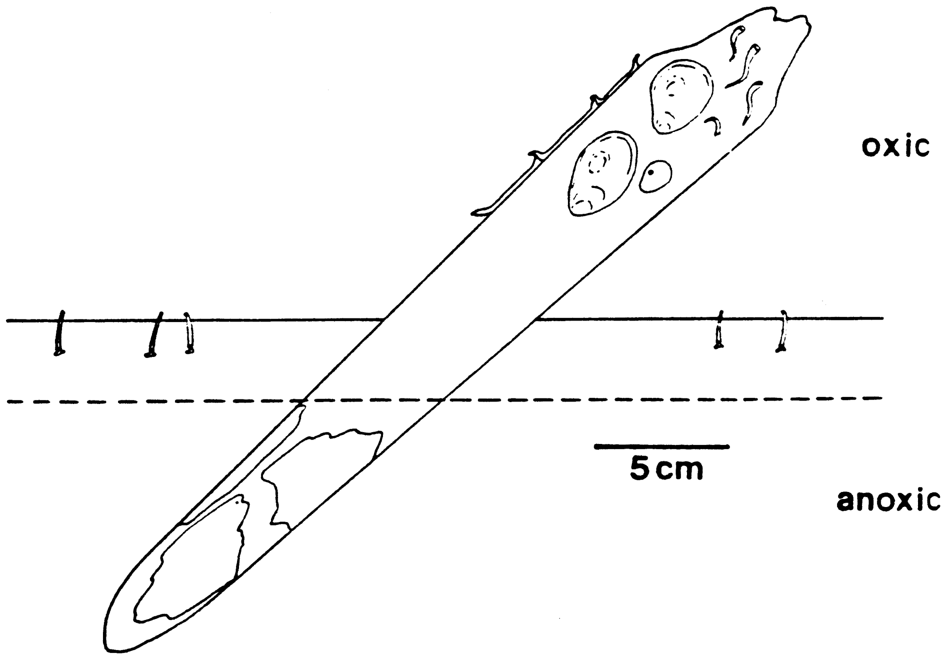


Fig. 17. Pre-maxilla of BCM 1008, 1983, showing epibionts on surface of bone within oxic sea water, and with patches of preserved "skin" on surface within anoxic pore water. Scaphopods live in top two or three centimetres of sediment.

The abundance of pyrite within the sediment and encrusting some of the bones shows that reducing conditions were present within the sediment. If the oxic/anoxic boundary was close to the sediment water interface, the penetration of the ichthyosaur carcase into the sediment may have introduced some of the soft tissues to reducing conditions, thus limiting the rate of decay.

Burial diagenesis

Burial diagenesis and compaction have had deleterious affects on the ichthyosaur specimen, and have caused differential preservation of the skeleton. Those parts of the skeleton that were lying within the bituminous mudstone have been uniaxially flattened by compaction. Failure of the bones is of a brittle nature (Plate 11A), with the complete shattering of all the inner trabeculae. The more solid sides of bones have resisted compaction, as have those bones with shapes that can transmit the pressure around their surface.

Compaction of some of the vertebrae has been greater than 50% and has been unaffected by the position of the bone in the sediment. Vertebrae lying flat on the bedding planes have been flattened into thin discs, while the articulated row of seven vertebrae have been flattened dorso-ventrally (Plate 11B).

Early diagenesis of the septarian calcareous and pyrite concretions protected many of the bones from compactional damage, but brecciation of the septarian concretion, with adjustment of the brecciated fragments and subsequent re-cementing with coarse calcite, has resulted in the almost complete destruction of the gross morphology of the individual bones, and the formation of a bone breccia. The microstructure of the bones in the concretion has been unaffected.

Late ferroan calcite cements have filled cavities within the bones, and have cemented together the highly crushed bones in the bituminous mudstone.

Many of the bones in the bituminous mudstone are coated with fibrous calcite up to 2 mm thick, with a thin film of clay sandwiched in between. This fibrous coating causes problems for the preparator as it requires removal with a vibratool, although it will sometimes flake off the surface if the underlying clay film has prevented cementation.

Discussion

General

The several different styles of vertebrate preservation which occur in the Oxford Clay are lithologically constrained. This is to be expected where different lithologies are controlled by different physical and biological conditions. Perfect preservation of skeletons is only possible if a carcase arrives on the sea floor intact, and remains undisturbed by current activity and the effects of scavenging. Under such conditions, usually attributed to deep anoxic basins, well preserved vertebrate skeletons frequently occur, e.g. parts of the Posidonia Shales of Holzmaden, West Germany.

The Oxford Clay basin at Peterborough was, however, not deep, and there is little, if any, evidence to suggest that bottom waters were anoxic even for short periods. That the pore water in the bottom sediment was anoxic is well shown by the abundance of pyrite as minute grains found disseminated throughout the sediment, and as a replacement of calcareous fossils. It is not known, however, at what depth within the sediment the pore water became anoxic, although in Coronatum Zone times in the area around Milton Keynes, anoxic conditions were prevelent just 4 to 5 cm below the sediment water/interface. The same may have been the case for the whole of the Lower Oxford Clay basin. In such conditions it is possible to have a restricted infauna and a diverse epifauna, providing the substrate is sufficiently firm to support burrowing and crawling. These conditions would not appear to be conducive to the perfect preservation of vertebrate skeletons; yet at Peterborough perfect preservation of reptiles, and delicate fishes is not uncommon.

In areas where the sediment/water interface is hard to define (soupy bottom) the invertebrate fauna may be restricted to only a few bivalves that can tolerate soupy sediment. Duff (1975) has amply demonstrated the restricted nature of the invertebrate fauna of the Lower Oxford Clay. It is most likely that in shallow basins perfect preservation of skeletons can take place when the bottom sediment is soft enough to allow a carcass to sink into it sufficiently to reduce the amount of scavenging that can take place. Bioturbation in the vicinity of the carcase may be reduced due to the presence of an anoxic micro-environment building up around a decomposing corpse.

Two special cases deserve more detailed discussion, namely, preservation in paper shales (Bed 10, base Bed 12) at Peterborough and vertebrates in the Gryphaea shell beds.

Preservation in the paper shales

The observed facts are as follows:-

1. Vertebrate skeletons are frequently fully articulated, with teeth still in the jaws. Any missing parts of the skeleton can easily be attributed to scavenging during post-mortem drifting of the carcase.

2. Articulated skeletons in the paper shales lack an encrusting epifauna of oysters and serpulids, yet these organisms are common in the intervening shell beds and frequently occur encrusting ammonites, and logs within the paper shales themselves. In Seilacher's (1982) Posidonia Shales model this would be used as evidence for anoxic bottom conditions, however a restricted, but abundant infauna occurs in the paper shales, including *Trautscholdia* and the semi-infaunal *Pinna mitis*. The *Pinna mitis* found in the Lower Oxford Clay is rather smaller than *Pinna* from the Middle and Upper Oxford Clay, although Duff (1978) considers them to be the same species, such a size reduction is possibly a response to an environmental constraint.

3. Fish skeletons from the paper shales are often perfect on the lower surface, with all the scales intact, have coprolitic material in the gut region, and have even the finest fin ray segments in perfect articulation. The upper surface is however usually disrupted, with many scales distributed, but not widely scattered.

4. Ammonites, fossil wood and rarely belemnites are found with encrusting epibionts, usually small oysters and serpulid worms. A single log of 3 m length was found to be covered with *Parainoceramus* on its underside.

5. Belemnites are occasionally found "point down" in the sediment. This occurs when the guard drops from a floating corpse and falls to the sea floor like a bullet (Barthel, 1978). The sediment must be soft enough to allow the guard to enter, but firm enough to prevent it from toppling over.

6. No bivalves are found in life position. All lie flat on bedding planes, possibly because upward migrations of anoxic pore water drove them out of the sediment. If the oxic/anoxic boundary migrated to a position just 2 to 3 cm above the sediment/water interface, then the bivalves would be killed. This explanation seems more likely than reworking by currents since this would lead to bivalve disarticulation, and would also prevent belemnites occurring vertically.

7. All *Pinna* valves are flat lying, articulated, and frequently aligned.

8. Orientated belemnites and other elongate fossils suggest that there was some gentle current activity on the sea floor, but this was not strong enough to dislodge vertical belemnites.

9. Burrows are not found within the paper shales, except at the top of bed 10, where it can be demonstrated that the burrows emanate from the overlying *Gryphaea* shell bed.

10. Thin sections of early diagenetic concretions from within the paper shales show that the paper shales are a compacted mud of small "faecal" pellets. These pellets may have been formed not on the sea floor, but in the water column itself by the activities of copepods.

11. Many ammonite conchs display primary breakage, indicating intense predation (Aigner 1980).

The data presented above do not fit the typical anoxic basin model, neither do they fit the oxygenated clay basin model in which normal clays are formed. The perfection of vertebrate preservation, and the lack of encrusted bones shows that bottom conditions did not support an epifauna. Bones can only be encrusted after the animal has died, whereas ammonites can be encrusted during life and logs can be encrusted while floating in the water column. Vertebrate skeletons in the shales of the Coronatum Zone are frequently encrusted with oysters and serpulids, so the absence of encrustation, in the paper shales is due, not to substrate preference, but to environmental inhibition.

It is not easy to see what is the cause of this environmental inhibition. Bottom water was not anoxic, although the pore water probably was anoxic below 4-5 cm. Infaunal activity was limited to only a few species, but the species present were in super abundance, with patches of twenty to thirty *Pinna* being common. One possibility is sedimentation rate. If this were high, then any organisms that prefer clear water, as many epifaunal filter feeders do, would get their filters clogged by sediment. A low or reduced sedimentation rate is indicated by the high organic carbon content of the shales (up to 10%) and also by its geological setting, the Jason Zone at Peterborough being the most condensed sequence in the Lower Oxford Clay basin.

To try to explain the numerous paradoxical data it appears that the sea floor must have been periodically swept by gentle currents, and was at times well oxygenated. Reduced sedimentation with high organic input; due to high productivity in surface waters, maintained low oxygen levels at times when current activity was reduced. Bottom waters were soupy, probably due to intermitent stirring of the sediment by storms and gentle currents. Rapid environmental switching contributed to a reduction of infaunal diversity, and prohibited any continued colonisation of the sea floor by epifaunal elements. Current strength was insufficient to disarticulate the carcases of the larger vertebrates, but was able to dislodge smaller fish carcases. The underside of a fish carcase may have remained intact as it could have stuck to the seafloor by an algal/fungal film.

Vertebrates of the *Gryphaea* shell beds

Partially articulated skeletons occur within the *Gryphaea* shell beds in the Jason Zone at Peterborough. The skeletons are more numerous than in the paper shales, but are rarely complete and never as well articulated. The sedimentology of the *Gryphaea* shell beds is complex, and it is interesting to note how the shell beds were formed.

After the deposition of the paper shales, as a fairly soft substrate, sedimentation was further reduced and the soft sea floor compacted to a moderately firm substrate allowing burrowing to take place. Several tens of centimetres of sediment may also have been removed by increased current activity or storms. *Thallassinoides* and *Rhizocorallium* occur in the top of bed 10 where they emanate from the base of bed 11. A very thin layer of green clay low in organic carbon occurs at this level and is found infilling the burrows. During this period the sea floor became littered with broken ammonite tests, the result of intense predation by the hybodont shark *Asteracanthus* and the chimaeras *Pachymylus, Brachymylus* and *Ischyodus*, whose dental plates are common in bed 11. The accumulation of this ammonite debris produced a shell gravel covering many square kilometres of sea floor, and provided a firm substrate for the attachment of *Gryphaea* spat, shown by xenomorphic ornament of both valves of *Gryphaea*.

The reduced sedimentation rate produced an increase in the number of skeletons found at this level, but due to current activity and scavenging the skeletons are often partly disarticulated. Isolated bones can be considerably worn due to the abrasive nature of the shell hash. Many bones found at this horizon have small numbers of oysters and serpulids attached to their surface. Although some of the *Gryphaea* shells found at this level are in life position, many are overturned, but remain articulated, suggesting that the overturning may be due to storm activity turning over live shells. These same storms had the affect of disarticulating the skeletons, but not of distributing them very far.

Conclusion

The Lower Oxford Clay is rich in vertebrates throughout the sequence, but the remains are concentrated at certain horizons due to sedimentological criteria. The high organic carbon content of the shales suggest high productivity levels in the surface waters, which presumably fed a diverse pyramid of organisms. As productivity declined so did the number of vertebrates living in the surface waters. This is reflected in the fossil record with high vertebrate diversity and abundance in the organic rich Lower Oxford Clay, followed by extreme scarcity in the clays with low organic carbon of the Middle and Upper Oxford Clay.

Acknowledgements

Collecting an *in-situ* fossil reptile requires much work. I am indebted to all those who helped me in this task. In the field Alan Dawn, Rod Branson, Nick Laffoley, Arthur Meadows and Ian Fisher; all toiled hard in the bottom of the brick pits. In preparing material Lorraine Cornish and Nick Laffoley made specimens, thought to be unpreparable, worthy of exhibition. To produce the skeleton plans I am grateful to Rod Branson, and to Henry, Collin and Ian in the University of Leicester Central Photographic Unit.

Many people made specimens available in their museums and the following were especially helpful, Dr Collin Patterson and Dr Angela Milner at the British Museum, Mr John Martin, Leicester Museum, Dr Gordon Chancellor, Peterborough City Museum, and Phil Powell, Oxford University Museum.

Dr C. Forbes and Dr R.G. Clements were kind enough to let me use their unpublished data.

The London Brick Company, and especially their chief geologist Mr J. Horrell, made many facilities available in their pits. Without their kind cooperation this study could not have taken place. I must also thank the pit men who kept an eye open for bones and also for supplying me with cups of tea during the hot summer months.

Dr J.D. Hudson and Dr R.G. Clements along with Dr Mike Taylor provided useful discussions and criticisms. Dr Trevor Ford kindly read the manuscript.

I thank Leicester University for a research Scholarship awarded for a three year study on vertebrate bearing bituminous shales.

References

Aigner, T., 1980. Biofabrics and Stratinomy of the Lower Kimmeridge Clay (U. Jurassic, Dorset, England). *N. jb. Geol. Palaeont. Abh.* 3, 324–338.

Andrews, C.W., 1910–13. *A descriptive catalogue of the marine reptiles of the Oxford Clay*, 1. 205pp., 10pls., (1910). 2. 206pp., 13pls., (1913). London British Museum (Natural History).

Appleby, R.M., 1956. The osteology and taxonomy of the fossil reptile *Ophthalmosaurus*. *Proc. Zool. Soc. Lond.* 126, 403–447.

— 1979. Fossil aches and pains, *New Scientist*, 16th Aug. 516–7.

Benton, M.J. & Taylor, M.A., 1984. Marine reptiles from the Upper Lias (Lower Toarcian, Lower Jurassic) of the Yorkshire coast. *Proc. Yorks. Geol. Soc.*, 44, 399–429.

Brenner, K. 1976. Schwarzschiefer. Biostratinomische, untersuchungen im Posidonienschiefer (Lias epsilon, Unteres Toarcium) von Holzmaden (Wurttemberg, Sud-Deutschland). In *Sondersforschungsbereich 53, Palokologie, Arbeitsbericht, 1970–1975, Zbl. F. Geol. u. Palaont.*, 2, S. 223–226.

Brongersma-Sanders, M., 1949. On the occurrence of fish remains in fossil and recent marine deposits. *Bijdr. Dierk.*, 28, 65–76.

Brown, D.S., 1981. The English Upper Jurassic Plesiosauroidea (Reptilia) and a review of the Phylogeny and classification of the Plesiosauria. *Bull. Br. Mus. Nat. Hist. (Geol.)*, 35, (4), 253–347.

Calloman, J.H., 1968. The Kellaways beds and the Oxford Clay. In: *The geology of the East Midlands* (Eds. Sylvester Bradley, P.C. & Ford, T.D.), 264–290. University of Leicester Press.

Camp, C.L., 1980. Large ichthyosaurs from the Upper Triassic of Nevada. *Palaeontographica. Abt.* A, 170, (4–6), 139–200.

Charig, A.J., 1980. A diplodocid sauropod from the Lower Cretaceous of England. In: *Aspects of vertebrate history, essays in honour of Edwin Harris Colbert.* (Ed. Jacobs, L.L.). Museum of Northern Arizona press, Flagstaff, 231–244.

— & Horell, J., 1971. The Fletton plesiosaur, *Rep. Huntingdon Flora Fauna Soc.* 23: 37–40.

Cope, J.C.W., Duff, K.L., Parsons, C.F., Torrens, H.S., Wimbledon, W.A., & Wright, J.K., 1980. A correlation of Jurassic rocks in the British Isles. Part Two: Middle and Upper Jurassic. *Spec. Rep. Geol. Soc.* Lond. 15, 1–109.

Delair, J.B., 1974. Two deformed ichthyosaur forelimbs from the English Lower Lias. *Mercian Geologist*, 5, (2), 101–103.

Duff, K.L., 1975. Palaeoecology of a bituminous shale—the Lower Oxford Clay of Central England, *Palaeontology*, 18, (3), 443–482.

Fisher, I. st. J., 1983. *Studies on pyrite in shales.* Unpublished PhD. Thesis, University of Leicester.

Fitch, J.E., & Brownell, R.L., 1968. Fish otoliths in cetacean stomachs and their importance in interpreting feeding habits. *J. Fish. Res. Bd. Can.*, 25, (12), 2561–2574.

Galton, P.M., 1980. European Jurassic ornithopod dinosaurs of the family Hypsilophodontidae and Camptosauridae. *N. Jb. Geol. Palaont. Abh.* 160, (1), 73–95.

Hudson, J.D., 1978. Concretions, isotopes, and the diagenesis of the Oxford Clay (Jurassic) of central England. *Sedimentology*, 25, 339–370.

— 1982. Pyrite in ammonite bearing shales from the Jurassic of England and Germany. *Sedimentology*, 29, 639–667.

Judd, J.W., 1875. The geology of Rutland. *Mem. Geol. Surv. England and Wales*, 320pp.

Jukes-Browne, A.J., 1885. The geology of the south west part of Lincolnshire, *Mem. Geol. Surv. England and Wales*, 180pp.

Kauffman, E.G., 1981. Ecological reappraisal of the German Posidonienschiefer (Toarcian) and the stagnant basin model, in: *Communities of the past*, (Ed. Gray, J., Boucot, A.J., & Berry, W.B.N.), Hutchinson Ross Publ. Comp., Stroudsberg, Penns.

Keller, T., 1976. Magen-und Darminhalte von Ichthyosauriern des suddeutschen Posidonienschiefers, *N. Jb. Geol. Palaont. Mh.* 5, 266–283, Stuttgart.

Leeds, A.N. & Woodward, A.S., 1897. Excursion to Peterborough, *Proc. Geol. Assoc.* 15, 188–193.

Leeds, E.T., 1956. *The Leeds collection of fossil reptiles from the Oxford Clay of Peterborough*, 104pp., Oxford.

Lydekker, R., 1889. *Catalogue of the fossil Reptilia and Amphibia in the British Museum* ... Part II 307pp., London, British Museum (Natural History).

— 1890. On ornithosaurian remains from the Oxford Clay of Huntingdonshire. *Q. J. Geol. Soc.* London, 46, 429–431.

Milner, A.R., 1980. The tetrapod assemblage from Nyrany, Czechoslovakia, In: *The terrestrial environment and the origin of land vertebrates*. (Ed. Panchen, A.L.), 439–496. Academic Press, London & New York.

Porter, H., 1861. *The geology of Peterborough and its vicinity*. Peterborough, 126pp.

— 1863. On the Occurrence of large quantities of fossil wood in the Oxford Clay near Peterborough. *Q. J. Geol. Soc.* London, 19, p.317.

Seeley, H.G. 1889. Note on the pelvis of *Ornithopsis*. *Q. J. Geol. Soc. Lond.*, 45, 391–397.

Seilacher, A., 1981. Posidonia shales (Toarcian, S. Germany)—stagnant basin model revalidated, *Proc. 1st international meeting on "Palaeontology, essentials of historical geology*, Venice, Ed. Gallitelli, E.M. 25–55.

Schafer, W., 1972. *Ecology and palaeocology of marine environments*, Oliver & Boyd, Edinburgh, 568pp.

Tarlo, L.B., 1960. A review of the Upper Jurassic Pliosaurs, *Bull. Br. Mus. Nat. Hist. (Geol.)*, 4, (5), 147–189, pls. 20–28.

Taylor, M.A., 1981. Plesiosaurs, rigging and ballasting. *Nature*, Lond. 290, 628–629.

Thies, D., 1983. Jurazeitliche neoselachier aus Deutschland und S-England (Jurasic neoselachians from Germany and s. England), *Cour. Forsch. Inst. Senckenberg*, 58, 1–116, Frankfurt/M.

Woodward, A.S., 1897. A contribution to the osteology of the Mesozoic amioid fishes *Caturus* and *Osteorachis*. *Ann. Mag. Nat. Hist.*, 19, 379–387, pls. 8–11.

— 1905. On parts of the skeleton of *Cetiosaurus leedsi*, a sauropodus dinosaur from the Oxford Clay of Peterborough, *Proc. Zool. Soc.* London, 232–243.

Wuttke, M., 1983. a. "Weichteil-Erhaltung" durch lithifizierte Mikroorganismen bei mittel-eozanen Vertebraten aus den Olschiefern der "Grube Messel" bei Darmstadt. *Senckenbergians lethaea*, 64, (5/6), 509–527, Frankfurt/M.

— 1983. b. Aktuopalaontologische studien uber den zerfall von wirbeltieren. Tiel 1: Anura, *Senckenbergians lethaea*, 64 (5/6), 529–560, Frankfurt/M.

David M. Martill,
Department of Geology,
University of Leicester,
Leicester, LE1 7RH.

Present address:

Field Museum of Natural History,
Roosevelt Road at Lake Shore Drive,
Chicago,
Illinois 60605-2496,
U.S.A.

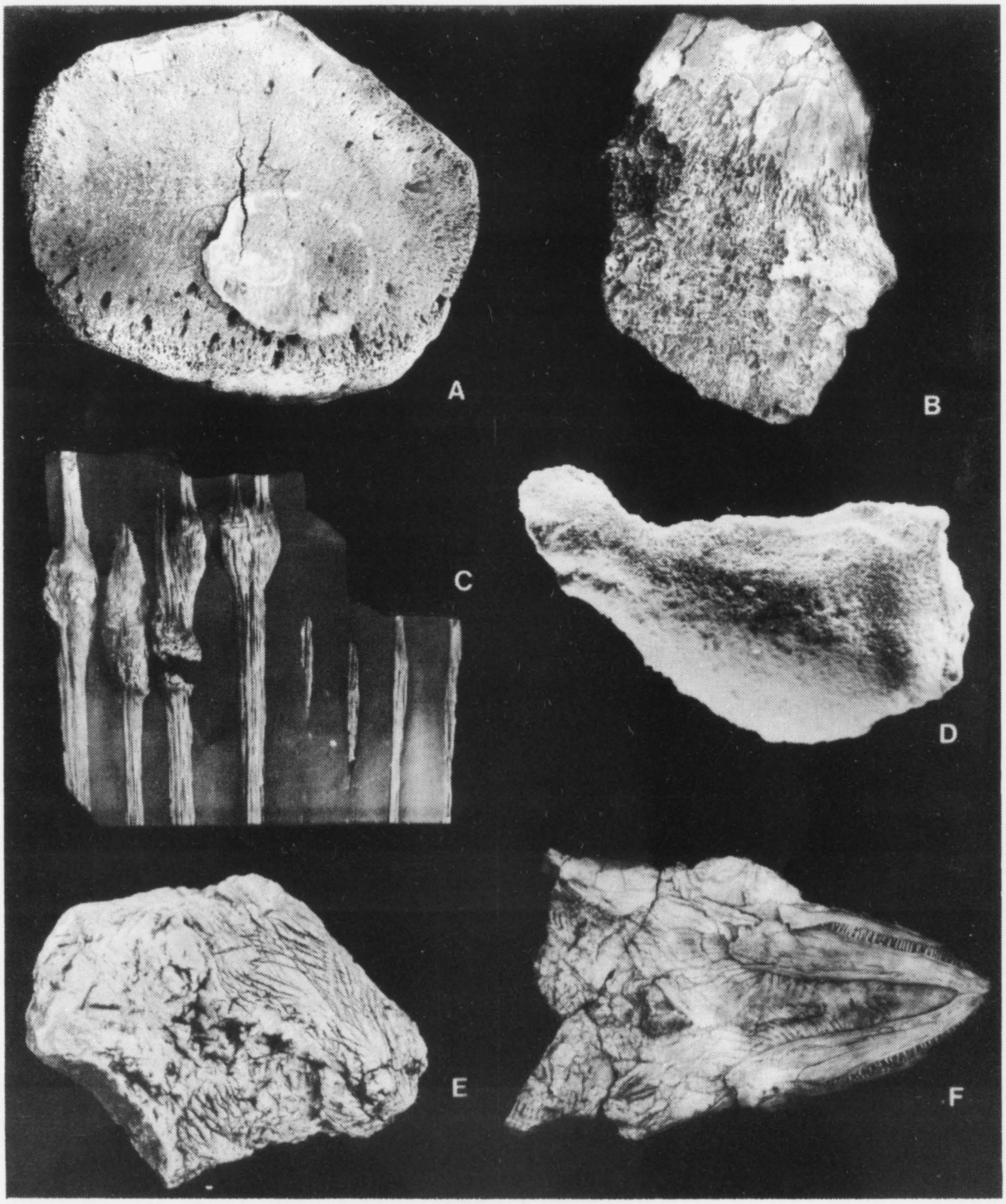


Plate 9A

Bone hardground. ?Ulna of *Ophthalmosaurus* sp. with encrusting oyster. Note late cracking of bone and oyster shell. Lower Oxford Clay. Milton Keynes, Bucks. ×½

Plate 9B

Partially eroded saurian girdle bone. Smooth outer surface has been eroded away exposing inner trabecular bone. Lower Oxford Clay, Bed 13, Farcet barrow pit. Peterborough. ×½

Plate 9C

Caudal fin rays of *Leedsichthys* sp. showing possible predation damage. ×½

Plate 9D

Drop shaped otolith with etched surface. ×30

Plate 9E

Coprolite with feeding traces. ×2

Plate 9F

Dorso ventrally crushed skull of *Caturus porteri* Rayner. ×½

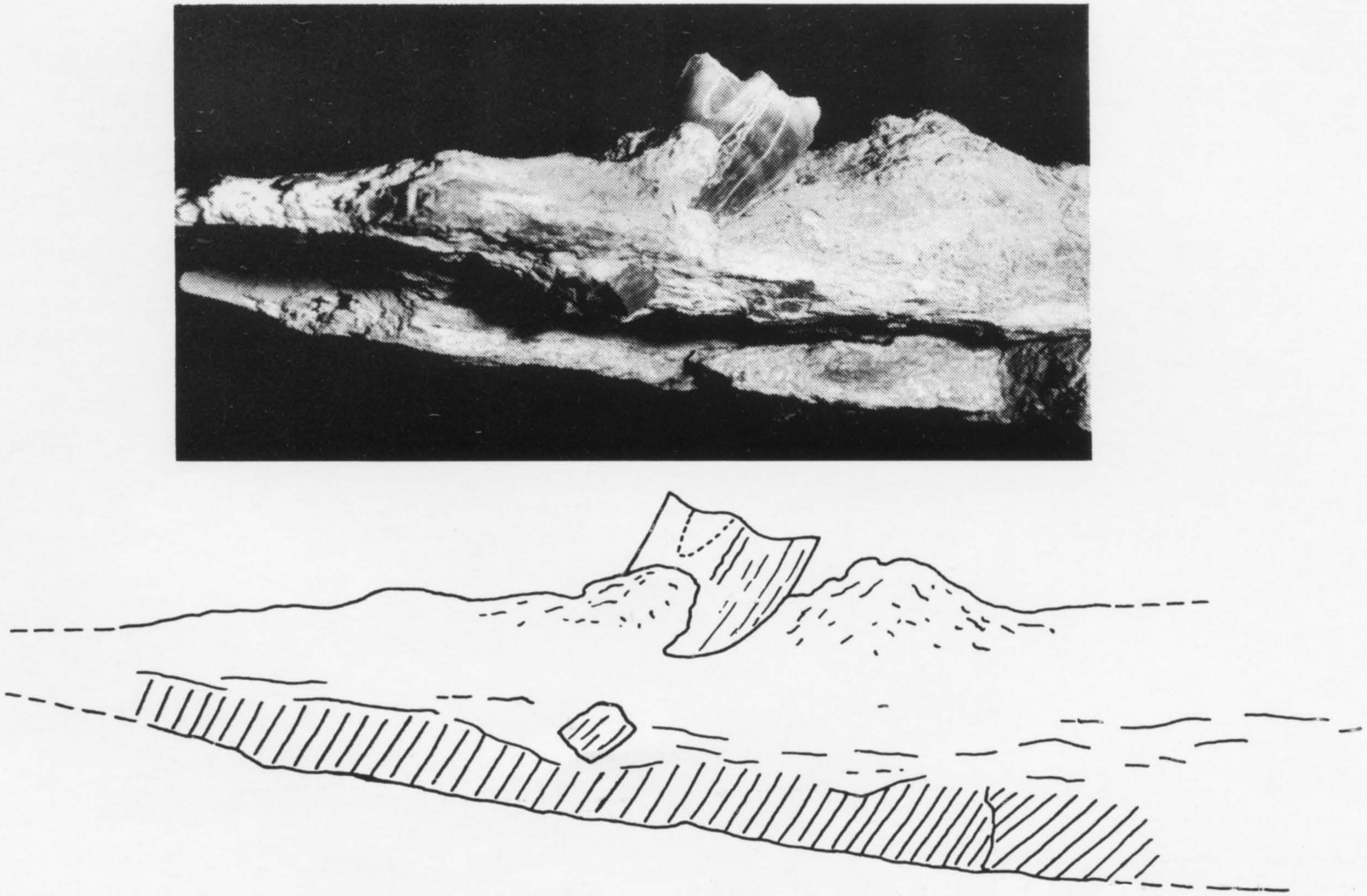


Plate 10

Frontal bone of the giant pachycormid fish *Leedsichthys* sp. punctured by crocodilian tooth. New bone has grown around the tooth showing that not all crocodile attacks are fatal. ×2

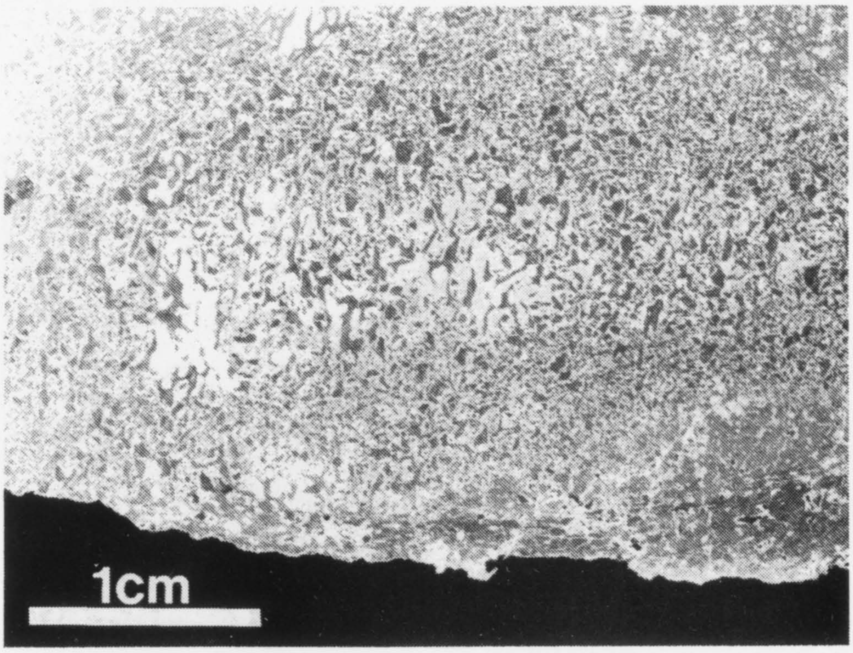


Plate 11A

Thin section of ichthyosaur centrum showing high degree of brecciation due to compaction. There has been more than 50% volume reduction due to crushing.

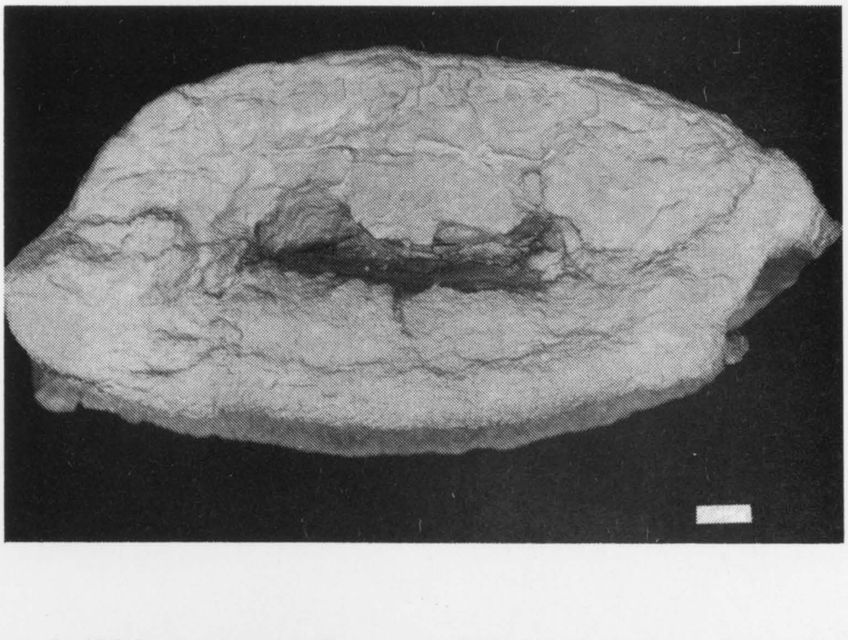


Plate 11B

Dorso-ventrally crushed ichthyosaurian thoracic centrum. BCM 1008, 1983, Lower Oxford Clay, Milton Keynes, Buckinghamshire. Scale bar 1 mm.

THE SEDIMENTS AND TRACE FOSSILS OF THE ROUGH ROCK GROUP ON CRACKEN EDGE, DERBYSHIRE

by

G.D. Miller

Summary

The sediments of the Yeadonian GI Rough Rock Group on Cracken Edge in north Derbyshire include basal silty mudstones, the Rough Rocks Flags and the Rough Rock. Three Facies Associations are identified and possible sedimentological origins are considered.

Trace fossils in the Rough Rock Flags are described. They include *Pelecypodichnus* resting traces, escape shafts and possible bivalve trails, with minor *Planolites, Cochlichnus* and *Didymaulichnus?*, in the lower levels. In higher beds *Didymaulichnus?, Planolites* and *Cochlichnus* are found, together with large concretions. Four ichnocoenoses are suggested, and their distribution is discussed.

Introduction

Cracken Edge (SK 038837) runs along the eastern face of Chinley Churn, a 451 m high hill near Chinley in the High Peak of Derbyshire (Stevenson and Gaunt, 1971, plate XVIIIB). The north-south trending Edge lies on the eastern limb of the Goyt Trough syncline, with the strata dipping to the west at angles of between 8 degrees and 20 degrees. The sequence to the east of Chinley Churn starts with Namurian shales and the *Reticuloceras gracile* marine band in the valley bottom, and moves upwards through the Chatsworth Grit and Simmondley Coal to the Rough Rock Flags and Rough Rock which have been extensively quarried (and in places, mined) along Cracken Edge itself (Fig. 1). Above these come shales and the *Gastrioceras subcrenatum* marine band forming a boggy depression, and then the Lower Westphalian Woodhead Hill Rock makes the summit of the Churn itself.

The Rough Rock Group

Somewhat surprisingly the Yeadonian G1 (N11 cycle of Ramsbottom 1977) Rough Rock Group has not received as much detailed study as other Namurian formations, although as Shackleton (1962) pointed out, it covers some 6,400 km^2 in the north of England. The area in which it is found can be divided into three principal sectors. The first—the axial zone—stretches from Bradford and Huddersfield to the Peak District and then on to Macclesfield and north Staffordshire. The Group attains thicknesses of 67m in the north, 106m in the centre, and 58m in the south. The corresponding figures for the Rough Rock Flags and Rough Rock are 36, 42 and 28m. The succession (with many local variations) above the *Gastrioceras cumbriense* marine band can be summarised as follows–

Pot Clay or Six Inch Mine Coal (present locally).
Seat-earth or shale.
The Rough Rock (medium to coarse-grained sandstones, commonly pebbly, with occasional shale lenses).
Shales (in places) with *Carbonicola, Naiadites, Spirorbis, Pelecypodichnus*.
The Rough Rock Flags (fine to coarse-grained micaceous sandstones, occasional grits, and shale partings), in several areas, with rare *Carbonicola, Pelecypodichnus*, and *Cochlichnus*.
Shales and occasional sandstones, with *Carbonicola, Naiadites, Spirorbis, Cochlichnus* and *Planolites*.

Mercian Geologist, vol. 10, no. 3,
pp. 189–202, 4 figs., plates 12 & 13.

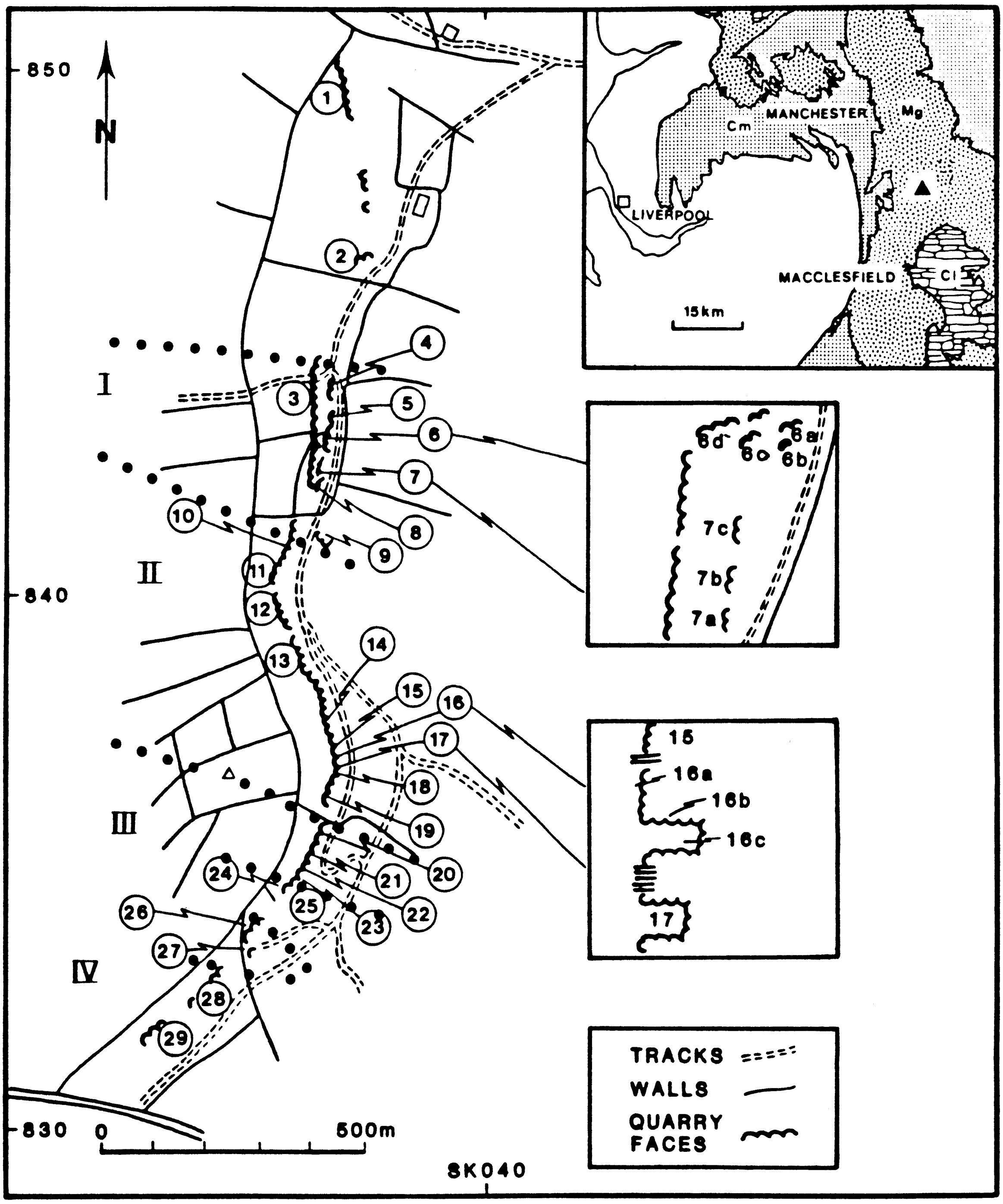


Fig. 1. Map of the location, outcrop and localities studied in the Rough Rock Group at Cracken Edge, Derbyshire.

The second sector forms the western flank of the first and is bounded by a line running from Colne through Blackburn to Parbold in central Lancashire, then east through Bury to the north-east and east of Manchester. Here the Rough Rock Group reaches thicknesses of 122m, and the Rough Rock itself 40m. The succession is distinctive–

Six Mine Coal (largely present).
Shales (in places).
Rough Rock upper leaf (shaley sandstones, very rare pebbly sandstones, and shales with *Carbonicola*).
Sand Rock Mine Coal.
Seat-earth or mudstone.
Rough Rock lower leaf (coarse and pebbly sandstones with a finer-grained flaggy base in the south).
Mudstones with *Carbonicola, Naiadites, Pelecypodichnus, Cochlichnus*, and *Limulicubichnus*.
The Haslingden Flags (in the north) or mudstones (in the south).

The remaining sector forms the eastern flank of the axial zone from the Leeds area through Barnsley and Sheffield to Chesterfield and south-east Derbyshire. The Rough Rock Group attains thicknesses of 70m in the north and 36m in the south, with the Rough Rock itself diminishing from 24 to 12m in the same direction. The succession is–

Pot Clay Coal.
Seat-earth or shales with *Carbonicola, Spirorbis*, and *Geisina*.
Rough Rock (non-pebbly sandstones, mudstone partings, very rare seat-earth or ganister).
Shales with *Carbonicola, Anthraconaia, Naiadites, Spirorbis*, and *Geisina*.

In lithological terms the Rough Rock Flags are fine-grained quartz arenites resembling the Shale Grit but with a substantial amount of mica. The Rough Rock is coarse, somewhat pebbly, subatkosic to arkosic, and broadly comparable with the Chatsworth Grit. On Cracken Edge, for example, the Flags are described by Harrison (in Stevenson and Gaunt, 1971) as well-sorted with igneous quartz, chert, feldspars and 13–21% micas. In contrast the Rough Rock is fairly well-sorted with igneous quartz, rock particles, feldspars (4.5—17%) and some mica (Stevenson and Gaunt, 1971, plate XX, fig. 1).

Ripple marks and primary current lineations are found in the Rough Rock Flags generally, and cross-bedding (mainly planar) is ubiquitous in the Rough Rock. According to Shackleton (1962) the palaeocurrent direction changes from southwards in the lower Rough Rock to south-westwards in the upper. As with other Namurian sandstones, large calcitic or ferruginous concretions—the 'mare's balls' or 'red horses' of the quarrymen—are common in the Rough Rock. The fauna of the Group above the marine bands—*Carbonicola, Anthraconaia, Naiadites, Spirorbis* and *Geisina* with the trace fossils *Pelecypodichnus, Cochlichnus, Planolites* and *Limulicubichnus*—are characteristic of the brackish to freshwater assemblages of the uppermost Namurian and Lower Westphalian in the Pennines (Calver 1968).

Interpretations of the origins of the Rough Rock Group sediments differ. The majority of authors have ascribed them to a shallow-water delta sheet (Collinson 1976), consisting of coarsening-upwards mudstone/siltstone slope deposits (without turbidites) topped by the sheet sandstones of migrating distributaries. On the other hand Shackleton (1962) concluded that the Rough Rock at least was deposited not by a large river system but by many relatively small rivers, aided by flash flooding, carrying sand and gravel over a slightly elevated continental margin very near sea level. Although Reading (1969) considered that Shackleton "underestimated the importance of lateral accretion by rivers", the latter's views have received support recently from Eagar et al (1985) who describe the Rough Rock as the sediments of "a complex of probably braided distributary channels flowing in general from the north-east and establishing the broad paralic basis of the subsequent Westphalian Coal Measures".

The southernmost extremities of the Rough Rock Group province present something of a puzzle. The Yeadonian deltas or river systems must ultimately have established a connection with the sea (or seas) responsible for the marine incursions of the *Gastrioceras cancellatum, cumbriense* and *subcrenatum* bands. But instead of marine sediments, the scanty borehole evidence from south Staffordshire and north Warwickshire (Mitchell 1954; Stevenson and Mitchell 1955; Taylor and Rushton 1971) suggests that the province dribbled away into marshland and lacustrine siltstones and mudstones with thin coals, seat-earths and very subordinate sandstones before the Mercian Highlands were reached. Did the deltas or rivers turn north-west into what is now the Cheshire Basin, or north-east into what is now the North Sea? An earlier north-westerly diversion has certainly been proposed for both the Roaches (Jones 1980) and Ashover (Chisholm 1977) deltas in the Marsdenian.

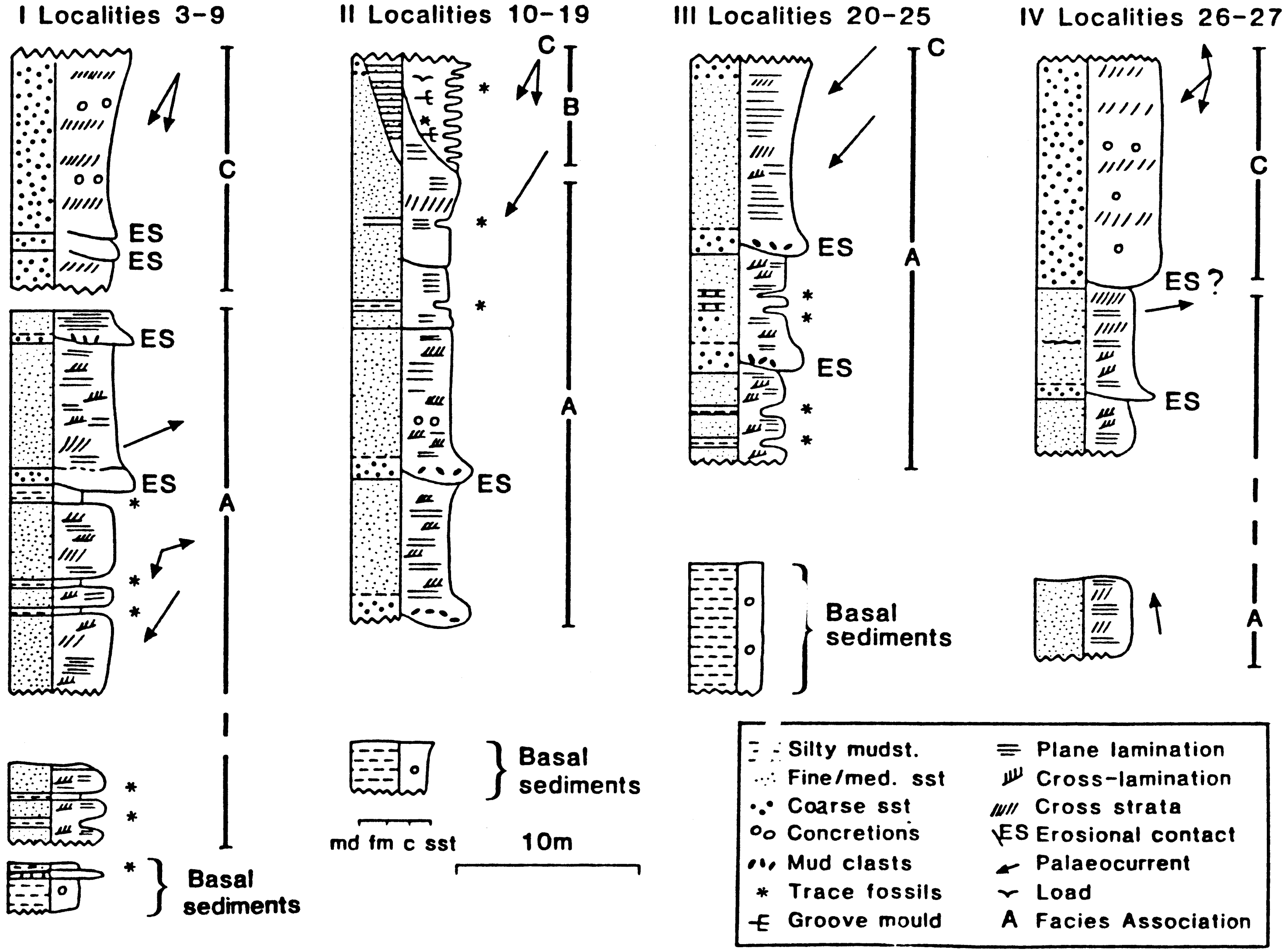


Fig. 2. Generalised graphic log of sediments and trace fossil horizons shown on Figure 1 (for discussion see text).

A. The Rough Rock Group Sediments on Cracken Edge

Introduction

Although the Cracken Edge quarries (see Fig. 1) extend for some 1500m from north to south, the detailed succession is not easily established. There are occasional hiatuses in the exposures, several changes in levels and relief, landslips and small faults. More important are the absence of good three-dimensional sections and the lack of persistent marker bands. The basal sediments of the Group are exposed at locality 25 and two smaller localities, although never in the full thickness seen a little further north at Foxhole Clough (SK 036859). They consist of dark grey to black mudstones and silty mudstones with horizons of small nodules, and weather to rusty iron hues. Their contact with the Rough Rock Flags is not visible at Cracken Edge. But at Foxhole Clough thin sandy laminae become increasingly frequent in the uppermost micaceous silty mudstones, and these are succeeded without an erosional break by an alternation of thin laminated and cross-laminated fine-grained sandstones with thin micaceous silty shales.

The lithofacies

In the succeeding Rough Rock Flags and Rough Rock five lithofacies can be recognised and arranged in three types of facies associations.

Facies 1. Silty mudstones and mudstones.

These are dark grey silty mudstones and mudstones containing some plant fragments. They form beds of 70–270mm thickness (generally 70–100mm) in the lower part of the succession and become infrequent thin lenses in the middle of it. Towards the very top, however, they occur again interbedded with sandstones in two areas and are thinner (mostly in the 30–80mm range).

Facies 2. Fine-grained laminated and cross-laminated sandstones.

These sediments—most of which probably indicate upper flow regime conditions—are found as follows:

(a) in the lower part of the Rough Rock Flags as sharp based sandstones, micaceous (with darker, more micaceous laminae alternating with lighter, less micaceous ones), and containing plant fragments. Amalgamations are locally present, some tops are cross-laminated, and loose slabs display poorly preserved ripple marks, 'rib-and-furrow' patterns and primary current lineations. A horizon of cross-laminated sandstone balls in siltstones at one locality resembles the ball-and-pillow structures of Reineck and Singh (1980), indicative of rapid sedimentation. Bed thicknesses vary considerably from 50mm to 1.5m, but the majority fall within the 100–300mm range.

(b) in the middle and upper parts of the Rough Rock Flags as thick (.5–1.5m) units, sharp based, weakly laminated, with some cross-laminated lenses and a number of large concretions.

(c) in two areas at the top of the Rough Rock Flags as thin (mostly 30–80mm), sharp based and weakly laminated sandstones alternating with lithofacies 1 silty mudstones in rhythmic sequences. They weather to distinctive colours—rusty brown, reddish, even purple—from their contact with the (presumably) iron-rich silty mudstones. They amalgamate and 'pinch-and-swell', and carry grooves and small loads as bottom structures. Some increase in size upwards is evident, and they appear to pass laterally into thicker sandstone units.

Facies 3. Fine-grained cross-bedded sandstones.

These are found locally as isolated units in the Rough Rock Flags. In the lower part of the succession they have been located at six localities, as single planar sets generally separated by laminated or cross-laminated beds. Forests dip at only 5–10 degrees, and set thicknesses vary from 200 to 400mm. Higher in the succession the sets become much larger on average. At locality 26 there are three trough cross-bedded sets up to 1m in thickness with tangential foresets dipping at 5 degrees, and separated from each other by thin units of laminated or cross-laminated sandstone. Similar trough cross-beds, incidentally, are to be found below an erosion surface at the Black Rocks (SJ 987830) a few kms away across the Goyt Trough.

Facies 4. Coarse pebbly sandstones above erosion surfaces.

Such sandstones with mud flakes, plant remains and large *Calamites* casts (up to 1.4m long and 270mm in diameter) occur at different levels throughout the succession. In the southern sector of the quarries there are two erosion surface units traceable for 140m, each 1-2m thick and some 4m apart. One such surface is found intermittently in the central sector, underlain in places by subsidiary erosion surfaces. In the northern sector two erosion surfaces are traceable in the Rough Rock Flags, and a number are scattered through the Rough Rock exposures (one with underlying subsidiaries). The bases of these surfaces undulate gently. Unfortunately no channel margins are visible, but in the southern part of the quarries the upper erosion surface appears to end abruptly as it is cut out by an overlying sandstone bed.

It is possible that the erosion surfaces in the Rough Rock Flags reflect two main erosional episodes. But with so many gaps in the exposures such a conclusion can only be speculative.

Facies 5. Coarse-grained bedded and cross-bedded sandstones.

These make up the Rough Rock at the top of the quarries. The beds have pebbly horizons and are generally thin (60–70mm). The cross-beds are mainly planar with rare trough sets; set thicknesses vary from 150 to 610mm, with most in the 200–300mm range, and foresets dip at low angles. Individual sets are more common than cosets. But at locality 1 a coset of three much larger planar sets (.9–1.8m in thickness) must constitute the megaripple beds of Wright (1964) with straight foresets inclined at an angle of nearly 30 degrees. Large concretionary masses are ubiquitous in this lithofacies, but no silty mudstone interbeds have been found.

Facies associations

Three associations appear to be present:

Type A. Consists of lithofacies 1 (silty mudstones) and 2a and b (fine-grained laminated and cross-laminated sandstones), together with occasional facies 3 (fine-grained cross-bedded sandstones) and facies 4 (coarse sandstones above erosion surfaces).

Type B. Facies 1 (silty mudstones) and 2c (fine-grained weakly laminated sandstones) alternating in rhythmic sequences. 19 sandstone beds are seen at locality 11, 38 at locality 12, and 19 at locality 15.

Type C. Facies 5 (coarse-grained bedded and cross-bedded sandstones) with locally facies 4 (coarser sandstones above erosion surfaces).

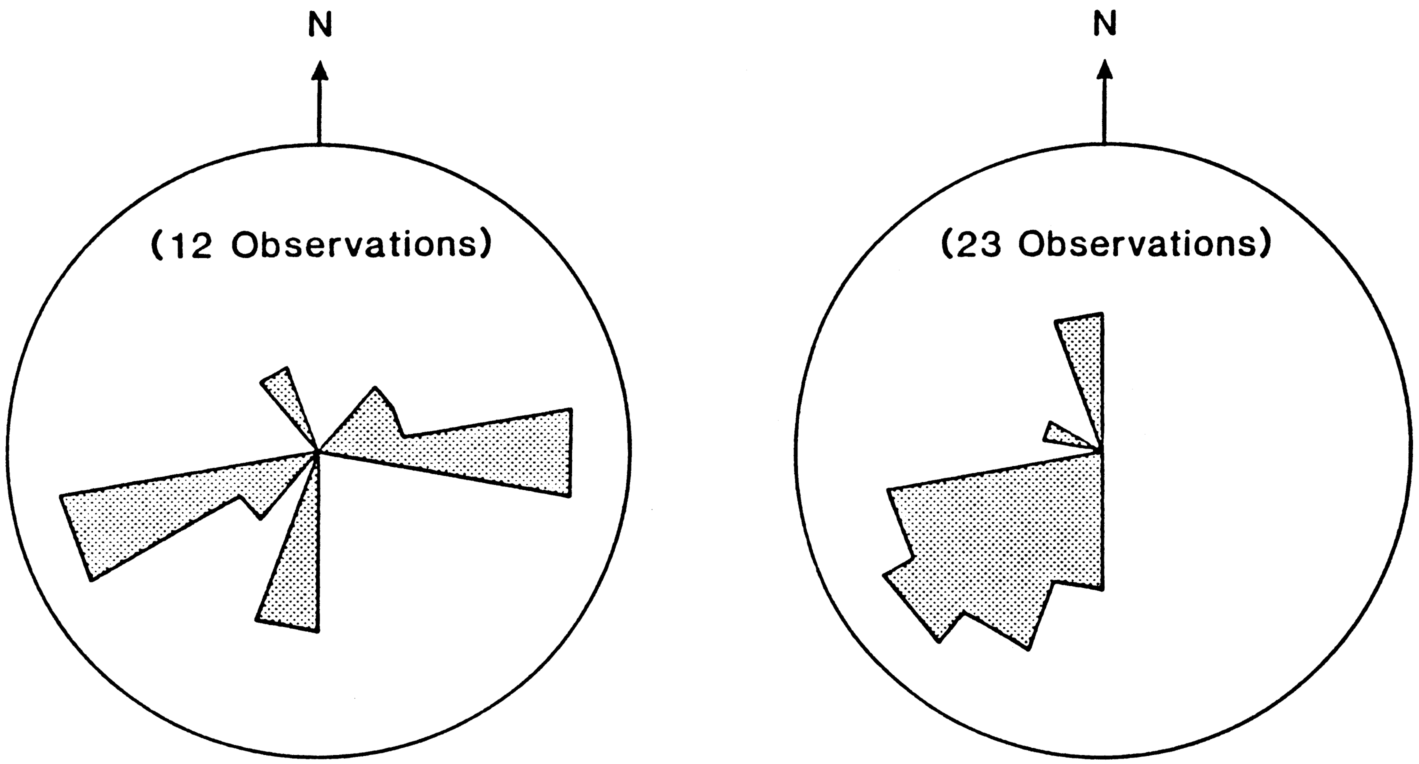
Distribution of facies associations

Working from north to south, the quarry at locality 1 (see Fig. 1) shows the top of Association A together with Association C. The crags to the south are in Association C, while locality 2 below is in the bottom of Association A. Localities 3–9 (Fig. 2, column I) display a much more complete section with almost the full thickness of Association A represented in the lower and middle exposures, and Association C at the top.

Localities 10–19 (Fig. 2, column II) show the upper part of Association A, Association B in two areas, and rare exposures (at the very top) of Association C. At localities 20–24, the line of crags to the south, and localities 26–27 (Fig. 2, columns III and IV) a fuller representation of Association A is present, together with Association C at the top. Finally, the crags to the south of locality 26 (see Fig. 1) are all in Association C.

The palaeocurrent evidence

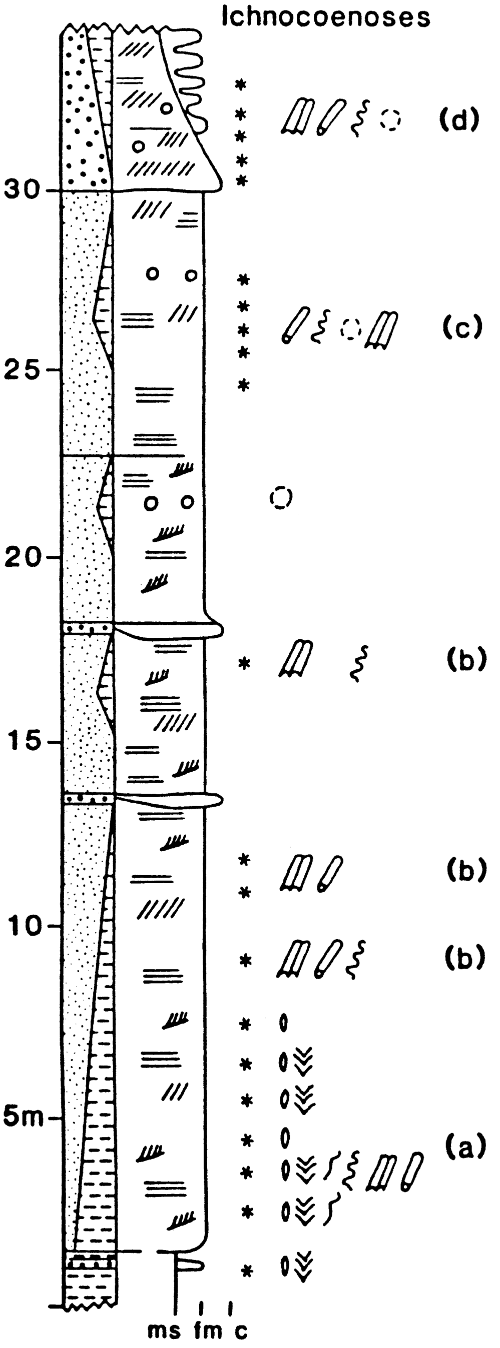
The data for Facies Association A is unfortunately too scanty to warrant firm conclusions. The small numbers of cross-beds, however, indicate (see Fig. 3) a distinctly polymodal current pattern. There are indications that currents to the NE-E were dominant in the lower Rough Rock Flags, and changed to the SW-W higher up in the succession. Only one groove has so far been found in situ in Association B, giving a current direction of either SW or NE. For Association C more data is available (Fig. 3) and this suggests that palaeocurrent flows were mainly to SSW-WSW, with a few flows to the NNW.



(a) Facies Association A

(b) Facies Association C

Fig. 3. Palaeocurrent data from cross-bedding for Facies Associations A and C.



Key to trace fossils

- * Trace fossil horizons
- 0 *Pelecypodichnus*
- ≚ Bivalve escape shafts
- ʃ Bivalve plough marks
- ξ *Cochlichnus*
- ⫽ cf. *Didymaulichnus*
- ∅ *Planolites*
- ◌ Nodules (carbonate?)

Distribution of trace fossils

Facies assoc.	0	≚	ʃ	ξ	⫽	∅	◌
B				P	C	C	
Upper				R	R	C	C
A							
Middle				R	C		C
Lower				R	C	P	
	C	C	P	R	R	R	
Basal sedm.	C	C					

Frequency
R–Rare
P–Present
C–Common

Fig. 4. Occurrence and diversity of trace fossils recorded from the Rough Rock Group at Cracken Edge.

Discussion—the sedimentary environment

In the broadest terms the Cracken Edge succession is a regressional, coarsening-up sequence. Silty mudstones of a probably brackish water environment are invaded by distal sandstones and silty mudstones as a consequence of hinterland uplift and/or climatic change. There are brief but violent influxes of much coarser sediments; silty mudstones become rare and isolated units of larger scale cross-bedding appear. Finally, the advancing fluvial system brings in coarser proximal sediments with many small channels before a final period of brief emergence.

Any attempt to provide a more detailed sedimentological interpretation encounters a number of problems. First, in Facies Association A. How do these laminated and cross-laminated fine-grained sandstones, with rare planar cross-beds, fit into the various Namurian delta models? Similar sandstones do make up the classical turbidites of Walker (1966) in the deep water deltaic sequences of Collinson (1976). But such deltas do not persist into the Yeadonian, and the Rough Rock Flags lack the grading, Bouma divisions, flutes and grooves of the classical turbidites; cross-bedding is very rare in the latter, and the mudstone/siltstone proportion is higher there.

In the shallow water sheet delta sequences of Collinson (op. cit.) fine-grained parallel—and cross—laminated sandstones appear to be restricted to the uppermost parts of some channel fills, as levees, or in interdistributary bay environments (Benfield 1969; Chisholm 1977; Jones 1980; Okolo 1983). But there is no evidence in the Rough Rock Flags of the large-scale channelling (with fills of coarse-grained sand-stone), the dominant trough cross-bedding, the significant proportions of mudstones and occasional seatearths that characterise the shallow water sheet delta sequences. Nor do the Rough Rock Flags compare well with the deposits of Collinson's shallow water, elongate delta type of sequence. In the Haslingden Flags (Collinson and Banks 1975) parallel-laminated sandstones are rare, and the dominantly cross-laminated bar finger sands of the delta front are backed by trough and planar cross-bedded sediments of migrating distributary channels.

Of the alternative fluvial models, the deposits of the large sandy, braided systems described by Collinson (1978) and Walker (1979) differ substantially from those of the Rough Rock Flags. Parallel-and cross-laminated sandstones are only a minor constituent in the former and are confined to bar tops in sequences made up of trough cross-bedded under planar cross-bedded sandstones. A more promising comparison is with the products of sheet floods—for example, the Bijou River type of sandy, braided river system (Miall 1977), although this has a semi-arid upland setting. Here repeated flash flood cycles produce a sequence which is dominated by fine to coarse, horizontally laminated sands with primary current lineations, but which also includes rippled sands, planar cross-bedded sands, erosion surfaces with some pebbles, and rare thin silt or clay beds.

Possible ancient examples of such sediments are not common. But in the United Kingdom they include the ORS Trentishoe Formation of North Devon (Tunbridge 1981). Here the main facies (A) consists of multistorey sand bodies of fine- to medium-grained laminated beds with erosive bases, primary current lineations and some ripples, together with occasional intra-formational conglomerates and some siltstones. These are interpreted by Tunbridge as the products of main (high energy) sheet floods, and they sometimes thin laterally and split into facies B sediments (thin-bedded, laminated sandstones alternating rapidly with siltstones) which represent lateral or distal floods. Cross-bedding, however, has not been found in the Trentishoe Formation.

Abroad, the braided river sediments in the lower Palaeozoic of the Cape Basin in South Africa (Vos and Tankard, 1981) suggest some comparisons with the Rough Rock Flags of Cracken Edge. Facies Association 6 (the distal alluvial plain sheet flood facies) consists of thick sequences of medium to coarse-grained laminated sandstones (with primary current lineations) and rare isolated sets of small-scale trough cross-beds. These are interpreted as the sediments deposited by sheet floods on a broad, distal alluvial plain with low gradients—a setting probably parallelled in the Yeadonian of the Pennines.

Next Facies Association B with its rhythmic alternations of fine-grained sandstones and silty mudstones. These have many of the characteristics of beds ascribed to levees or crevasse splays in the Namurian and indeed the Lower Westphalian (Broadhurst, Simpson and Hardy, 1980) delta complexes. But on Cracken Edge the setting is entirely different. There the rhythmic sequences appear to pass laterally into thicker sandstones and very thin silty beds of Association A, or on one flank into Association C. No deep channels are apparent at this level and there are no signs of flood plain silt-stones and mudstones. It seems more likely that the rhythmic sequences represent the distal or lateral accumulations of the repeated sheet floods which were responsible for Association A sediments. These floods did not necessarily cover the whole area with an even flow of sediments, and the strength of the palaeocurrents would vary from place to place, as in the Trentishoe Formation (Tunbridge, op. cit.).

Lastly there is the Facies Association C assemblage of coarse-grained bedded and cross-bedded sandstones with local erosion surfaces but no silty mudstones. Examples of this assemblage can be found in most of the shallow water sheet delta sequences of the higher Namurian. But the Rough Rock of Cracken Edge appears to lack many other features of such delta sequences—large concave-up channels, silty interbeds or lenses, a strong element of trough cross-bedding, and evidence of adjacent inter-distributary bay mudstones and siltstones. This is puzzling, and it is perhaps possible that the Rough Rock sediments are closer to those of the Platte type of sandy braided rivers (Miall, 1977) although here too the environment is a semi-arid upland one. In this very shallow, virtually non-cyclic flows produce a succession dominated by coarse (sometimes pebbly) sandstones with rare massive sandstones, horizontal gravels and sandstone/siltstone interbeds. An ancient relative of this type is perhaps the middle to distal braided alluvial plain facies association in the Cape Basin of South Africa (Vos and Tankard, op. cit.). This consists mainly of planar cross-bedded, coarse-grained and pebbly sandstone units with erosion surfaces and thin conglomerate lenses—all deposited by sedimentation within the transverse to linguoid bars of many small channels.

But perhaps the final word on the Cracken Edge problems must lie with Bridge (1985)-

> "we must ... be prepared to accept partial solutions to palaeogeographic reconstructions if exposure is inadequate".

B. Trace fossils from Cracken Edge

These were first discovered and described by Hardy (1970) who attributed the majority to the activities of bivalves under the ichnogenus *Pelecypodichnus*, including resting traces, escape shafts and plough marks. The resting traces—*Pelecypodichnus amygdaloides* Seilacher (or *Lockeia*)—occurred as hypichnial casts and epichnial depressions, between 5 and 30mm long. Escape shafts were commonly associated with them, varying from a few centimetres to 1m in height, normally vertical but sometimes slightly inclined. The plough marks sometimes led into, or from, the resting traces, and were preserved as hypichnial ridges and epichnial grooves. They varied from "a few" to 20–30cm in length, straight to irregularly and slightly curved, unbranched (but occasionally meeting), and at Cracken Edge showing evidence of both lateral and vertical movement. A preferred orientation was detected in both the resting traces and plough marks, parallel with the direction of prevailing currents.

In addition to bivalve trace fossils Hardy found a possible *Limulicubichnus* arthropod trace, and several *Cochlichnus* trails—mainly hypichnial, sinuous and unbranched, with a diameter of 1—4mm and a common association with *Pelecypodichnus*. Lastly, the concretions of the area were described as carbonate (usually ankeritic)—cemented and were interpreted as the product of the accumulated shells of dead bivalves.

Details

Trace fossils have been found as hypichnia at several horizons on Cracken Edge where sandstones and silty mudstones are juxtaposed (Fig. 2) in Facies Associations A and B. Their broad distribution is shown in Fig. 4 on a composite section through the succession. The ichnofauna consists of *Pelecypodichnus* resting traces, escape shafts and possible plough marks; *Cochlichnus, Planolites* and *Didymaulichnus*?

Ichnogenus *Pelecypodichnus* Seilacher 1953.

Plate 12A

1. *Resting traces*

The characteristic almond-shaped bivalve resting traces are present at the top of the basal sediments in Foxhole Clough and in the lowest part of Facies Association A at localities 4–9 on Cracken Edge itself. Loose slabs from above locality 25 show that they were also present at the same level in the southern sector of the quarries. Resting traces in the lowest exposures are moderate sized—up to 15mm in length, 10mm in width and 3mm in height. They are irregularly distributed but sometimes paired, without a preferred orientation. Most show a steeper slope down one side than the other, and one end is commonly facetted. Some have a short 'tail'—resembling a tadpole—and are similar to the *Lockeia siliquaria* James 1879 shown in Pickerill (1977, plate 2a).

Higher in the succession the beds of localities 6a and b show a profusion of classic resting traces, up to 25mm long, 20mm wide and 5mm high. There are indications of a preferred orientation with long axes aligned 120–300 degrees T. Higher still, resting traces of moderate size have been found at localities 7b and 8, and small ones at 6c (lower beds).

2. *Escape shafts*

These vertical structures perforating and downturning laminations in the sediments have been found in the Foxhole Clough exposures and at localities 9, 4, 6a and 7b. They are especially plentiful at 6a and are up to 210mm in height.

3. *Plough marks*

Straight to slightly sinuous ridges and grooves, crossing but not branching, up to 15mm in length and 2mm in width, have been found at locality 4. These are only rarely connected to resting traces, and indeed are sometimes overlain by the latter. They compare closely with those of Unit 2, Standedge Cutting (Eagar et al, 1985, Plate 7A) and are therefore interpreted as possible bivalve plough marks. No similar traces have been identified at locality 6a or in any of the higher *Pelecypodichnus*-bearing beds. But two loose sandstone slabs from the general area of localities 15–18 carry slightly sinuous median furrows and cylindrical lateral ridges (cf Hardy 1970, figure 3.6). The least weathered trail is 130mm long and 6mm wide. It displays more than a hint of transverse striations on the lateral ridges, suggesting a comparison with *Chevronichnus* Hakes (Hakes, 1976) interpreted as a bivalve trail.

Ichnogenus *Cochlichnus* Hitchcock 1857

Plate 12B

Typical sinuous trails up to 18mm long and 1mm wide are present at locality 4, sometimes clustered together and associated with *Pelecypodichnus* (see Eagar et al, 1985, Plate 12 E, F). They have also been found higher up in Facies Association A at 6c and 21, and still higher at locality 16. They are commoner in Facies Association B at localities 11, 12 and 15.

Ichnogenus *Planolites* Nicholson 1873

Plate 13A

The sandstones of locality 4 carry several horizontal hypichnial traces, up to 80mm long and 5mm wide, which are straight to slightly sinuous and occasionally cross. They have no apparent connection with the *Pelecypodichnus* resting traces, and probably belong to the *Planolites* group of Pemberton and Frey (1982) who tentatively identify them as the feeding or foraging burrows of deposit-feeding polychaete worms. *Planolites* also occurs in the middle of 6c and is there associated with nodules and with more substantial traces of bold relief, up to 65mm long, 15mm wide and 5mm in height.

Planolites burrows are found in Facies Association A at localities 20–24 in the southern sector of the quarries. They are also present higher up at locality 16–a medium-sized type, and also a profusion of delicate, very thin and short (4–9mm) traces which resemble the *Planolites montanus* of Pemberton and Frey (op. cit.). Medium-sized *Planolites* are found in Facies Association B at localities 11, 12 and 15.

Ichnogenus *Didymaulichnus* Young 1972

Plate 13A, B

A few of the horizontal hypichnial ridges of locality 4 are bilobed with a median furrow, straight to slightly sinuous in direction and up to 140mm long. These trails are tentatively included in *Didymaulichnus*, endogene trails of a gastropod or arthropod (Young 1972). Higher up in Facies Association A several similar trails have been found at localities 20–24. They are straight to slightly sinuous, crossing but not branching, and on average 120mm long, 5mm wide and 3mm high. They have a preferred orientation–N-S in lower beds, ENE-WSW in higher ones. Associated with these trails are nodules, often large and irregularly circular in shape, and in some cases with trails radiating away from them.

Such trails and nodules are also found still higher at localities 20–21 with an ENE-WSW orientation, and they may also be present at localities 16 and 17. They have been identified in Facies Association B at localities 11–12 and 15. Here they are bold with a pronounced relief, and attain 150mm in length, 9mm in width and 8mm in height. Only a small number display the median groove, but all attain the same dimensions. They cross only occasionally, and most show the 'pinch and swell' variation in width and height noted by Pickerill, Romano and Melendez (1984). A preferred orientation is usual, varying from bed to bed but mostly aligned ENE-WSW. There are many nodules, sometimes connected to the trails.

The ichnocoenoses

The distribution of the traces through the succession (Fig. 4) appears to justify recognition of four trace fossil assemblages or ichnocoenoses–

Ichnocoenosis a.

This is found in the basal silty mudstones and in the lowest beds of Facies Association A. It is dominated by *Pelecypodichnus* (peaking at the level of localities 6a and b, and declining thereafter) with rare *Cochlichnus*, *Planolites* and *Didymaulichnus*?.

Ichnocoenosis b.

Found in higher beds of Facies Association A. Dominated by *Didymaulichnus?*, with some *Planolites* and rare *Cochlichnus*.

Ichnocoenosis c.

Found towards the top of Facies Association A. Dominated by *Planolites* with rare *Cochlichnus* and *Didymaulichnus?*.

Ichnocoenosis d.

Found in Facies Association B. Dominated by *Didymaulichnus?*, with *Planolites* and *Cochlichnus*.

Discussion—the trace fossil distribution

The most surprising outcome of the present inquiry has been its failure to find the *Pelecypodichnus* assemblage present throughout the Cracken Edge succession. Resting traces, escape shafts and possible plough marks are certainly there, but only, it would appear, at the lowest levels. In higher beds they are absent and the traces of *Planolites* and *Didymaulichnus?* are dominant.

A similar separation (in space and time) between the traces of suspension feeders like *Pelecypodichnus* and those of internal sediment feeders such as *Planolites* is not without parallel in other Rough Rock exposures. At Millbrow quarry (SJ 97908954) not far away a sequence of thin sandstones and silty mudstones is exposed towards the middle of the section. *Pelecypodichnus*, *Cochlichnus* and rarer horizontal linear traces are found beneath the two lowest sandstones. *Pelecypodichnus* then disappears and is replaced by *Cochlichnus*, short trails of the *Planolites* type, and nodules which become more frequent upwards. But under the seventh sandstone large resting traces with excellent escape shafts reappear. Billinge Hill quarries (SJ 955777), also in the Rough Rock, seem to tell much the same story with bivalve shells, resting traces and escape shafts in the lower levels and *Planolites*-type traces at the top.

Further down in the Namurian distinct levels for *Pelecypodichnus* and *Planolites*, with little overlapping, are the general rule in the Grindslow Shales—as for example, in the excellent exposures at Torside Clough (SK 070971), Yellowslacks Brook (SK 074954), Crooked Clough (SK 0944), and Blackden Brook (SK 119883). As Eagar et al (1985) say, "the two trace fossils are mutually exclusive in terms of their host lithology, but can alternate in an interbedded sequence" with *Planolites* flourishing in organic-rich muds and the bivalves only in fine to medium-grained sandstones.

But what could have caused the separation on Cracken Edge between the *Pelecypodichnus* assemblage and that of *Didymaulichnus?*/*Planolites?*. No dramatic change in the sedimentary regime appears to have taken place since the laminated sandstones and silty mudstones which provided the host sediments are indistinguishable (macroscopically at least) at the relevant levels. The ratio of silty mudstone to sandstones does not increase upwards but in fact decreases as the bivalves disappear and the internal sediment feeders take over. Overall the thickness of individual beds and lenses of silty mudstones shows little increase upwards. There is some increase in the thickness of sandstone beds, but this is interrupted from time to time by sequences of thinner beds. Sedimentological control, therefore, does not seem to have operated in this case at least.

All that the available exposures apparently indicate is that the characteristic traces of the bivalves appear with the early influxes of sand into the muddy environment. As Broadhurst et al (1980) point out, this suggests "either that the bivalves gained some advantage from an environment subject to the periodical arrival of flood detritus, or that the bivalves arrived with the floodwater, survived and re-established themselves". They reach a moderate size; tolerate the presence of *Cochlichnus* and a few other internal sediment feeders; disappear at some levels but with restocking reappear at higher ones. Then a little higher up, very large bivalves take over the whole environment. No pause in sand sedimentation can be found to explain their growth. Some environmental change in channel fill may have been responsible; and the presence of complex cross-bedded sandstones below the *Pelecypodichnus*-rich horizon might suggest more variable and turbulent currents bringing larger food supplies for the new generation of bivalves.

This generation was able to survive further influxes of sand—perhaps 620mm in thickness on the evidence of the escape shafts at locality 6a. But the resting traces are noticably fewer and smaller at the top of this section, and with a further 1.5 m of sand (with very thin mudstone intercalations) these large bivalves died out. With restocking a new generation of moderate size established itself at slightly higher sandstone/silty mudstone interfaces, but it could not survive further substantial influxes of sand and died out. The supply of bivalves and/or their food supplies dried up—perhaps because of changes in current directions or the advance of more proximal, sand-laden water—and the environment was left to the more adaptable, internal sediment feeding arthropods and worms. Bivalves might well have been expected to reappear, as at Millbrow quarry, in the rhythmic sandstone-silty mudstone sequences of Facies Association B. But perhaps the muds here carried too much iron to allow of their establishment.

Finally, something should be said about the large concretions in the Cracken Edge quarries. These appear for the first time in the middle of Facies Association A (see Figs. 2 and 4). They are well above the *Pelecypodichnus* horizons; they are only rarely close to silty mudstone lenses (in which presumably bivalves could flourish); and those accessible for testing give no definite calcareous reaction. It seems unlikely, therefore, that they are the product of the accumulation of dead bivalve shells (Hardy 1970).

Acknowledgments

I am grateful to Dr. Peter Hardy for directing my footsteps to Cracken Edge through his pioneering study—and to the long-dead quarrymen there for opening up so many good exposures. I am also greatly indebted to Dr. John Pollard of the University of Manchester on two counts—first, for arousing my interest in trace fossils, and second, for reading earlier drafts of this paper with critical sympathy and suggesting a great many improvements.

G.D. Miller, B.A.,
'Oaklea'
Diglee Road,
Furness Vale,
via Stockport, SK12 7PW.

References

Benfield, A.C., 1969. The Huddersfield White Rock cyclothem in the central Pennines. Report of Field Meeting. *Proc. Yorks. Geol. Soc.* 37, 181–187.

Bridge, J.S.P., 1985. Palaeochannel patterns inferred from alluvial deposits: a critical evaluation. *J. Sed. Petrology*. 55, 579–589.

Broadhurst, F.M., Simpson, I.M. and Hardy, P.G., 1980. Seasonal sedimentation in the Upper Carboniferous of England. *J. Geology*. 88, 639–651.

Calver, M.A., 1968. Coal Measures invertebrate faunas. *In*, Murchison, D., and Westoll, T.S. (Eds.), *Coal and Coal Bearing Strata*. Edinburgh, Oliver and Boyd, pp. 147–177.

Chisholm, J.I., 1977. Growth faulting and sandstone deposition in the Namurian of the Stanton syncline. *Proc. Yorks. Geol. Soc.* 41, 305–323.

Collinson, J.D., 1976. Deltaic evolution during basin fill—Namurian of Central Pennine Basin (abstract) *Bull. Am. Assoc. Petroleum Geol.* 60, 52.

Collinson, J.D., 1978. Alluvial sediments. *In*, Reading, H.G. (Ed). *Sedimentary Environments and Facies.* Oxford: Blackwell, pp. 15–60.

Collinson, J.D., and Banks, N.L., 1975. The Haslingden Flags (Namurian GI) of south east Lancashire: bar finger sands in the Pennine Basin. *Proc. Yorks. Geol. Soc.* 40, 431–458.

Eagar, R.M.C., Baines, J.G., Collinson, J.D., Hardy, P.G., Okolo, S.A., and Pollard, J.E., 1985. Trace fossil assemblages and their occurrence in Silesian (Mid-Carboniferous) deltaic sediments of the Central Pennine Basin, England. *In*, Curran, H.A. (Ed), *Biogenic structures: their use in interpreting depositional environments. Society of Economic Paleontologists and Mineralogists Special Publication* No. 25. Tulsa, Oklahoma, pp. 347.

Hakes, W.G., 1976. Trace fossils and depositional environments of four clastic units, Upper Pennsylvanian megacycolthems, north east Kansas. *Univ. Kansas Paleont. Contributions*, 63, 1–46.

Hardy, P.G., 1970. *Aspects of Palaeoecology in the arenaceous sediments of Upper Carboniferous age in the area around Manchester.* Unpub. Ph.D. dissertation, University of Manchester.

Jones, C.M., 1980. The Roaches Grit. *Proc. Yorks. Geol. Soc.* 43, 39–67.

Miall, A.D., 1977. A review of the braided river depositional environment. *Earth Sci. Revs.* 13, 1–62.

Mitchell, G.H., 1954. The Whittington Heath Borehole. *Bull. Geol. Surv.* G.B. 5, 1–60.

Okolo, S.A., 1983. Fluvial distributary channels in the Fletcher Bank Grit (Namurian R2b) at Ramsbottom, Lancs. *In*, Collinson, J.D. and Lewin, J. *Modern and Ancient Fluvial Systems.* Oxford: Blackwell, pp. 575.

Pemberton, S.G. and Frey, R.W., 1982. Trace fossil nomenclature and the *Planolites-Palaeophycus* dilemma. *J. Paleontol.* 56, 843–881.

Pickerill, R.K., 1977. Trace fossils from the Upper Ordovician (Caradoc) of the Berwyn Hills, Central Wales. *Geol. J.* 12, 1–16.

Pickerill, R.K., Romano, M., and Melendez, B., 1984. Arenig trace fossils from the Salamanca area, Western Spain. *Geol. J.* 19, 249–269.

Ramsbottom, W.H.C., 1977. Major cycles of transgression and regression (mesothems) in the Namurian. *Proc. Yorks. Geol. Soc.* 41, 261–391.

Reading, H.G., 1969. Sedimentation sequences in the Upper Carboniferous of N.W. Europe. *C.R. 6me Cong. int Carb. Strat. Geol.*, Sheffield 1967, vol IV, 1401–1411.

Reineck, H.E. and Singh, I.B., 1980. *Depositional Sedimentary Environments.* Berlin: Springer-Verlag. pp. 549.

Shackleton, J.S., 1962. Cross-strata of the Rough Rock (Millstone Grit series) in the Pennines. *Geol. J.* 3, 109–118.

Stevenson, I.P. and Gaunt, G.D., 1971. Geology of the Country Around Chapel-en-le-Frith. *Mem. Geol. Surv. U.K.* HMSO, London. 444pp.

Stevenson, I.P. and Mitchell, G.H., 1955. Geology of the Country between Burton upon Trent, Rugeley and Uttoxeter. Mem. Geol. Surv. U.K. HMSO, London. 178pp.

Taylor, K. and Rushton, A.W.A., 1971. The pre-Westphalian geology of the Warwickshire coalfield. *Bull. Geol. Surv. G.B.* 35, 1–150.

Tunbridge, I.P., 1981. Sandy high-energy flood sediments—some criteria for recognition, with an example from the Devonian of South West England. *Sedimentary Geology.* 28, 79–95.

Vos, R.G. and Tankard, A.J., 1981. Braided fluvial sediments in the Lower Palaeozoic Cape Basin, South Africa. *Sedimentary Geology.* 29, 171–193.

Walker, R.G., 1966. Shale Grit and Grindslow Shales: transition from turbidite to shallow water sediments in the Upper Carboniferous of northern England. *J. Sed. Petrology.* 36, 90–114.

Wright, M.D., 1964. Cross bedding in the Millstone Grit of the Central Pennines and its significance. *Geol. Mag.* 101, 520–530.

Young, F.G., 1972. Early Cambrian and older trace fossils from the Southern Cordillera of Canada. *Can. J. Earth Sci.* 9, 1–17.

Plate 12A

Pelecypodichnus resting traces and bivalve plough marks. Ichnocoenosis (a). Locality 4, Cracken Edge, Derbyshire (specimen MGSF 96. Dept. Geology, University of Manchester Special Collections).

Plate 12B

Cochlichnus sp. associated with *Planolites* burrows. Ichnocoenosis (c). Locality 16, Cracken Edge, Derbyshire (specimen MGSF 97).

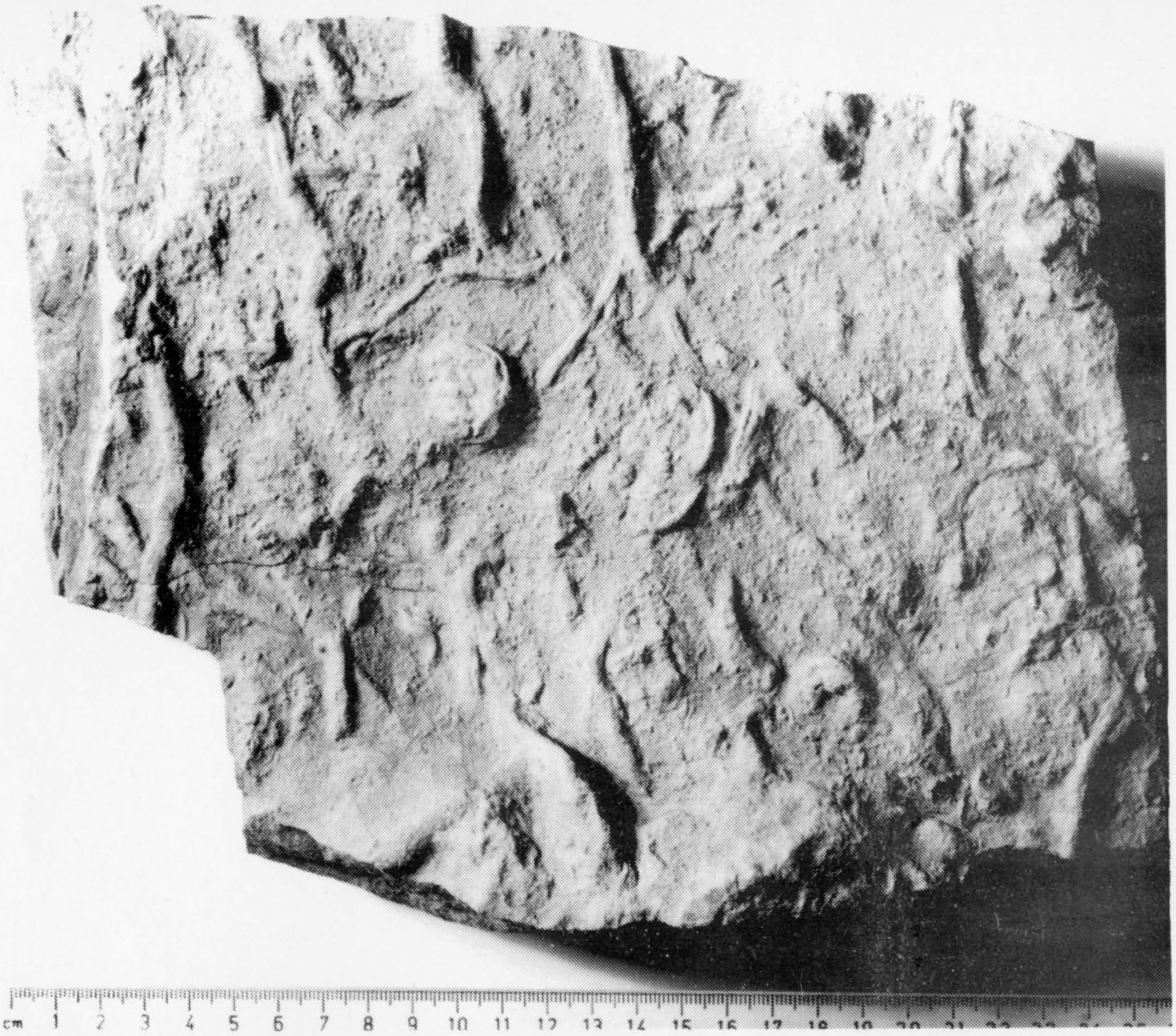


Plate 13A

Didymaulichnus? (bilobed hypichnial ridges) and *Planolites* (horizontal curved burrows). Ichnocoenosis (b). Locality 24, Cracken Edge, Derbyshire (specimen MGSF 98).

Plate 13B

Didymaulichnus? (variable length, parallel bilobed hypichnial ridges) and cross cutting *Planolites*. Ichnocoenosis (d). Locality 11, Cracken Edge, Derbyshire (specimen MGSF 99).

PETROGRAPHIC VARIATION ASSOCIATED WITH HUMMOCKY CROSS STRATIFICATION IN THE PERMIAN OF NOTTINGHAMSHIRE, ENGLAND

by

Ian D. Bryant

Summary

The Cadeby Formation of Nottinghamshire accumulated on a shallow shelf at the margin of the Zechstein Sea and is predominantly composed of dolomitised pelloidal carbonates with dispersed siliciclastic material. Hummocky cross-stratified units exposed in quarry sections through the formation contain high proportions of siliciclastic fine sands together with concentrations of shell debris and are interpreted as storm beds. The non-carbonate materials are interpreted as being derived from erosion of littoral sediments which were transported offshore during storms. These clastic grains are not uniformly distributed through the beds with hummocky upper surfaces but rather are concentrated in the lowest divisions of the units. This petrographic variation therefore appears to indicate that the major basinward flux of shore-derived material preceded the development of hummocky relief upon the sea bed during the deposition of these beds.

Introduction

Hummocky cross-stratification (HCS) (Harms et al., 1975) has been described from both carbonate and siliciclastic shallow marine sediments, although the mechanisms by which it may be generated are still controversial particularly with regard to the relative timing of sediment input and hummock formation. Walker *et al.* (1983) have proposed a turbidity current mechanism to emplace sediments which may *subsequently* be reworked by storm waves thereby producing 'turbidite-HCS beds', whilst Swift *et al.* (1983) favour formation of hummocky cross-stratification concomitant with deposition of sediment in a combined flow regime. Part of this controversy no doubt arises from the wide variety of bedding styles which have been described as 'hummocky stratification' and, as Walker *et al.* (1983) suggest, different hydrodynamic models may be appropriate for each of these different varieties. It is the purpose of this paper to document evidence provided by petrographic variation within hummocky cross-stratified dolostones of the Cadeby Formation of Nottinghamshire, which indicates that, in this instance, the major influx of sediment preceded the development of hummocky relief on the sea bed.

The Cadeby Formation (Smith *et al.* 1986) (formerly the Lower Magnesian Limestone) of Nottinghamshire is of Upper Permian age and represents part of the first Zechstein cycle (Taylor and Colter, 1975). The sediments discussed herein accumulated in an embayment of the Zechstein Sea termed the Nottingham Bight (Smith, 1970). In this area the Cadeby Formation consists predominantly of dolomitised carbonates which grade into dolomitic sandstones at the western margin of the Bight. The presence of dispersed siliciclastic and plant materials within the dolostones at the westernmost outcrops of the formation suggest that the shoreline of the contemporary Zechstein Sea lay only a little further west than the present outcrop limit (Taylor, 1968). From this limit the Cadeby Formation extends eastwards across the gently sloping East Midlands Platform for some 40 km to the contemporary shelf edge where it passes beneath a thick evaporite sequence (Smith, 1974). Sedimentary facies varied across the shelf from nearshore pelloidal and shelly carbonates with dispersed siliciclastic grains to oolitic limestones with a low siliciclastic content at the shelf edge (Taylor and Colter, 1975). In the study area (Fig. 1) most of these carbonate sediments have been strongly altered to coarse euhedral dolomite crystals in which the primary carbonate grains are only discernable as ghost textures.

Hummocky cross-stratification has been reported from the Cadeby Formation of Yorkshire by Kaldi (1986) and is exposed in two working quarries at Bulwell (Grid ref. SK538438), north Nottinghamshire (Fig. 1). These quarries lie approximately 8 km east of the western outcrop limit of the formation and expose successions

Mercian Geologist, vol. 10, no. 3,
pp. 203–208, 3 figs. and plate 14.

dominated by evenly bedded dolostones separated by thin muddy interbeds. However, several beds are characterised by hummocky bedding surfaces (Fig. 2) which are associated with variation in the composition of the carbonates and it is this variation in bedding style and petrography which provides information regarding the mechanism of hummock development.

Field observations

In the summer of 1983 the Bulwell quarries exposed a thickness of approximately 5 m of dolostones of the Cadeby Formation. Bedding within the sequence was clearly defined by thin (5 to 30 mm) clay and sandy clay partings between thicker (typically 10 to 30 cm) dolostones which showed a tendency to thin upwards (Fig. 2). In the lowermost 1.3 m of section the beds exhibited localised disturbance resulting in a series of "folds" which were truncated by overlying beds (horizon A; Fig. 2). This relationship indicates a synsedimentary origin for the structures, possibly associated with rapid dewatering. The overlying strata were not deformed in this way and consisted predominantly of sub-horizontally disposed parallel bedded dolostones. However, at several prominent horizons, (horizons B to E; Fig. 2) anomalously thick beds were marked by flat lower contacts but undulose upper contacts. In sections parallel to bedding these upper surfaces were seen to consist of a series of domes and basins with a spacing of approximately 1 m. Shell moulds of bivalves which were scarce within the sequence as a whole, were concentrated at the bases of horizons B (Plate 14A) and C. These beds rich in shell moulds have been found elsewhere in the local area (Taylor, 1968; Nutting, 1980). No lamination was discernable in this lowest, shelly part of the hummocky units although faint parallel lamination characterised the sediments immediately superimposed upon them. Lamination of a 'scour and drape' type (cf. Dott and Bourgeois, 1982), was, however preserved in dolostone of the overlying hummocky division. These relationships, based on observations of all four hummocky horizons (B to E; Fig. 2), are summarised schematically in Fig. 3.

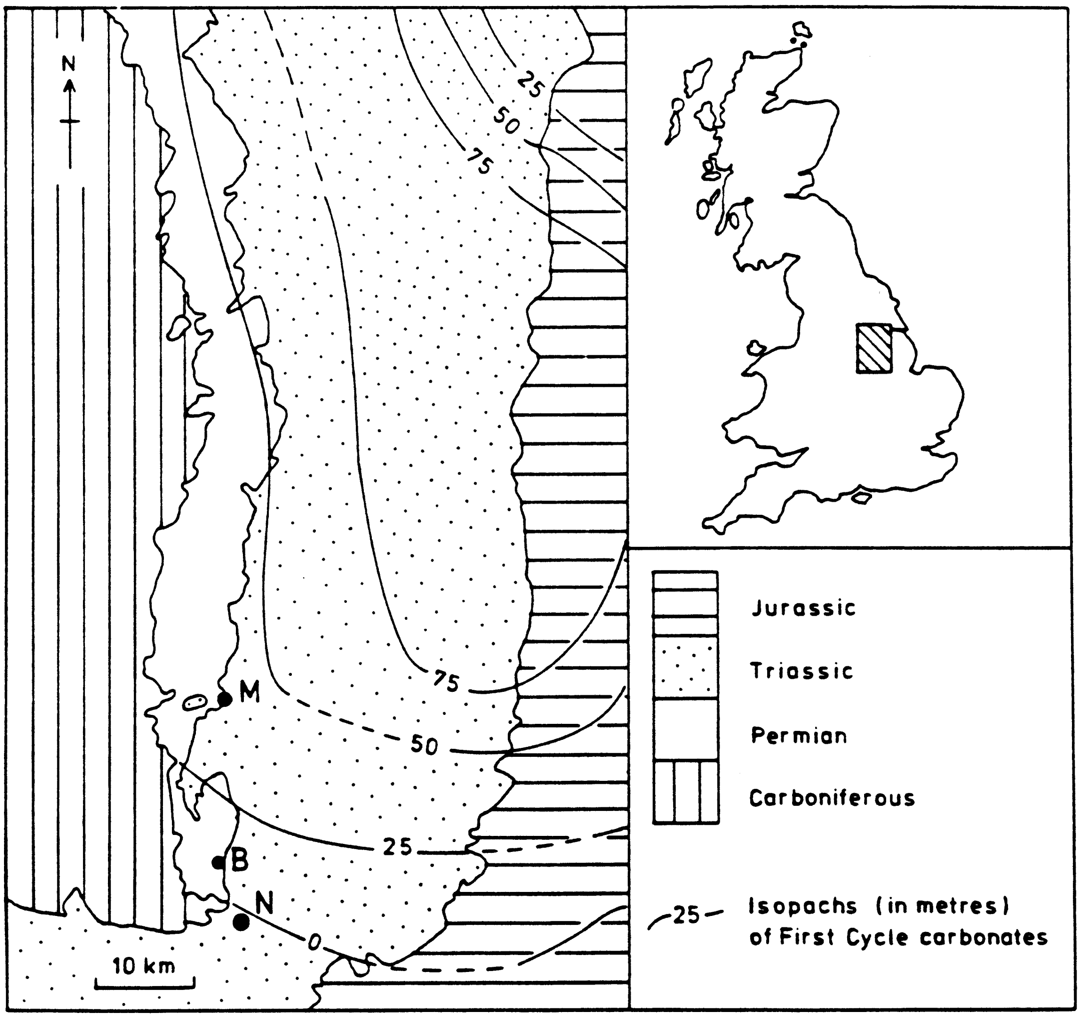


Fig. 1. Map to show the regional setting of the Permian rocks of Nottinghamshire. Inset map shows location of large scale map in eastern England. N = Nottingham, M = Mansfield, B = Bulwell. Isopachs of First Cycle carbonates after Taylor and Colter (1975).

The amplitude of the hummocks had in some cases been reduced by ripple reworking of material from the crests into the trough areas (Plate 14A) which were also sites of increased shell concentration. The ripple-reworked dolostones contained thin laminae of micaceous muds similar to the sandy clays which draped the hummocky unit as a whole. Commonly these drapes thickened into the swales between hummocks where they exceptionally attained thicknesses of 0.2 m.

The concentration of shelly material in the swales between the hummocks and the well preserved ripple lamination (distinguished by the thin mud drapes between adjacent ripple sets) which draped the upper surfaces of some hummocks provide evidence that the beds genuinely had primary hummocky relief rather than resulting from a modification of primary bedding by diagenetic processes.

Field examination of the hummocky units and intervening parallel bedded horizons suggested that significant variation in the proportion of shell and clastic material occurred both: (i) between the hummocky and parallel-bedded units, and (ii) between the various divisions of the hummocky strata. This contention was further investigated by laboratory analyses.

Laboratory analyses

Oriented thin sections were produced from samples collected in the field and examined using conventional light microscopy and cathodoluminesence techniques. Acid insoluble residues of the dolostones and untreated samples of the muddy drapes were examined by X-ray diffraction and scanning electron microscopy. The grain size of the clastic material was determined by sieve and settling tube analyses.

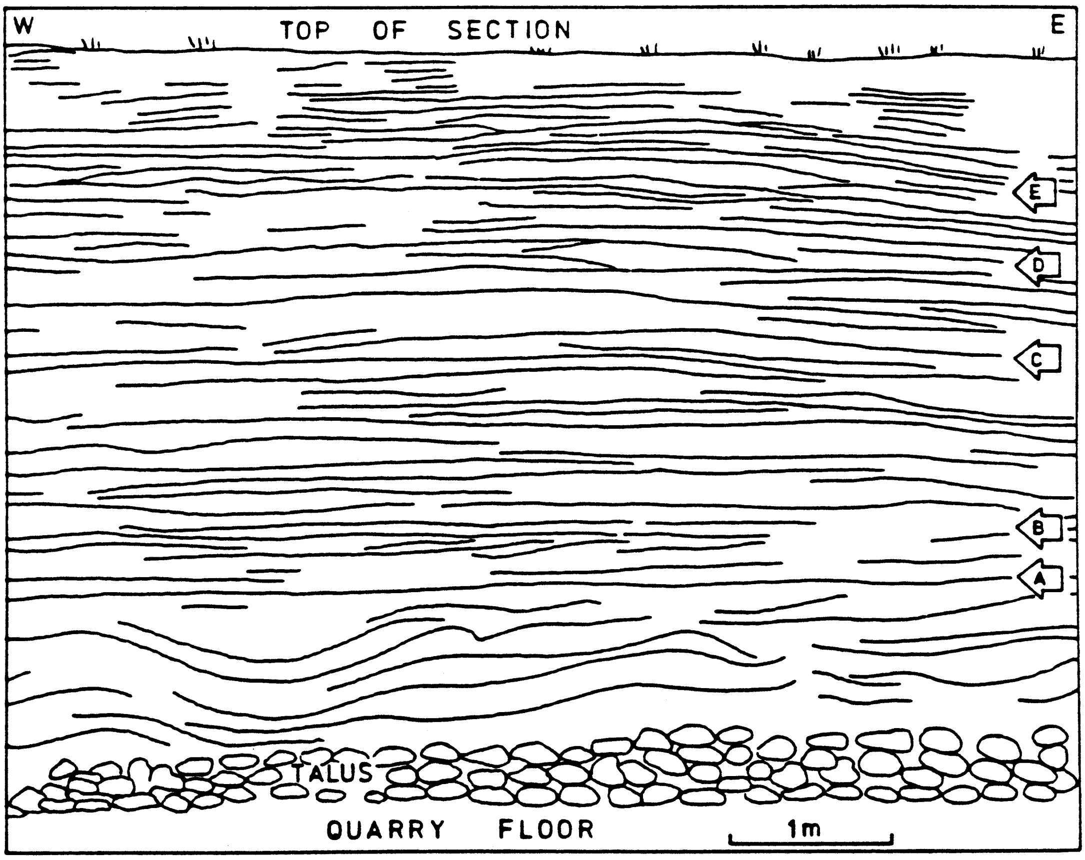


Fig. 2. Drawing taken from a photograph of a quarry wall to illustrate the major bedding surfaces exposed in Wilkinson's Quarry, Bulwell during the summer of 1983. Horizon A truncates underlying deformed strata; horizons B to E show development of hummocky bedding.

Composition of the Parallel Bedded Strata

The parallel bedded rocks between the hummocky units consisted of coarse dolomite with dispersed siliciclastic material. In thin section, ghost textures preserved within the dolomite crystals indicated that pelloidal carbonate grains made up a significant proportion of the rock prior to dolomitisation. Up to 12% of these dolostones was non-carbonate material of which 46% was of fine siliciclastic sand. The mud-grade sediments were dominated by a kaolinite-illite clay mineral assemblage together with some muscovite. These non-carbonate materials were indistinguishable from the material which constituted the thin muddy layers between the dolostone beds.

Composition of the Hummocky Strata

Bulk dissolution of samples from the hummocky strata resulted in a similar proportion of non-carbonate material (9 to 12%) to that found in the parallel bedded units. However, unlike the latter this material was not uniformly dispersed within the beds but could be seen to be differentially distributed between the divisions shown in Figure 3 when examined in oriented thin sections.

Basal Division—Coarse dolomite crystals and dolomitised shell fragments occurred in roughly equal proportion with quartz and feldspar medium to very fine sand grains (Plate 14B). Diagenetic ovegrowths occurred on many of the detrital grains but the well rounded outlines visible beneath the overgrowths testify to the detrital origin of the grains. The shell fragments occurred both in convex-up and concave-up orientations; in accordance with observations of shell moulds made in the field.

Parallel Laminated Division—Coarse dolomite crystals and medium to fine siliciclastic sand also occurred in this division although the sand proportion increased to over 60% and included lithic fragments in addition to quartz and feldspar grains (Plate 14C).

Hummocky Cross-stratified Division—This division possessed a lower siliciclastic sand content than the underlying divisions (10–20%). The sand was predominantly of fine to very fine grade and was evenly dispersed within the dolomite rhombs.

Flat Laminated Division—This division was petrographically indistinguishable from the underlying division.

Cross Laminated Division—The dolomite spar and dispersed sand of this interval were interbedded with thin mud laminae containing abundant muscovite mica flakes aligned parallel to the bedding. The clay mineral assemblage was predominantly kaolinite-illite and was indistinguishable from that of the overlying division.

Muddy Division—The clays and sands which draped the hummocky units were of similar composition to those occurring between the parallel bedded units and within the hummocky units.

Discussion

Clastic material, probably derived from the nearby shoreline, occurs dispersed within the dolostones of the Cadeby Formation and declines in abundance eastwards (Taylor and Colter, 1975; Nutting, 1980). Muddy laminae between dolostone beds possess similar mineral assemblages to the dispersed siliciclastic material and hence seem likely to have a similar provenance. The dispersed clastic sediment would therefore seem to indicate a steady input of shorederived sediment onto the shelf ('facies mixing *sensu* Mount 1984). If the muddy interbeds are of primary origin they would seem to indicate a periodic increase in the rate of the clastic flux relative to the rate of carbonate sedimentation: however, it is possible in some cases that these interbeds are of diagenetic origin.

The preservation of primary bedding structures and the differentiation of the constituent minerals between divisions precludes a diagenetic origin for the hummocky strata recognised at Bulwell. Since these hummocky strata are distinguishable from the majority of the sediments exposed at the quarries they seem likely to represent anomalous sedimentation events which are inferred to be associated with storms (cf. Harms, 1979; Tucker, 1982; Duke, 1985) and represent 'punctuated mixing' (*sensu* Mount 1984). Furthermore the sequence of primary sedimentary structures and variation in the petrography of the various divisions indicate a sequence of processes operating within each storm event which are summarised below.

1. The sharp base of each hummocky division represents an initial phase of erosion. No directional sole structures are present on the base of the overlying B division and consequently it is not possible to determine whether unidirectional or oscillatory flows caused this erosion. Erosion by lowering of wave base or bottom return currents (cf. Allen, 1982; Aigner and Reineck 1982) associated with the storm are possible causative mechanisms.
2. The earliest phase of deposition above each erosion surface incorporates shell debris and increased concentration of siliciclastic material. It is suggested that these sediments indicate a flux of material from the shore onto the shelf since the shoreward sediments have a higher siliciclastic component and shells are not usually found within the parallel bedded strata.
3. Increased erosion of shoreface sediments and shelfward transport by unidirectional flow appears to be indicated by the parallel laminated division. The highest proportion of siliciclastic sediment occurs within this division and therefore, by interference, the highest rate of shelfward sediment flux appears to have preceded the development of hummocky relief on the seabed indicated by the overlying hummocky cross-stratified division.
4. Scour and drape structures within the hummocky cross-stratified division are taken as indicators of dominantly oscillatory flows (cf. Walker *et al.*, 1983). The lower proportion of siliciclastic material in this division by comparison with the underlying divisions also suggests that the unidirectional flux of clastic sediment was waning at the time of hummock development. The carbonate material in this division seems unlikely to have been derived by wave scour of the underlying sediment since this is rich in clastic grains and it is suggested therefore that the bulk of the hummocky cross-stratified sediments were supplied by settling from suspension as the intensity of the storm decreased.
5. Ripple reworking of the tops of the hummocks appear to indicate that the hummocks came into disequilibrium with the flow and this seems likely to be a result of either further reduction in wave energy and or a reduced rate of sediment deposition. Certainly the occurrence of micaceous clay drapes between adjacent ripple sets appears to indicate reduced energy conditions.
6. The final phase of deposition of the hummocks is represented by sedimentation of very fine sands and muds, presumably from suspension, in the waning stages of the storm.

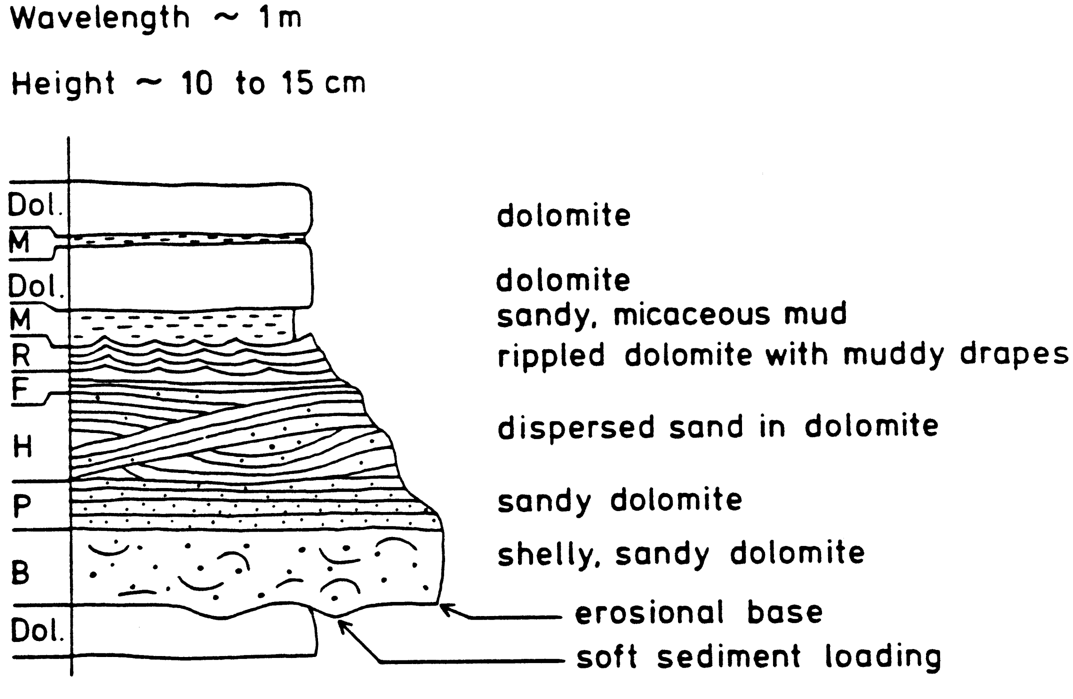


Fig. 3. Schematic representation of a hummocky cross-stratified unit. Dol. = parallel bedded dolostone, B = basal division, P = parallel laminated division, H = hummocky cross-stratified division, F = flat laminated division, X = ripple laminated division, M = muddy division.

Acknowledgements

I am grateful to Dr. F.M. Taylor for bringing the exposures at Bulwell to my attention and for valuable discussion. C. Atkinson, J. Bourgeois, E. Clifton, G. Harwood, D. Leckie, D. Smith and A. Swift are also thanked for helpful criticisms of earlier drafts of this paper.

References

Aigner, T. & Reineck, H.E. 1982. Proximality trends in modern storm sands from the Helgoland Bight (North Sea) and their implications for basin analysis. *Senckenbergiana Martima*, 14, 183–215.

Allen, J.R.L., 1982. *Sedimentary structures: their character and physical basis*. Amsterdam, Elsevier, 2, 471–506.

Dott Jr., R.H. and Bourgeois, J., 1982. Hummocky stratification: significance of its variable bedding sequences. *Bull. Geol. Soc. Am.*, 93, 663–680.

Duke, W.L., 1985. Hummocky cross-stratification, tropical hurricanes and intense winter storms. *Sedimentology*, 32, 167–194.

Harms, J.C., 1979. Primary sedimentary structures. *Ann. Rev. Earth Plant. Sci.*, 80, 227–248.

Harms, J.C., Southard, J.B., Spearing, D.R. and Walker, R.G., 1975. Depositional environments as interpreted from primary sedimentary structures and stratification sequences. *Soc. Econ. Paleont. Miner. Short Course* 2, 166pp.

Kaldi, J., 1986. Bedforms of the upper member, Cadeby Formation (Lower Magnesian Limestone EZI Ca) of the Yorkshire Province, eastern England. In Harwood, G.M. and Smith, D.B. (eds.) English Zechstein and related topics. *Spec. Publ. Geol. Soc. Lond.*

Mount, J.F., 1984. Mixing of siliciclastic and carbonate sediments in shallow shelf environments. *Geology*, 12, 432–435.

Nutting, M., 1980. *The Lower Magnesian Limestone of Nottinghamshire*, (unpub. M.Phil. thesis) University of Nottingham, 433pp.

Smith, D.B., 1970. The palaeogeography of the British Zechestein, *in* Rau, J.L. and Dellwig, L.F., eds., 3rd Symposium on Salt. *Ohio Geol. Soc.* Cleveland, Ohio, 20–23.

—, 1974. Permian, *in* Rayner, D.H. and Hemmingway, J.E., eds., *The Geology and Mineral Resources of Yorkshire*. Yorks. Geol. Soc. Leeds, 115–144.

Smith, D.B., Harwood, G.M., Pattison, J. and Pettigrew, T.H., 1986. A revised nomenclature for Upper Permian strata in eastern England. In Harwood, G.M., and Smith, D.B. (eds.), The English Zechstein and related topics. *Spec. Publ. Geol. Soc. Lond.*

Swift, D.J.P., Figueiredo, A.G., Freeland, G.L., Oertel, G.F., 1983. Hummocky cross-stratification and megaripples: a geological double standard? *J. Sed. Petrology*, 53, 1295–1317.

Taylor, F.M., 1968. Permian and Triassic Formations, *in* Sylvester-Bradley, P.C. and Ford, T.D., eds., *The Geology of the East Midlands*. Leicester University Press, Leicester, pp. 149–173.

Taylor, J.C.M. and Colter, V.S., 1975. Zechstein of the English sector of the Southern North Sea Basin, *in* Woodland, A.W., ed., *Petroleum and the Continental Shelf of North-West Europe*. London, Applied Science Publishers, 1, 249–263.

Tucker, M., 1982. Storm-surge sandstones and the deposition of interbedded limestone: Late Precambrian, Southern Norway, in Einsele, G. and Seilacher, A., eds., *Cyclic and Event Stratification*: Berlin, Springer-Verlag, 363–370.

Walker, R.G., Duke, W.L. and Leckie, D.A., 1983. Hummocky stratification: significance of its variable bedding sequencies: discussion. *Bull. Geol. Soc. Am.*, 94, 1245–1249.

Ian D. Bryant,
Production Geology Research,
Koninklijke/Shell Exploratie en Produktie Laboratorium,
Postbus 60,
2280AB Rijswijk (ZH),
Nederland.

14A

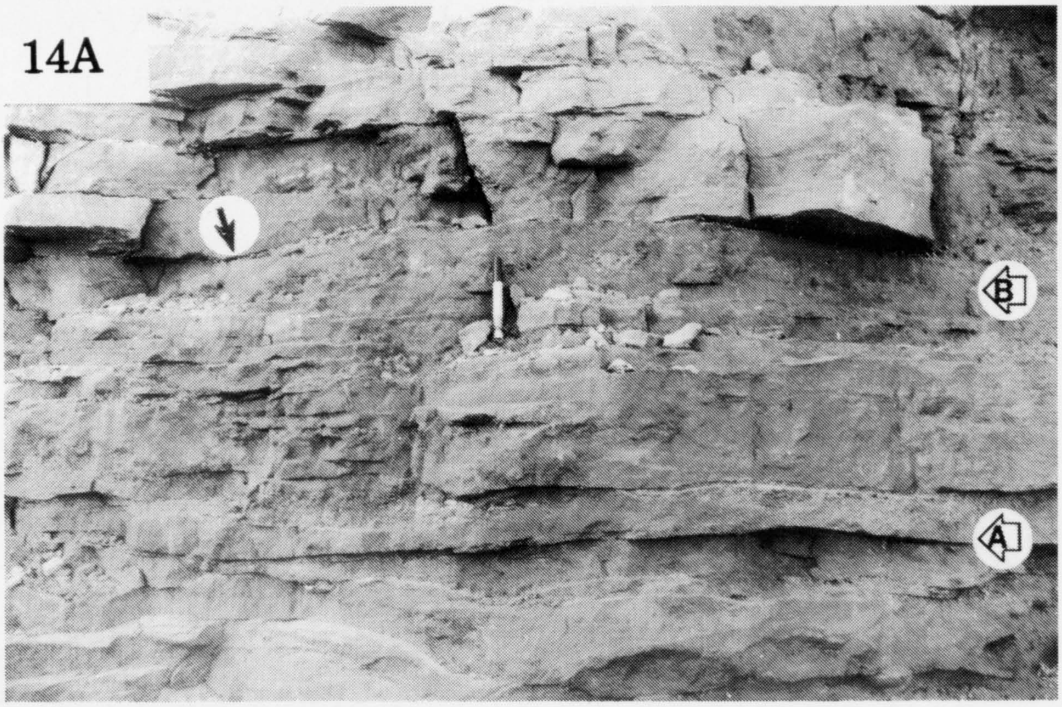


Plate 14A. Photograph of horizon B (Fig. 2) illustrating a well developed hummock at the level of the marker pen (length 145 mm). Note shell debris in the lower part of the hummock and reworking of material from the crest of the hummock into the swale (arrowed).

14B

14C

Plate 14B. Photogicrograph of an oriented thin section prepared from the junction between the basal (B) and parallel laminated (P) divisions of a hummocky cross-stratified unit. Note the dolomitised shell fragments (arrowed) within the dolomite-rich B division (lower half of photograph) and increase in the proportion of quartz present in the overlying P division. Plane polarised light.

Plate 14C. Photomicrograph of an oriented thin section prepared from the parallel laminated division (P) of a hummocky cross-stratified unit. Note the abundant siliciclastic grains, including a lithic fragment (L), some of which possess quartz overgrowths. Dolomitised pelloidal carbonate grains (G) are also discernable as 'ghost' textures.

A SEDIMENTARY BASIN EVOLUTION MODEL FOR ORE GENESIS IN THE SOUTH PENNINE OREFIELD

by

M.A. Mostaghel and T.D. Ford

Summary

The genesis of ore mineralisation in the South Pennine Orefield has been studied in the light of the sedimentological development of the Pennine and adjacent basins and a multi-stage genetic model is proposed in which three separate stages of ore precipitation are recognised:–

1. Base metal sulphides, especially framboidal pyrite, formed during the early diagenesis phase, sulphur being supplied by decomposition of organic matter and by sulphur-reducing bacteria, and metals by pore waters. The later mobilization of these sulphides could have provided rich sources of metal and sulphur for subsequent ore deposition.

2. During Permian and Triassic, the main stages of ore mineralisation in the orefield took place by episodic discharge of heated saline connate brines from deeply buried sediments near the centres of the adjacent basins. The ore fluids were generated by release of formation waters during compaction of sediments and clay dehydration of the shale units and had an outward and upward movement particularly from the North Sea basin to zones of lower pressure. The ore minerals precipitated behind a "front" of hydrocarbons over a temperature range of 50 to 150 °C. These temperatures were obtained by a combination of "normal burial" temperature and diagenetic exothermic reactions. Metals and sulphur were derived from more than one source.

3. During the uplift and weathering phase of the orefield secondary alteration minerals were formed and some early-formed minerals, especially galena and fluorite, were transported by groundwater circulatory system and re-deposited as residual sediments in caves.

Introduction

The South Pennine Orefield lies at the southern end of the north-south trending Pennine Hills in central England and consists of a plateau of about 90 km^2 of Lower Carboniferous (Dinantian) limestones, often bituminous, with dolomite, chert and inter-bedded basic igneous rocks. Although some 1600 metres of limestone have been penetrated by a deep borehole (Dunham, 1973), only the top 450 metres are exposed in the orefield and mining activity has been restricted to the top 300 metres of the limestone (Ford and Ineson, 1971). The ore mineralisation in the orefield consists of hundreds of fissure-fill veins (locally known as rakes and scrins) and stratiform ore bodies of void-filling or replacement character (known as pipes and flats) with galena, sphalerite and minor pyrite as the metallic minerals. More than 90 per cent of the ore bodies are made up of different proportions of calcite, fluorite and baryte as the principal ore minerals in the present-day exploitation of the orefield (Mostaghel, 1984). In contrast to the earlier periods of mining development, minor quantities of lead and zinc are raised only as by-products today. It has been estimated that between 3 and 4 million tons of lead concentrates and between ¼ and ½ million tons of zinc concentrates have been produced since mining began in the South Pennine Orefield during the Roman occupation of the British Isles (Ford and Rieuwerts, 1983).

Several authors (Mostaghel, 1984; Worley, 1978; Emblin, 1978; Ineson and Ford, 1982; Dunham, 1983) have given accounts of the evolution of ideas and hypotheses concerning the genesis of ore mineralisation in the South Pennine Orefield. These hypotheses range from a magmatic source for the ore fluids to a hydrothermal origin with igneous heat drive, a sabkha-type derivation, precipitation by downward percolation of Triassic ground waters, formation by up-dip movement of saline connate waters, and a sedimentary-diagenetic model of

Mercian Geologist, vol. 10, no. 3,
pp. 209–224, 5 figs.

origin. From a review of the proposed genetic models of ore deposition in the orefield, however, it is possible to deduce that:

(1) no direct evidence has been found of a genetic relationship between the ore mineralisation in the orefield and igneous activities, and advocates of the magmatic-hydrothermal theories can do no more than postulate the hypothetical existence of magmatic bodies beneath the orefield; and (2) in recent years, a number of authors have advocated, with some variations, a sedimentary-diagenetic model involving connate brines from the basins to the east and west of the orefield. Although the source of the brines which entered the orefield from the west is thought to be the Cheshire Basin (Ineson and Ford, 1982), there is some controversy on the possible source of the brines which penetrated the limestones of the orefield from the east. Ford (1976), for example, suggested the North Sea Basin as the possible source of these brines but Robinson and Ineson (1979) and Brown *et al*, (1980) pointed out that this proposal requires the brines to travel up-dip over a distance of at least 160 km with no significant heat loss. Alternatively, the basinal sediments in the Gainsborough, Edale and Widmerpool Gulfs were proposed as the possible source of the brines responsible for ore mineralisation in the eastern margin of the orefield (Robinson and Ineson, 1979). However, as noted by Ineson and Ford (1982), "the Somerton Borehole on the Norfolk coast ... encountered mineralised ground in the Carboniferous Limestone at a depth of over 1000 m", and this tentatively supports the proposal that the North Sea Basin could have been the source of brines derived from the east.

A Dinantian North Sea Basin is itself an unproven hypothetical concept and is a generalization of what may be a group of basins and swells, now deeply buried beneath thick Upper Carboniferous, Permian and Mesozoic sediments. The lack of deep drilling information on anything older than the Westphalian precludes anything more than this simplified concept, though the Westphalian (Coal Measures) undoubtedly accumulated in a wide basin in the southern North Sea.

The origin of the galena-sphalerite-fluorite-baryte-calcite deposits of the South Pennine Orefield is here proposed to be best explained by a multi-facet sedimentary-diagenetic model, which relates ore deposition in the orefield to the sedimentological development of the adjacent basins, together with a combination and modification of several genetic models, namely refluxing brines, original deposition of the host rocks and the metals, leaching and secretion of metals by upward moving brines, downward and horizontal movement of groundwater and a karstic model with secondary enrichment and transportation processes.

Evolution of sedimentary rocks and ore deposition

The historical evolution of any sedimentary rock can be divided into four distinctly different phases: (1) sedimentation (the sedimentary particles are transported to the basin or directly precipitated from seawater); (2) early diagenesis—unconsolidated sediments are either in direct contact with seawater or seawater can penetrate between the grains into the sediment; (3) late diagenesis (direct contact with seawater is lost but the sediments are saturated by formation waters): increased temperatures and chemical reactions (commonly collectively called "hydrothermal activity") between grains and formation waters are the prime factors in causing late diagenetic changes; and (4) uplift and weathering (strata are uplifted above sea level and are exposed to chemical and mechanical erosion). These phases could all simultaneously be in progress during the course of development of a sedimentary basin unless sedimentation is totally terminated, and often sedimentary basins show repetition of sedimentation-diagenesis-erosion cycles as the result of marine transgressions and regressions.

In Figs. 1, 2 and 5, the paragenetic relationships in the South Pennine Orefield are contrasted with corresponding phases of evolution of the enclosing host rocks.

Structural History

An interpretation of Bouguer gravity anomalies (Maroof, 1976) suggested that the Carboniferous sediments were deposited on a basement which has a graben structure in which the central block of the basement is down-thrown relative to the northern and southern blocks. By analogy with the basement beneath carbonate platforms elsewhere, Miller and Grayson (1982) have suggested that the Derbyshire Dinantian rests on a tilted fault block, with the downthrown side beneath the Staffordshire basin and a dip-slope falling eastwards beneath the limestone massif. This model has been supported by seismic studies (Rogers, 1983; McDonald, 1984), though refuted by Smith *et al.* (1985) on the basis of unspecified "confidential" geophysical evidence. Smith *et al.* have suggested a series of westward tilted blocks with a NW-SE trend crossing such Hercynian structures as the Longstone Edge monocline obliquely. Gutteridge's (1983) analysis of the sedimentary history and thickness variations of the later Brigantian beds in the Monyash-Lathkill area clearly supports the Miller & Grayson-

Rogers-McDonald interpretation. So little is known of the structure of the basement and its possible effects on later sedimentation and structures that it must be discounted in any study of mineralization for the present.

The predominant structural element of the orefield is the Derbyshire "Dome" which is an asymmetrical anticline with a flat culmination trending north-south near the western margin of the limestone outcrop. This anticline is really formed of the westward culmination of a series of easterly plunging folds within both the limestones and the younger rocks. Some folding developed during sedimentation of the Lower Carboniferous limestones as shown by the development of lagoonal and reef environments on the anticlines and shallow basinal environments in the synclines (Ford, 1977). The folds of the limestone have mainly E-W and NW-SE trends except in the extreme SW where folds trend N-S. Some folds and faults were active during Dinantian sedimentation, and may have relationships to basement faults. Compressional reverse faults are locally associated with east-west asymmetrical folding, whereas some normal faults may be related to post-folding relaxation (Worley, 1978; Butcher, 1976). Both compressional and relaxation faults appear to have been re-activated and extended during mineralization (Firman, 1977). Deeply buried NW-SE growth faults have been proposed by Smith *et al.* (1985) though without evidence.

Periodically during Dinantian times, volcanic activity resulted in the extrusion of vesicular basalt lava flows, tuffs and ashes, with a few associated vents and rare sills. These were folded along with the limestones during the Hercynian orogeny. The relatively impervious basaltic volcanic rocks locally controlled the disposition of individual mineral deposits. A further period of structural deformation affected the area in the Miocene when the Alpine Orogeny produced faulting and gentle folding in the region (Frost and Smart, 1979).

Sedimentation and Diagenesis

Phase I: Sedimentation

A deep borehole at Eyam in the eastern side of the orefield penetrated 48 metres of Ordovician (?Llanvirn) mudstones (Dunham, 1973; Strank, 1985; Aitkenhead et al. 1985). These Ordovician mudstones are the oldest known sediments in the area, and overlying them are more than 1.8 km of Dinantian sediments, mostly limestone but with a minor group of anhydrites, dolomites and shales at the base. Apart from the latter the limestones were deposited in an association of basin, lagoon and reef environments. The Dinantian tends to be thicker in the east of the exposed orefield than in the west because: (*a*) sedimentation started earlier in the east; and (*b*) the basement surface occurs at a greater depth in the east (Maroof, 1976; Rogers, 1983; McDonald, 1984). Sedimentation continued during Upper Carboniferous times and it is estimated that the orefield was covered by 1.3 to 2.3 km of Namurian (Millstone Grit) and Westphalian (Coal Measures) sediments (Worley, 1978). However the thickness of the Carboniferous sediments under the North Sea is probably greater and the Dinantian is more deeply buried (Ford, 1976). Although sedimentation was resumed after the Hercynian movements during Upper Permian and Triassic times with some deposition of carbonates and sandstones over the orefield, little is known of the thickness of these beds or of any later sedimentation during the rest of the Mesozoic era (Ford, 1977). A late Tertiary sheet of clays, sands and gravels covered the orefield and is now preserved only in karstic solution-collapse "pockets" in the Dinantian limestones. Walsh *et al.*, (1972) estimated that in Lower Pliocene times a stratigraphic sequence of approximately 53 metres of Mio-Pliocene sediments (Brassington Formation), a few metres of Namurian shales and an insoluble residue of chert gravel lay horizontally on top of the Dinantian limestones and then sagged into solution cavities (Walsh *et al.*, 1972; Ford, 1972). The Pleistocene period has also seen the deposition of screes, sands, gravel, loess and boulder clays over parts of the orefield.

At least four major periods of hiatus occurred in sedimentation: (1) if any sediments were deposited during Silurian times they were removed by erosion before the Dinantian; (2) toward the end of the Dinantian period, some erosion took place especially on the northern, western and southern margins of the present orefield before the Upper Carboniferous seas and deltas covered the area; (3) a period of erosion during Lower Permian times resulted in removal of much of the Upper Carboniferous cover; and (4) the Permian dolomites and Triassic sandstones were removed from the orefield by erosion during the early Tertiary period.

As noted by Kent (1966), both the Millstone Grit and Coal Measure sediments, and probably the Lower Carboniferous limestones, thicken into the Central (=Pennine) Basin which probably resulted in eastward migration of fluids out of the Pennine Basin towards the North Sea Basin during later Carboniferous times. However, the structural upwarping of the South Pennines by the Hercynian Orogeny "inverted" the basin and reversed this migration so that since the end of the Carboniferous the potential fluid migration path has been westwards out of the North Sea basin (Ineson and Ford, 1982) and its subsidiary Edale, Gainsborough and Widmerpool "Gulfs". Expulsion of metal-enriched saline formation waters during compaction has also been proposed as a source for ore fluids by Smith *et al.*, (1985).

Phase II: early diagenesis

Early diagenetic changes occur from the sediment-sea-water interface to a depth of a few hundred metres (Berner, 1980). The more important changes include formation of framboidal pyrite, lithological changes and bacterial decomposition of organic matter.

Experimental studies and field observations (Sweeney and Kaplan, 1973; Farrand, 1970; Love, 1967; Park, 1967) show that microscopic metal sulphides, and especially framboidal pyrite, can form during early diagenesis even before compaction at the sediment-water interface, as the result of precipitation of metals in pore waters by sulphur supplied by decomposition of organic matter possibly by sulphur-reducing bacteria. The organic compounds in recent sediments play a key role in the formation and preservation of framboids in sedimentary environments (Farrand, 1970). Therefore the formation of framboids and small grains of pyrite should be considered the first stage of sulphide deposition in sedimentary rocks.

One of the important diagenetic changes of the calcareous sediments in the orefield is the formation of bedded chert and chert nodules in the Dinantian limestones. Chert formation is thought to be the result of siliceous organic activity (Wise and Weaver, 1974) and in the orefield it formed during the earlier phases of diagenetic evolution (Orme and Ford, 1970). Another important lithological change of the sediments deposited in the orefield is the transformation of unstable aragonitic mud and fossils into stable calcite during early diagenesis which is accompanied by partial expuslion of base metals (Ferguson *et al.*, 1975) and barium and fluorine from aragonite (Worley and Ford, 1977). Dolomitisation of the calcite mud is also accompanied by expulsion of metallic elements into formation waters and results in loss of volume and development of secondary porosity in limestones which may provide a favourable environment for precipitation of ore minerals.

Towards the end of the early diagenesis phase, sediments start to lose both their free formation waters and some absorbed waters (Wolf and Chilingarian, 1976) as the result of reduction in initial porosity of sediments due to compaction. Movement of the formation waters results in reactions which may cause precipitation of cementing materials between grains. These reactions involve dissolution, replacement and recrystallisation processes. It should be noted that, although the direction of compactive pore water movement during the early diagenetic phase is mainly vertical, as the depth of burial increases it may also have a lateral component to where permeability is higher (Berner, 1980).

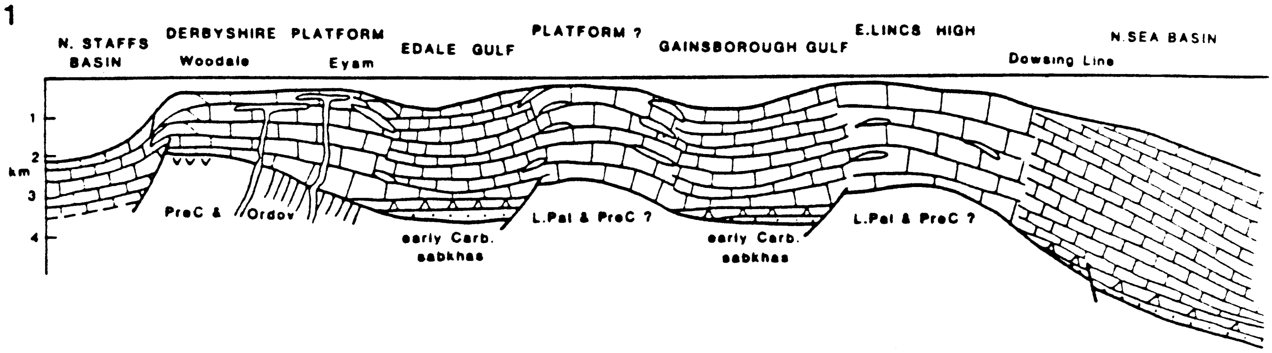
The most important diagenetic addition to the sediments deposited in the orefield was the formation and accumulation of hydrocarbons in these sediments, especially in the limestones (Pering, 1973). Many oil "shows" have been encountered in the colliery workings in the areas surrounding the orefield (Frost and Smart, 1979), and oil and gas have been discovered in commercial quantities in both Upper Carboniferous sediments and near the top of the Dinantian limestones (Smith *et al.*, 1967). The hydrocarbons are mostly present in the orefield in the form of asphalts, bitumen, pitch, or thick, heavy and unconsolidated oil. These hydrocarbons are sometimes localised in the limestones but often they are disseminated through the pore spaces of the carbonate rocks either in the matrix or as bonding material (Pering, 1973). Although the decomposition of organic matter results in formation of low-molecular-weight hydrocarbons during the early diagenesis phase, the transformation and thermal maturation of these hydrocarbons into polyhydrocarbons (petroleum) takes place during the late diagenesis phase (Hitchon, 1977; Bailey, 1977).

Phase III: late diagenesis

The late diagenesis phase is characterised by the slow compaction and maturation of sediments that results from overburden and hydrostatic pressures. It begins at a depth of a few hundred metres and continues to where sediments become completely lithified. Compaction results in concomitant expulsion of connate formation waters and will cease only when the sedimentary rocks are able to support the weight of the overlying sediments, and withstand hydrostatic pressures by their internal stability. Increase in depth of burial after this point results in initiation of metamorphism due to higher burial temperatures. After lithification, significant reduction in volume of these rocks may occur as the result of stylolitisation in consolidated carbonate rocks.

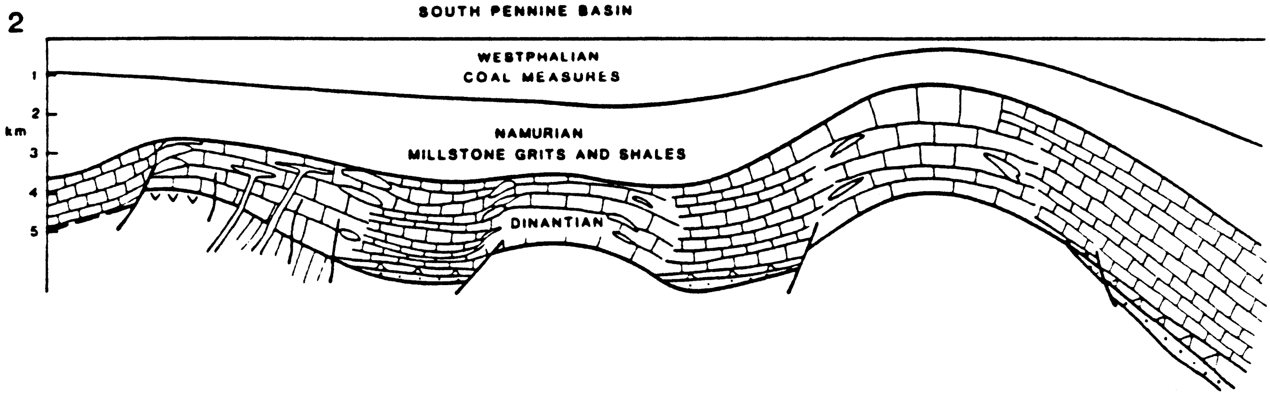
Due to differential depth of burial the compaction forces nearer the centre of sedimentary basins are greater than those nearer the margins and formation water expelled from the sediments is thought to move generally both upward and outward to zones of lower pressure (Ohle, 1959) carrying with it droplets of oil and gas (Beckmann, 1976). During this movement, which may cover hundreds of kilometres (Beckmann, 1976), formation water can become enriched in metals and other ingredients essential for ore mineralisation. In order to derive these ingredients from consolidated sedimentary rocks, Noble (1963) concluded that the fluids must be able to penetrate the rocks, be sufficiently reactive to leach metals and be able to move out of the leached rocks. During the late diagenesis phase formation (connate) water is already in the sedimentary units, in a position to leach individual particles, and is expelled as a natural consequence of compaction. Pre-compaction leaching of sedimentary units is probable because the chloride, sulphate and carbonate characters of the connate waters make them solvents for the ingredients needed in ore mineralisation. Thus, connate waters can be regarded as ore-forming fluids during the compaction of sediments.

1



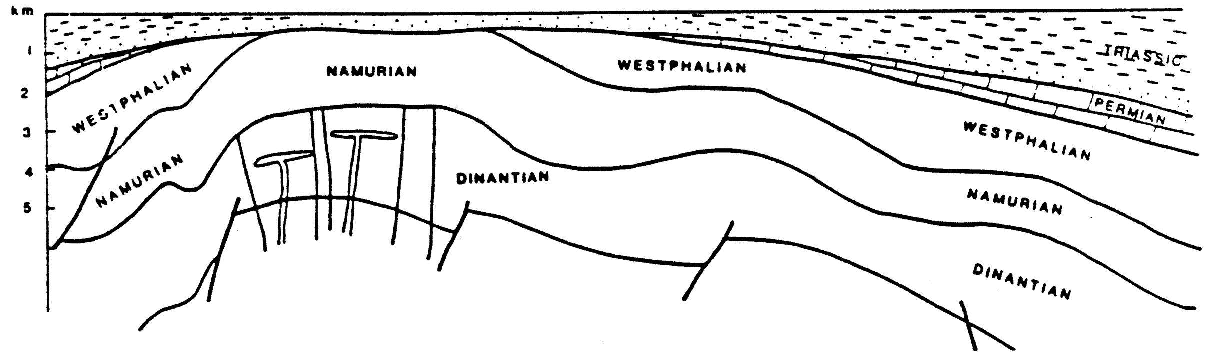
1. LOWER CARBONIFEROUS-SEDIMENTATION PHASE: deposition of a thick sequence of Dinantian limestones with anhydrite beds at the base developed particularly in "gulfs" between positive "highs"; formation of chert and dolomite in buried limestones; initiation of folds and faults bounding highs; episodic changes of sea level with alternating marine transgressions and regressions resulting in contrasting lithofacies of massive limestones on highs, marginal reefs, and shaly thin limestones in gulfs. Local eruption of lavas and tuffs within limestone sequence.

2



2. LATE CARBONIFEROUS-EARLY DIAGENESIS PHASE: deposition of a cover of thick Namurian Millstone Grit deltaic sandstones and shales followed by Westphalian Coal Measures swamp sediments. Thicknesses of clastic cover greatest in South Pennine and southern North Sea Basins. Early diagenesis in limestones yields framboidal pyrite and possibly other sulphides, particularly well-developed in basinal facies of gulfs. Petroleum formation is initiated and migration towards highs begins with loss of sediment formation waters. Volume reduction in sediments.

3



3. PERMO-TRIASSIC-LATE DIAGENESIS PHASE: partial removal of part of Westphalian and Namurian cover during structural inversion yielding South Pennine anticline, followed by dolomitic and clastic sedimentation in upper Permian and Triassic times. Hydrocarbons matured; movement of hydrocarbons and connate/formation waters to low pressure zones. Separation of hydrocarbons and connate waters towards basin margin where they are trapped beneath remaining Namurian cover. A front of liquid hydrocarbons is followed by ore-fluids depositing minerals in fracture systems and other voids; hydraulic fracturing re-opens wrench faults giving vein deposits; local fluoritization of host limestones; further volume reduction and compaction of sediments.

Fig. 1. Stages 1, 2 and 3 in the geological evolution of the South Pennine Orefield (see also Fig. 5, p. 220).

Maturation and accumulation of hydrocarbons

Hydrocarbons continue to form and mature during the late diagenesis phase. The maturation of hydrocarbons is largely a temperature-dependent phenomenon which occurs within a "liquid window" between the approximate temperatures of 60 to 150°C (Bailey, 1977; Macqueen and Thompson, 1978; Pudsey, 1973). During the primary migration (movement of fluids and hydrocarbons from a source sediment to a reservoir rock owing to compaction), hydrocarbons have similar outward and upward flow patterns to those of connate waters (Hunt, 1979). Price (1976) has shown that hydrocarbons and connate waters can exist, initially, as a single phase at high temperatures, but on raising the salinity, or decreasing the temperature, hydrocarbons will exsolve from solution. The ability of hydrocarbons to migrate also increases as increasing temperatures convert solids to liquids and liquids to gases (Hunt, 1979). Therefore, as the connate waters increase their salinity, and decrease in temperature on upward and outward migration, hydrocarbons, maturing at different depths in the sedimentary succession, would be separated, collected and, because petroleum is lighter than connate waters, pooled in front of the advancing connate brines. Hydrocarbons move in response to compactional and hydrostatic pressures supplied by connate brines. Eventually, the upward movements of these pools are stopped by stratigraphical and/or structural traps and oil and gas reservoirs accumulate within reservoir rocks (secondary migration; Hunt, 1979).

In the South Pennine Orefield the advancing hydrocarbons and connate brines were stopped by Edale Shales overlying the Dinantian limestones. Eventually, most of the hydrocarbons either moved upward along faults and fractures of the overlying rocks until they reached the surface and became oxidised, or, as the cover of the limestones was removed by erosion, they were exposed to oxidation and escaped into the atmosphere. Some of the hydrocarbons were trapped in both limestones and the overlying Upper Carboniferous sandstones where they formed small oil and gas reservoirs. The heavy fraction of the hydrocarbons formed bitumen deposits in the pores and cavities of the limestones especially below the Dinantian-Namurian boundary. The thermal alteration and oxidation of hydrocarbons also resulted in formation of scattered black bitumens in the orefield, especially within some ore deposits. The hydrocarbons in fluorites from the orefield are very similar in composition to those of hydrocarbons in the Edale Shales and the Dinantian limestones. This is consistent with mixing of the hydrocarbons from both sedimentary units, prior to crystallization of fluorite (Pering, 1973). Thus, both Dinantian limestones and the Upper Carboniferous Edale Shales were probable source rocks for hydrocarbon generation in the region including the orefield (Pering, 1973; Nooner *et al.*, 1973). Whilst it is difficult at first sight to see how the Edale Shales could form a cap-rock in the South Pennines and at the same time be the source rock, the same shale formation can do both if it is much more deeply buried and thus more matured in the basins to the east. Also, if stratigraphic "inversion" is taken into account, it may be that there has been a "two-pass" situation with the Edale Shales in the Pennine Basin being a source rock during later Carboniferous times, whilst their equivalents in the North Sea became the source rock in post-Carboniferous times. If the Dinantian lithofacies are more argillaceous in the deeper basins in contrast to the Derbyshire massif (as yet unproven by deep borings) then a single-pass contribution to hydrocarbon and ore-rich fluids could have occurred in post-Carboniferous times as a result of the Hercynian pressures.

As matured liquid hydrocarbons moved to low pressure zones at basin margins (i.e. the South Pennine Orefield) in front of the advancing connate brines, they were able to supply sulphur species for ore mineralisation. Pering (1973) found that "elaterite", a bitumen complex present in joints and fissures of the Dinantian limestones, contains 0.47 percent elemental sulphur. The black and brown bitumens from the Windy Knoll bitumen deposit in the north of the orefield also contain 1.01 and 1.64 percent sulphur, respectively (Pering, 1973). Additional elemental sulphur, produced by bacteria, could also have been generated in significant quantities in the Carboniferous sediments. Since hydrocarbons reached the orefield before the connate brines, they could have been retained within the sediments. Sulphur liberated from these hydrocarbons as H_2S would have enabled sulphide and sulphate minerals to precipitate from the metalliferous connate brines as these followed the same path taken by the earlier hydrocarbons. Being covered by thick shales, the carbonate rocks have the potential to trap both hydrocarbons and H_2S and this is considered to be a major factor controlling precipitation of sulphide minerals in carbonate environments (Beales and Jackson, 1968).

Depth of burial and palaeotemperature

The limestones of the orefield were covered by between 1.3 to 2.4 km of Namurian and Westphalian sediments prior to erosion during Lower Permian. The present thickness of the Dinantian sediments at Eyam on the eastern margin of the orefield is about 1.8 km (Dunham, 1973) and therefore, before Permian erosion, the lower beds of the Dinantian in the eastern side of the orefield were buried by up to 4.2 km of Carboniferous sediments, and later had about 1 km each of Permian and Triassic covers, so that by the end of Triassic times there could have been 6 km of cover on the Dinantian. These estimates are mostly based on the thicknesses of the

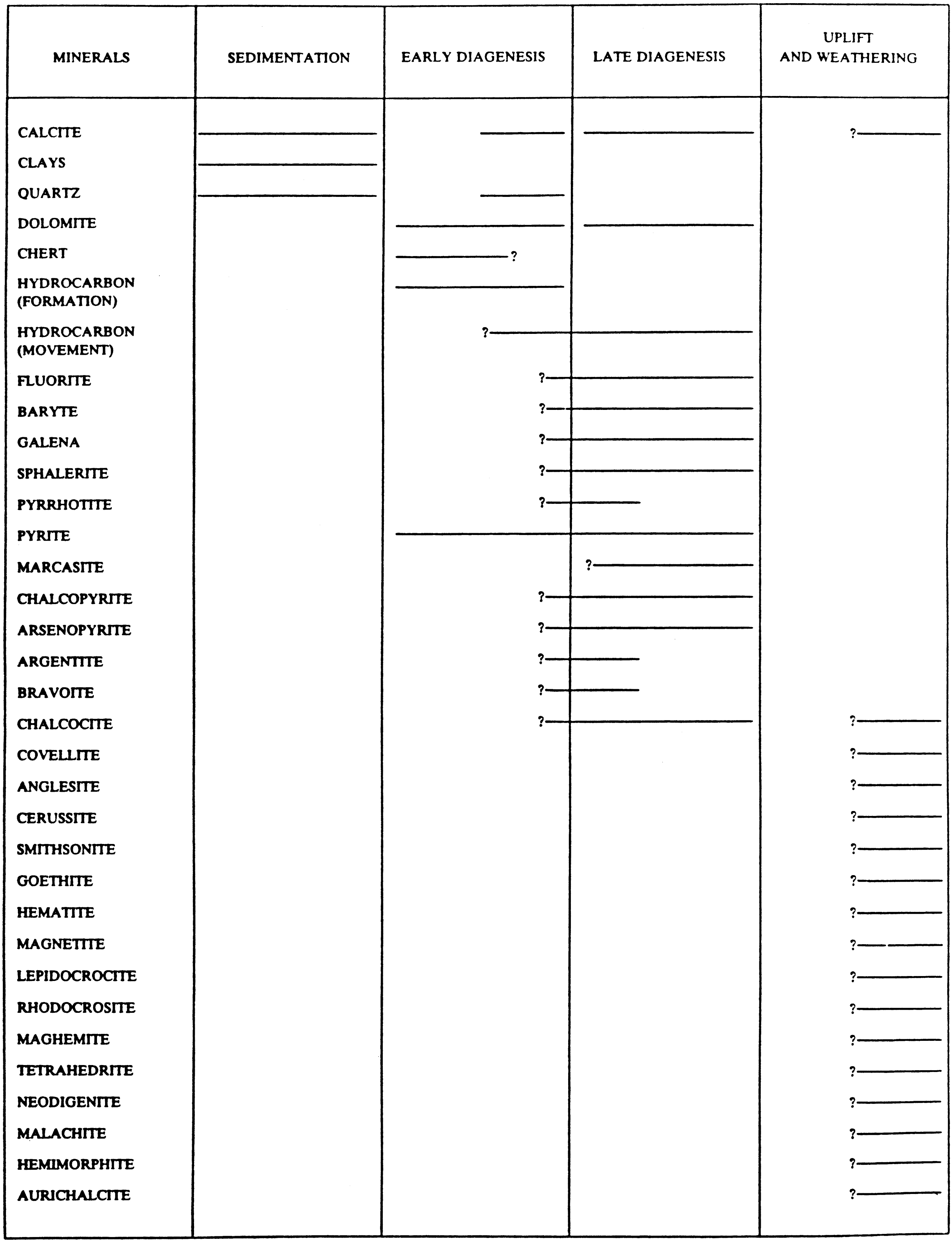


Fig. 2. Paragenesis of minerals, and hydrocarbon accumulation, in the South Pennine Orefield, as a function of evolution of the enclosing Lower Carboniferous strata.

lithified sedimentary units and should be adjusted to allow for the compaction and late diagenetic changes which occurred in all these units. These are loss of pore waters, dehydration of clay minerals as the result of progressive conversion of illite-poor mixed-layer illite/smectites to illite-rich mixed-layer illite/smectites, dissolution, cementation, dolomitisation and stylolitisation (Mostaghel, 1984).

Of these changes, stylolitisation is perhaps the most important one and can acount for as much as 50 percent reduction in volume of carbonate rocks (Glover, 1968). The carbonate rocks of the orefield contain numerous stylolites and microstylolites and the clay wayboards in the Carboniferous sediments are very rich in illite with 10 to 30 percent smectite (Walkden, 1972). If all the compaction and diagenetic changes produced a 25 percent loss of volume in the sedimentary column, then the depth of burial at the end of Carboniferous of the base of the Dinantian would be greater than 5 km in the eastern side of the orefield and considerably more in the North Sea.

Geothermal gradients of 7.3 °C/100 m in the uppermost least compacted sediments and 1.8 to 3.5 °C/100 m in the deeper buried sediments have been reported in the northern North Sea Basin (Cooper et al, 1975). A geothermal gradient of 2.5 °C/100 m for the whole sedimentary succession in the late Palaeozoic—early Mesozoic period would have resulted in connate waters, originating in or migrating from the Dinantian limestones under the North Sea having temperatures of more than 150 °C assuming a 6 km cover by the end of Triassic. These connate waters, moving upward and outward from the centre toward the basin margins, could have maintained a higher temperature than the host rocks at the sites of ore deposition in the orefield, if the rates of heat exchange to the walls of the migration paths were low. Also, additional heat may have been added by diagenetic chemical reactions governed by the first part of the Van't Hoff Law (Fairbridge, 1967), long-lived isotopes (Brown *et al.*, 1980), and exothermic biogeologic reactions involving bacteria and algae. Therefore, the formation temperatures of the ore minerals, estimated to range between less than 50 up to 150 °C (Mostaghel, 1984; Rogers, 1977; Smith, 1973; Atkinson, 1983; Atkinson et al, 1982) could have been achieved by a combination of "normal burial" temperatures and diagenetic, exothermic reactions.

Ore mineralisation

The model favoured by the authors is that during migration connate waters become enriched in salts as well as Pb, Zn, F and Ba. These essential ingredients of ore mineralisation became available as the result of leaching of different lithological units. The fluids were generated by expulsion of formation waters during compaction of sediments and clay dehydration of the shale units in the succession. The dominant salt components in the ore fluids were calcium and sodium chlorides (Atkinson, 1983). As the ore fluids reached the orefield, the ore minerals precipitated behind the preceding front of liquid hydrocarbons. The main controls of ore minerals are difficult to establish due to the episodic nature of ore mineralisation were structural, stratigraphical and lithological (Firman and Bagshaw, 1974). Faults, fractures, joints and stylolite seams provided channelways for migration of ore fluids. The effectiveness of the Upper Carboniferous Edale Shales, which overlie the Dinantian limestones as a cap-rock, has resulted in concentration of the ore minerals in the limestones and dolomites though not always in the highest carbonate beds. Although the precise paragenetic sequences of the ore mineralisation in the orefield and large local variations, the generalised regional paragenetic sequences indicate the following phases of ore deposition: early calcite-baryte-fluorite followed by the main phase of galena-sphalerite-iron and copper sulphide mineralisation followed by late calcite-baryte-fluorite precipitation (Mostaghel, 1984).

The ore fluids penetrated the orefield from two directions; one from the east, i.e. from the North Sea Basin, which was responsible for major and prolonged episodes of fluorite-baryte-calcite-galena-sphalerite mineralisation in the eastern and central parts of the orefield. Other fluids entered the orefield from the west and were responsible for localised mineralisation of lead, zinc and copper sulphide ore bodies in the western part of the orefield. These fluids are thought to have come from the Cheshire-Irish Sea Basin. In terms of metal concentration, copper was the dominant component in the fluids from the Cheshire-Irish Sea Basin whereas lead had a far greater concentration than the other metals in the fluids from the North Sea Basin. The ore fluids may have been responsible for reopening, by hydraulic fracturing, of pre-existing primary and secondary wrench faults (Firman, 1977). The precipitation of ore minerals from these fluids in faults and fractures resulted in formation of the rakes and scrins which form a substantial part of the ore mineralisation in the South Pennine Orefield. It is generally believed that chloride complexes are the most important transporting agents for metals under the conditions of formation of the ore deposits in the South Pennine Orefield (Anderson, 1975).

The ore mineralisation in the South Pennine Orefield was not the result of a single "surge" of ore fluids but the result of at least a partial two-pass migration system resulting in several separate episodic pulses of ore-forming solutions (Ineson and Al-Kufaishi, 1970; Ineson and Mitchell, 1973). The episodic expulsion of fluids may account for some mineral banding and, since episodic dewatering would be accompanied by a higher flow rate, variable and higher temperature of ore fluids in near-surface sites of ore deposition.

Source of metals

Although no systematic study has been made of metal concentration in the Carboniferous rocks, Monteleone (1973) found between 5 to 6560 ppm Ba and up to 1205 ppm Pb and 416 ppm Zn in 56 Carboniferous limestones from Leicestershire. Burek and Cubitt (1979) reported mean values of 15 ppm Pb and 209 ppm Zn in 15 dolomitic limestones and 31 ppm Pb and 16 ppm Zn in 15 limestone samples.

Harrison and Adlam (1985) summarized many hundreds of analyses as a mean Pb content of 17 ppm, range 0 to 2000, in non-dolomitized limestones, and a maximum of 10100 ppm in dolomitized beds, and a mean Zn content of 40 ppm, range 0–1750 ppm, in non-dolomitized beds, maximum 3800 in dolomitized beds. Values were highly variable between stratigraphic units and lithofacies with no clear pattern: the very high values in dolomites may reflect local dispersed ore deposits. In any case the values should not be taken to represent original concentrations of metals in the sediments owing to diagenetic redistribution.

By using a figure of 4 km for the average thickness of the Carboniferous sediments in the orefield and the western part of the North Sea, the volume of these sediments in an area 40 km long (the length of the orefield) and 300 km wide (from the centre of the orefield to the North Sea Basin in the east) is equal to $48\times10^3\,km^3$. By using an average density of 2.5 for all the rock types, the mass of these sediments in this area is 12×10^{13} metric tons. If this mass contains 10 ppm combined Pb and Zn, 12×10^8 metric tons of metal are present. If only 10 percent of the metals present in this mass was leached by connate waters, 12×10^7 metric tons of metal could be available for transportation to the sites of ore deposition. If 10 percent of this metal in solution actually precipitated, then 12×10^6 metric tons of metals (not sulphides) would have been formed in the orefield. The values used in these calculations are conservative and probably underestimates but they are realistic; thus the calculated tonnage of precipitated metals is almost 3 times the maximum estimated tonnage of extracted lead and zinc concentrates from the orefield.

Volcanic activities during the Carboniferous could also have enriched the metal concentration of the Carboniferous sea and the alteration of the igneous rocks in the orefield probably resulted in the release of some metals. Another possible source of metals is from the numerous tuff horizons deposited between the limestone beds (Walkden, 1972). Ineson (1970) reported a tuff horizon in Ladywash Mine containing on average 175 ppm Pb and 2500 ppm Zn.

Sources of sulphur

Sulphur isotope studies have shown that sulphur in galena, sphalerite and baryte was derived from more than one source (Coomer and Ford, 1975; Robinson and Ineson, 1979). Galenas from the South Pennine Orefield have sulphur isotope composition of −23.2 to 6.6‰ whereas the analysed sphalerite and baryte samples show a spread of −16.0 to 9.5‰ and 4.4 to 2.6‰, respectively. The observed sulphur isotope spread in the galenas is interpreted to be the result of mixing of biogenic H_2S (low sulphur isotope values) with H_2S derived from the reduction of sulphate (Robinson and Ineson, 1979). The sulphur isotope composition of baryte is also consistent with partial mixing of fresh-water sulphate and connate sea-water sulphate (Robinson and Ineson, 1979).

Anderson (1975) concluded that mixing of metal-ion solutions with reduced-sulphur species, supplied at the sites of ore deposition, caused the precipitation of sulphide ore assemblages. Reduced sulphur could be supplied by inorganic or bacterial reduction of sulphate, thermal degradation of hydrocarbons, and replacement of pre-existing sulphides (Anderson, 1975). In the South Pennine Orefield different generations of reduced sulphur were formed at shallow depths in the orefield and at greater depths in the North Sea which later moved to the orefield with migrating hydrocarbons. Additional sources of sulphur could have included localised sulphur and sulphate deposited with the sediments and biogenic production of sulphur in limestones during hydrocarbon generation. Mixing of sulphur from different sources, which have different isotopic ranges, with some isotopic disequilibrium and secondary exchanges can best explain the heterogeneity of the sulphur isotope compositions of the minerals in the orefield.

Smith *et al.*, (1985) have revived Llewellyn and Stabbins' (1968) hypothesis of a sulphate source in evaporitic beds in sabkha facies at the base of the Dinantian sequence particularly in the down-faulted troughs of the tilted fault-blocks. However, as the Eyam borehole (Dunham, 1973) shows that the anhydrite beds are still in place it is difficult to see how they could have been the source. If early Dinantian evaporites in the deeper and more highly matured basins to the east are postulated the problem may be resolved, but there is no direct evidence as yet.

Volume of ore fluids

Atkinson (1983) calculated that for an estimated 20 million tons of fluorite which formed in the orefield 17.38×10^3 km^3 of fluids containing 1 ppm CaF_2 are required. If the calculated volume of Carboniferous sediments in the orefield and the western part of the North Sea basin (48×10^3 km^3) contained, on average, 10 percent formation waters, then only 4.8×10^3 km^3 of fluids would have been released. The discrepancy between these two calculations becomes smaller if it can be shown that: (*a*) the calculated volume of sediments was greater than 48×10^3 km^3; (*b*) the volume of formation waters released from these sediments was greater than 10 percent; or, more likely, (*c*) the concentration of base metals, barium and fluorine in these fluids was greater than 1 ppm. If the fluids contained 10 ppm Pb, Zn, Ba and F then less than 2×10^3 km^3 of fluids are required to form the ore deposits in the orefield. In the sedimentary basin evolution model for carbonate-hosted lead-zinc deposits, unlike convecting heated brine models postulated for ore deposits such as volcanogenic massive sulphides, the ores are formed by fluids in a "one-pass" situation (Anderson, 1978). Therefore, since the ore-forming fluids have limited reservoirs (i.e. the basinal formation waters), they must have higher concentration of metals and be able to precipitate their minerals effectively when passing through a depositional site.

Causes of mineral deposition

The major causes of precipitation of galena and sphalerite in the orefield were fluid mixing and dilution (as deduced from the heterogeneity of the sulphur isotope compositions of sulphide minerals), decrease in temperature (due to upward movement of the ore-forming fluids from the deeper areas of the basin to the positive structures on the margins), and increase in reduced sulphur (supplied in the orefield by hydrocarbons, trapped H_2S in limestones, and in situ reduced sulphur and sulphate). The causes of fluorite precipitation and localisation may have included: (*a*) decrease in temperature in the flow direction; (*b*) availability of both calcium and fluorine ions; and (*c*) suitable depositional environments. However, the distribution and precipitation of baryte in the orefield was very much dependent on the availability of *in situ* sulphate-rich fluids (Firman and Bagshaw, 1974). The irregular distribution of calcite in the orefield (Mostaghel, 1983) may have been the result of precipitation of this mineral from fluids which were super-saturated with respect to calcium carbonate introduced by dissolution of the limestone host rocks.

Some general observations regarding the conditions of ore precipitation in the orefield can be made by calculating the thermodynamic behaviour of standard reactions between specific pairs of minerals (cf. Vaughan and Ixer, 1980).

A promising method is sphalerite geobarometry wherein the mole percent concentration of iron in sphalerite as seen in pressure/composition phase diagrams of minerals forming in the Fe-Zn-S system can be used to estimate the formation pressure of sphalerite but this is dependent on the sphalerite being demonstrably in equilibrium with pyrite and pyrrhotite.

It is, however, possible to define the limits of the physical conditions by using the presence or absence of certain mineral species in the orefield, as well as thermochemical data of different Fe minerals and the iron content of sphalerite from the orefield (Figs. 3 and 4).

Using these criteria, the shaded areas indicate the theoretical conditions under which sphalerite precipitated in the South Pennine Orefield. Figs. 3 and 4, based on Vaughan and Craig (1978) and Vaughan and Ixer (1980), can also be used to deduce the optimum chemical conditions at different temperatures; in particular, taking points in the centres of the shaded areas the sulphur and oxygen activities at 100 °C, during ore precipitation in the orefield, are estimated to be $10^{-22.7}$ atm and 10^{-58} atm respectively. For a temperature of 150 °C, the activities are somewhat higher: aS_2 is 10^{-19} atm and $a0_2$ is 10^{-50} atm. Fluid inclusion studies on gangue minerals (Rogers, 1977, Atkinson, 1983) suggest that most of the sulphides in the orefield precipitated between 100 and 150 °C and thus these calculations were performed only for this temperature range. The activity of CO_2 is estimated to be 10^{-3} atm at 100 °C and $10^{-1.5}$ atm at 150 °C (Fig. 4). These conditions are comparable with those in the North Pennine orefield (Vaughan and Ixer, 1980, Fig. 4).

Whilst these calculations place constraints on the conditions at the time of sphalerite precipitation, much more work is needed before the conditions of precipitation of other minerals can be similarly constrained.

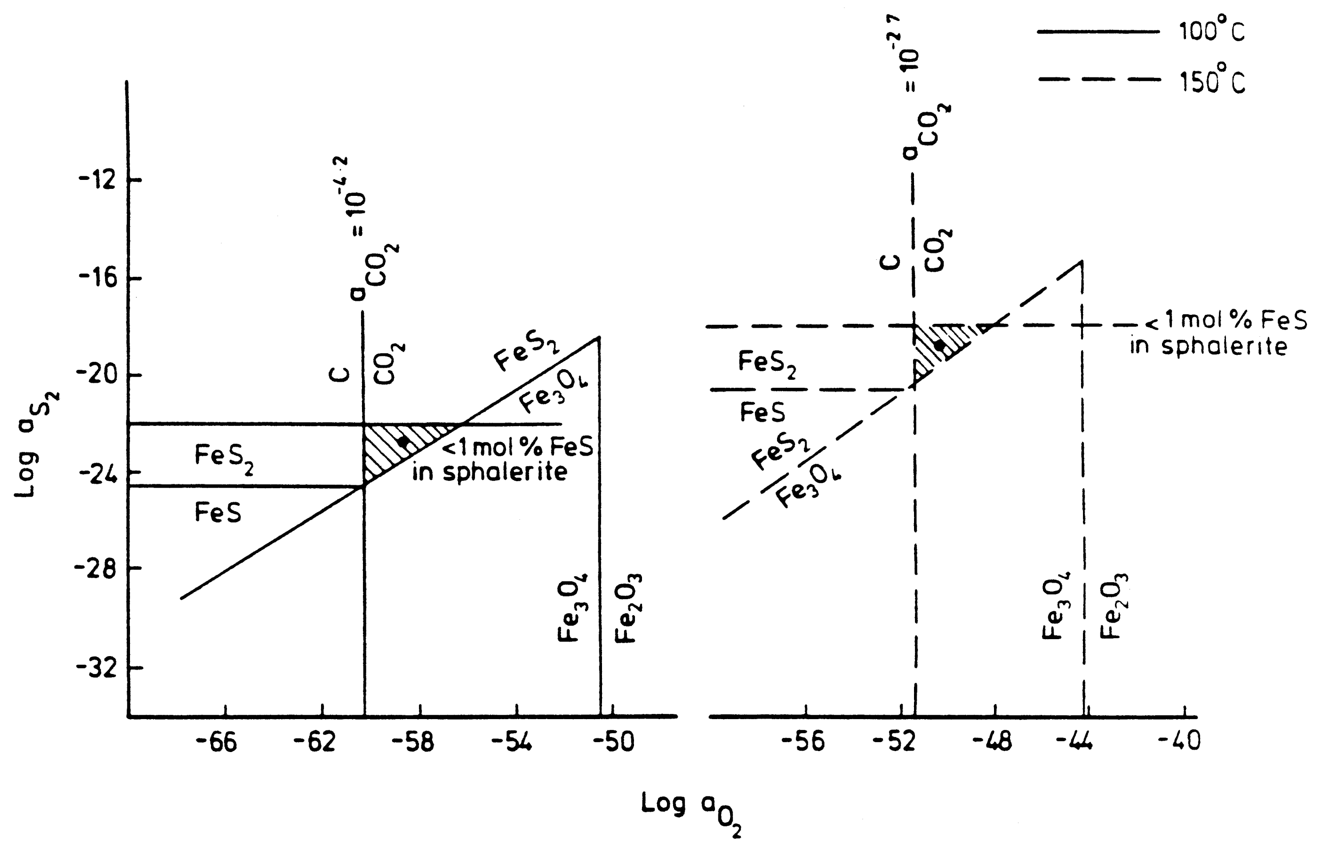


Fig. 3. Plots of Log a_{S_2}–Log a_{O_2} for the South Pennine ore assemblages at 100 and 150 °C (based on Vaughan and Craig, 1978, fig. 10.10). The shaded area constrains the conditions of precipitation of sphalerite in the South Pennines.

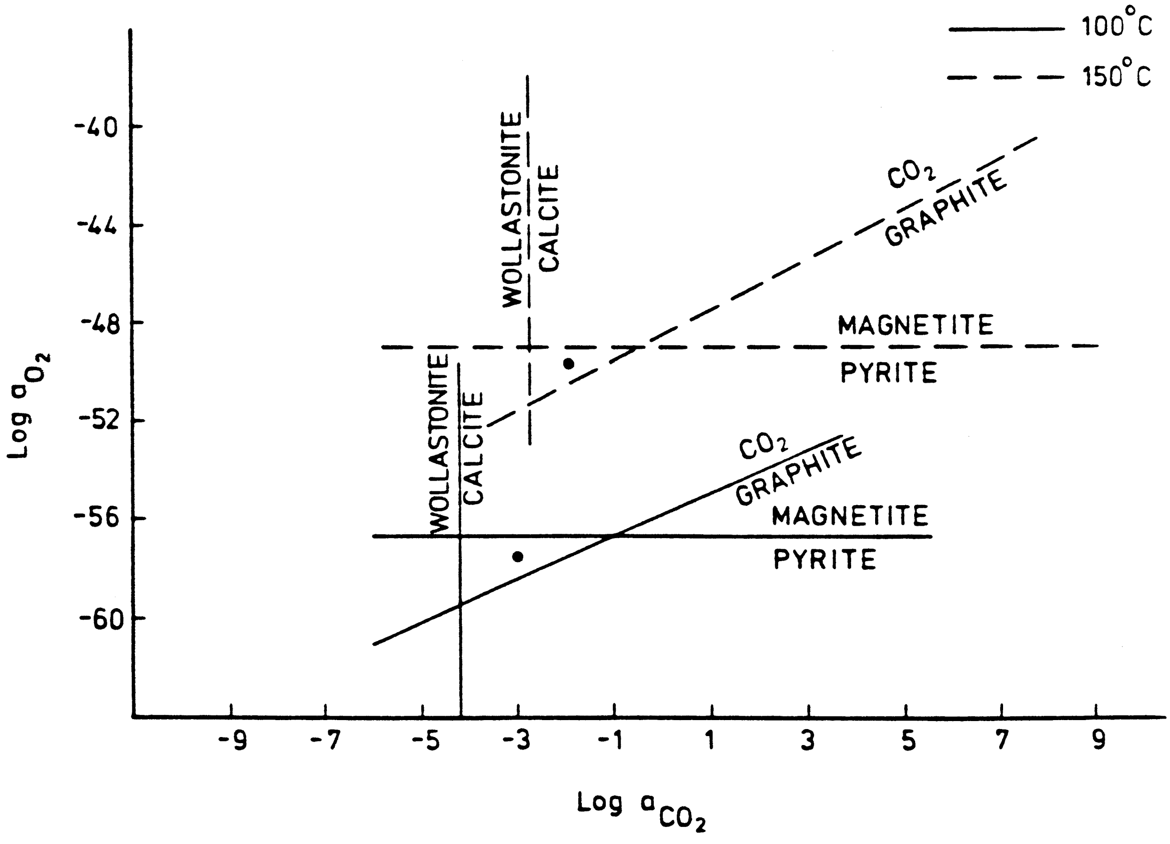


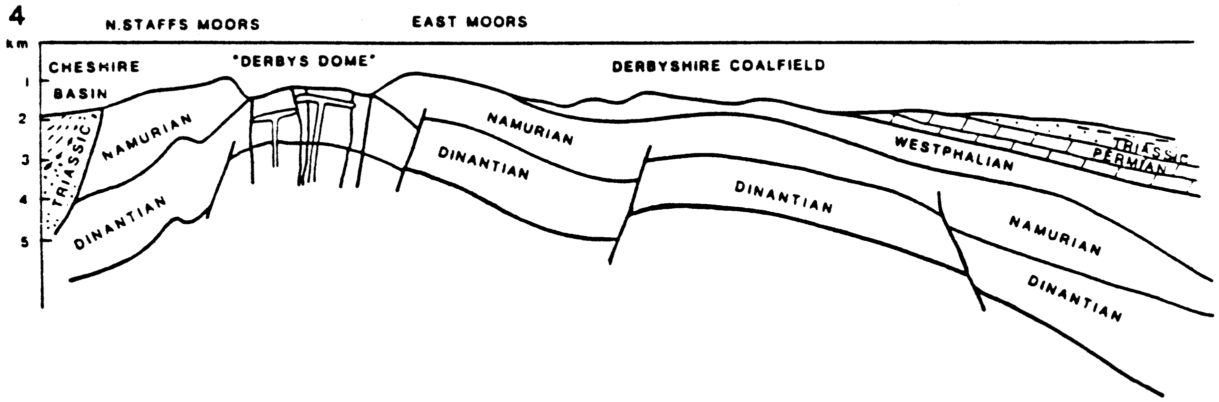
Fig. 4. Plots of Log a_{O_2}–Log a_{CO_2} for the South Pennine ore assemblages at 100 and 150 °C (based on Vaughan and Craig, 1978, fig. 10.10). The triangles with black spots indicate the conditions of precipitation of calcite and pyrite in the South Pennines.

Timing of ore mineralisation

A study of lead isotope ratios in galenas from the orefield has shown that the lead in these galenas is anomalous J-type and gives negative ages (Coomer and Ford, 1975). Isotope studies of metasomatised Carboniferous volcanic rocks have indicated that primary ore mineralisation (hydrothermal alteration of the basalts in the orefield) started at 290 million years before present in association with the Hercynian Orogeny and was followed by subsequent hydrothermal events at 280–265, 225, 170 and 130 m.y. before present (Fitch *et al.*, 1970). Ineson and Mitchell (1973) reported K-Ar dating of 34 samples of clay minerals, formed as the result of alteration of wall rock by mineralising fluids. The results showed ages from about 280 to 180 m.y. before present with major activities in early and late Permian and continuing activity to late Triassic. Therefore, it seems the ore mineralisation in the orefield started shortly after the Hercynian tectonic movements structurally "inverted" the orefield and continued intermittently into late Triassic times.

Phase IV: uplift and weathering

The host rocks in the South Pennine Orefield have been going through the final phase of evolution for some considerable geological time. The surface erosion and weathering phase starts when sedimentary rocks are uplifted above sea level and exposed to chemical and mechanical weathering. The most important characteristic of this phase is downward percolation of meteoric waters in permeable zones which results in internal chemical weathering of rocks, especially in carbonate rocks. The carbonate rocks in the orefield were exposed to weathering processes during at least some of the non-depositional periods (mid-Carboniferous, Lower Permian, earliest Triassic) and, almost continuously, since the late Mesozoic. Some of the groundwaters and springs in the orefield are considered to be thermal waters though with temperatures of less than 30 °C (Edmunds *et al.*, 1969). The higher than normal temperatures of these waters may be due to mixing of near surface meteoric waters with heated connate brines being expelled at the present time from the sediments beneath the Southern North Sea Basin (Ineson and Ford, 1982) or, as the result of long-lived isotopes and the high surface heat flow in the orefield (Brown *et al.*, 1980), the meteoric waters are heated to temperatures of around 30 °C without deeply circulating in the Dinantian limestones. The circulation of meteoric waters in the limestones has resulted in development of extensive cave systems in these rocks. Some of these cave systems, which probably had their initial developments during the first period of the Dinantian erosion in mid-Carboniferous times, provided palaeokarstic depositional sites for ore minerals that were precipitated from connate waters during the late diagenesis phase (Ford, 1977, 1984).



4. JURASSIC-HOLOCENE-UPLIFT AND WEATHERING PHASE: following limited cover by Mesozoic sediments these were removed as a result of mid-Tertiary renewal of uplift. Late Tertiary thin cover of Brassington Formation sand and clays, followed by further uplift. Development of karstic features; downward movement of meteoric waters and formation of secondary oxidized minerals, with transportation and deposition of derived minerals in caves etc. Late fluid expulsion from North Sea Basin establishes thermal springs.

Fig. 5. Stage 4 in the geological evolution of the South Pennine Orefield.

As far as the ore minerals in the orefield are concerned, the circulation of meteoric waters in the Dinantian limestones has resulted in: (*a*) formation of secondary alteration minerals (Fig. 5); (*b*) physical transportation of some minerals, especially fluorite and galena, with re-deposition in the residual sediments of some cave systems; (*c*) formation of secondary dispersion patterns of elements, derived from the ore deposits in the Dinantian rocks, in soils and superficial deposits on the orefield (Burek and Cubitt, 1979); and (*d*) leaching of the ore minerals and the host rocks which has a considerable effect on the chemistry of groundwaters near mineralised areas. Some limited transportation and re-deposition of ore minerals has resulted in minor residual and alluvial ore deposits at a few locations in the orefield.

Conclusions

It is proposed that the ore-forming fluids of strata-bound carbonate-hosted Pb-Zn deposits, such as those in the South Pennine Orefield, were formed as the result of interaction of many processes taking pace during the diagenesis of both their source and host rocks.

The Dinantian and early Namurian rocks of the Central Pennine Basin were deeply buried by late Carboniferous times with resultant expulsion of some formation water during diagenesis, but a stratigraphic inversion as a result of Hercynian tectonics made the formation waters from much more extensive, deeply buried and matured equivalent strata in the North Sea Basin and associated Gulfs available as ore-fluids, migrating to the basin margin in the South Pennines. Thereby a "one-pass" Carboniferous fluid became a more enriched "two-pass" fluid by Permo-Triassic times.

The ore minerals could have been precipitated in three stages: (*a*) as early generations of base metal sulphide during the early diagenesis phase which either remain preserved or broken down in later stages of sedimentological evolution of the enclosing rocks and provide additional sources of metal and sulphur; (*b*) during the late diagenesis phase when the main phase of ore mineralisation took place by episodic upward and outward circulation of heated saline connate brines generated by release of formation waters during compaction of sediments and clay dehydration; and (*c*) during the uplift and weathering phase when secondary alteration minerals were formed and some minerals from pre-existing ore deposits were transported by the groundwater circulatory system and re-deposited in residual sediments of some karst depressions and cave systems. The essential conditions for ore mineralisation include: availability of different ions in sufficient concentration for low-temperature ore deposition; availability of sulphur and sulphate species in the sites of ore deposition; an appropriate temperature range of 50 to 150 °C for thermal maturation of hydrocarbons and ore deposition; an appropriate depth of burial; suitable depositional sites and channelways in the host rocks; regional and local structural and lithological controls; availability of transporting agents for different ions and sulphur; presence of factors causing precipitation of ore minerals and a large source area for leaching of metals and decomposition of organic matters. The absence of these conditions would result in barren carbonate rocks.

Acknowledgments

The authors are grateful to Mrs. Elisabeth Mostaghel and Mrs. Maureen Prime for typing several drafts of the manuscript and for preparation of the figures.

References

Aitkenhead, N., Chisholm, J.I. and Stevenson, I.P., 1985. Geology of the Country around Buxton, Leek and Bakewell. *Mem. British Geol. Surv.*, 168pp.

Anderson, G.M., 1975. Precipitation of Mississippi Valley-type ores. *Econ. Geol.*, 70, 937–942.

Anderson, G.M., 1978. Basinal brines and Mississippi Valley-type ore deposits. *Episodes*, 1978, 15–19.

Atkinson, P., 1983. *A fluid inclusion study and geochemical investigation of the fluorite deposits in the Southern Pennines*. Ph.D. thesis, University of Leicester, 284pp.

Bailey, N.J.L., 1977. Hydrocarbon and hydrogen sulphide generation in early diagenesis and by thermal maturation. *In Forum on oil and ore in sediments*, Garrard, P., ed. (London: Imperial College, 1977), 93–107.

Beales, F.W. and Jackson, S.A., 1968. Pine Point—a stratigraphical approach. *Can. Min. Metall. Bull.*, 61, 867–878.

Beckmann, H., 1976. *Geological prospecting for petroleum.* London, Pitman Pub., 183pp.

Berner, R.A., 1980. *Early diagenesis, a theoretical approach.* Princeton University Press, 241pp.

Brown, G.C., Cassidy, J., Oxburgh, E.R., Plant, J., Sabine, P.A. and Watson, J.V., 1980. Basement heat flow and metalliferous mineralization in England and Wales. *Nature, Phys. Sci.* 288, 657–659.

Burek, C.V. and Cubitt, J.M., 1979. Trace element distribution in the superficial deposits of northern Derbyshire, England. *Minerals and the Environment*, 1, 90–100.

Butcher, N.J.D., 1976. *Aspects of the structural control of fluorite mineralization in the south Pennine orefield with notes on the mining potential.* Ph.D. thesis, University of Leicester, 218pp.

Coomer, P.G. and Ford, T.D., 1975. Lead and sulphur isotope ratios of some galena specimens from the south Pennines and north Midlands. *Mercian Geol.*, 5, 291–304.

Cooper, B.S., Coleman, S.H., Barnard, P.C. and Butterworth, J.D., 1975. Palaeotemperatures in the northern North Sea Basin. *In Petroleum and the continental shelf of north-west Europe, volume 1, Geology*, Woodland, A.W., ed. (Barking: Applied Science Publishers), 487–492.

Dunham, K.C., 1973. A recent deep borehole near Eyam, Derbyshire. *Nature, Phys. Sci.*, 241, 84–85.

Dunham, K.C., 1983. Ore genesis in the English Pennines: a fluorite subtype. *Proc. Int. Conf. on Mississippi Valley type lead-zinc deposits*, Rolla, University of Missouri, 86–112.

Edmunds, W.M., Taylor, B.J. and Downing, R.A., 1969. Mineral and thermal waters of the United Kingdom. *23rd Int. Geol. Cong.*, Prague, Czechoslovakia, 18, 139–158.

Emblin, R., 1978. A Pennine model for the diagenetic origin of base metal ore deposits in Britain. *Bull. Peak Dist. Mines Hist. Soc.*, 7, 5–20.

Fairbridge, R.W., 1967. Phases of diagenesis and authigenesis. *In Diagenesis in sediments*, Larsen, G. and Chilingar, G.V., eds. (Amsterdam: Elsevier), 19–89.

Farrand, M., 1970. Framboidal sulphides precipitated synthetically. *Mineral. Deposit*, 5, 237–247.

Ferguson, J., Bubela, B. and Davies, P.J., 1975. Simulation of sedimentary ore-forming processes: concentration of Pb and Zn from brines into organic and Fe-bearing carbonate sediments. *Geol. Rundschau*, bd 64, (3), 767–782.

Firman, R.J., 1977. Derbyshire wrenches and ores—a study of the rakes' progress by secondary faulting. *Mercian Geol.*, 6, 81–96.

Firman, R.J. and Bagshaw, C., 1974. A re-appraisal of the controls of non-metallic gangue mineral distribution in Derbyshire. *Mercian Geol.*, 5, 145–161.

Fitch, F.J., Miller, J.A. and Williams, S.C., 1970. Isotopic ages of British Carboniferous rocks. *C.R. 6th Int. Congr. Carbonif. Stratigr. Geol.*, Sheffield, 1967, 2, 771–789.

Ford, T.D. and Ineson, P.R., 1971. The fluorspar mining potential of the Derbyshire ore field. *Trans. Inst. Min. Metall.* B80, B186–210.

Ford, T.D., 1972. Evidence of early stages in the evolution of the Derbyshire karst. *Trans. Cave Research Group G.B.*, 14, 73–77.

Ford, T.D., 1976. The ores of the south Pennines and Mendip Hills, England—a comparative study. *In Handbook of strata-bound and stratiform ore deposits, volume 5, regional studies*, Wolf, K.H., ed. (Amsterdam: Elsevier), 161–195.

Ford, T., ed., 1977. *Limestones and caves of the Peak District.* Norwich, Geo Abstracts, 469pp.

Ford, T.D., 1984. Palaeokarsts in Britain. *Cave Sci.*, 11, 246–264.

Ford, T.D. and Rieuwerts, J.H., 1983. *Lead mining in the Peak District.* Bakewell, Peak Park Joint Planning Board, 3rd edn., 160pp.

Frost, D.V. and Smart, J.G.O., 1979. Geology of the country north of Derby. *Mem. Geol. Surv.* G.B., sheet 125.

Glover, J.E., 1968. Significance of stylolites in dolomitic limestones. *Nature, Phys. Sci.*, 217, 835–836.

Gutteridge, P., 1983. *Sedimentological study of the Eyam Limestone Formation of the East-Central part of the Derbyshire Dome.* Ph.D. thesis, Univ. Manchester, 2 vols.

Harrison, D.J. and Adlam, K.A.McL., 1985. Limestones of the Peak. *British Geol. Surv. Mineral Assess. Rept.* no. 144, 45pp.

Hitchon, B., 1977. Geochemical links between oil field and ore deposits in sedimentary rocks. *In Forum on oil and ore in sediments*, Garrard, P., ed. (London: Imperial College), 1-34.

Hunt, J.M., 1979. *Petroleum geochemistry and geology*. San Francisco, W.H. Freeman & Co., 617pp.

Ineson, P.R., 1970. Trace-element aureoles in limestone wallrocks adjacent to fissure veins in the Eyam area of the Derbyshire ore field. *Trans. Inst. Min. Metall.* 79, B238-245.

Ineson, P.R. and Al-Kufaishi, F.A.M., 1970. The mineralogy and paragenetic sequence of Long Rake vein at Raper mine, Derbyshire. *Mercian Geol.*, 3, 337-351.

Ineson, P.R. and Ford, T.D., 1982. The South Pennine orefield: its genetic theories and eastward extension. *Mercian Geol.*, 8, 285-303.

Ineson, P.R. and Mitchell, J.G., 1973. Isotopic age determination on clay minerals from lavas and tuffs of the Derbyshire orefield. *Geol. Mag.*, 109, 501-512.

Kent, P.E., 1966. The structure of the concealed Carboniferous rocks of north-eastern England. *Proc. Yorks. Geol. Soc.*, 35, 323-352.

Llewellyn, P.G. and Stabbins, R., 1968. Lower Carboniferous evaporites and mineralization in the eastern and central Midlands of Britain. *Trans. Inst. Min. Metall.*, B77, 170-173.

Love, L.G., 1967. Diagenesis and the origin of ores. *In* Genesis of stratiform lead-zinc-barite-fluorite deposits in carbonate rocks, Brown, J.S., ed., *Economic Geology* Monograph No. 3, 343-348.

Macqueen, R.W. and Thompson, R.I., 1978. Carbonate-hosted lead-zinc occurrences in northeastern British Columbia with emphasis on the Robb Lake deposit. *Can. J. Earth Sci.*, 15, 1737-1762.

Maroof, S.I., 1976. The structure of the concealed pre-Carboniferous basement of the Derbyshire Dome from gravity data. *Proc. Yorks. Geol. Soc.*, 41, 59-69.

McDonald, A.J.W., 1984. *The anelastic structure and deep geology of the Derbyshire Dome from high frequency Rayleigh waves.* Ph.D. thesis, Univ. Leeds, 304pp.

Miller, J. and Grayson, R.F., 1982. The regional context of Waulsortian Facies in Northern England, pp. 17-33 *In Symposium on the Paleoenvironmental Setting and Distribution of the Waulsortian Facies.* El Paso Geol. Soc., Univ. Texas at El Paso, (eds. K. Bolton, H.R. Lane and D.V. LeMone), 202pp.

Monteleone, P.H., 1973. *The Geology of the Carboniferous limestone of Leicestershire and south Derbyshire.* Ph.D. thesis, University of Leicester.

Mostaghel, M.A., 1983. Evolution of the south Pennine orefield: I. regional distribution of major non-metallic minerals. *Bull. Peak Dist. Mines Hist. Soc.*, 8, 369-372.

Mostaghel, M.A., 1984. *Trace elements in sulphide minerals and their genesis in the south Pennine orefield.* Ph.D. thesis, University of Leicester, 547pp.

Noble, E.A., 1963. Formation of ore deposits by waters of compaction. *Econ. Geol.*, 58, 1145-1156.

Nooner, D.W., Updegrove, W.S., Flory, D.A., Oro', J. and Mueller, G., 1973. Isotopic and chemical data of bitumens associated with hydrothermal veins from Windy Knoll, Derbyshire, England. *Chem. Geol.*, 11, 189-202.

Ohle, E.L., 1959. Some considerations in determining the origin of ore deposits of the Mississippi Valley type. *Econ. Geol.*, 54, 769-789.

Orme, G.R. and Ford, T.D., 1970. Polyphase mineralization in chert from the Ashford Black Marble Mine, Derbyshire. *Proc. Yorks. Geol. Soc.*, 38, 163-173.

Park, W.C., 1967. Early diagenetic framboidal pyrite, bravoite and vaesite from the Cave-In-Rock fluorspar district, Southern Illinois. *Mineral. Deposita*, 2, 372-375.

Pering, K.L., 1973. Bitumens associated with lead, zinc and fluorite ore minerals in North Derbyshire, England. *Geochim. Cosmochim. Acta.*, 37, 401-417.

Price, L.C., 1976. Aqueous solubility of petroleum as applied to its origin and primary migration. *Am. Assoc. Pet. Geol. Bull.*, 60, 313-344.

Pusey, W.C., III, 1973. The E.S.R.-Kerogen method, a new technique of estimating the organic maturity of sedimentary rocks. *Petroleum Times*, 77, 21-26.

Robinson, B.W. and Ineson, P.R., 1979. Sulphur, oxygen and carbon isotope investigations of lead-zinc-barite-fluorite-calcite mineralization, Derbyshire, England, *Trans. Inst. Min. Metall.*, B88, B107-117.

Rogers, D.E., 1983. *Seismic studies on the Derbyshire Dome.* Unpub. Ph.D. thesis, Univ. Leeds, 345pp.

Rogers, P.J., 1977. Fluid inclusion studies in fluorite from the Derbyshire orefield. *Trans. Inst. Min. Metall.* B86, B128–132.

Smith, E.G., Rhys, G.H. and Eden, R.A., 1967. Geology of the country around Chesterfield, Matlock and Mansfield. *Mem. Geol. Surv. G.B.*, sheet 112.

Smith, F.W., 1973. Fluid inclusion studies on fluorite from the North Wales orefield. *Trans. Instn. Min. Metall.*, B82, B174–176.

Smith, K., Smith, N.J.P. and Holliday, D.W., 1985. The deep structure of Derbyshire. *Geol. J.*, 20, 215–225.

Strank, A.R.E., 1985. The Dinantian stratigraphy of a deep borehole near Eyam, Derbyshire. *Geol. J.*, 20, 227–237.

Sweeney, R.E. and Kaplan, I.R., 1973. Pyrite framboid formation: laboratory synthesis and marine sediments. *Econ. Geol.*, 68, 618–634.

Vaughan, D.J. and Craig, J.R., 1978. *Mineral Chemistry of Metal Sulphides.* Cambridge University Press, 493pp.

Vaughan, D.J. and Ixer, R.A., 1980. Studies of sulphide mineralogy of North Pennine ores and its contribution to genetic models. *Trans. Inst. Min. Metall.*, B89, B99–109.

Walkden, G.M., 1972. The mineralogy and origin of interbedded clay wayboards in the Lower Carboniferous of the Derbyshire Dome. *Geol. J.*, 8, 143–160.

Walsh, P.T., Boulter, M.C., Ijtaba, M. and Urbani, D.M., 1972. The preservation of the Neogene Brassington Formation of the southern Pennines and its bearing on the evolution of Upland Britain. *J. Geol. Soc. Lond.*, 128, 519–559.

Wise, J.R. and Weaver, F.M., 1974. Chertification of oceanic sediments. *In* Pelagic sediments on land and under the sea, Hsü, J.K. and Jenkyns, H.C., ed. *Int. Assoc. Sediment. Spec. Publs.* No. 1, 301–326.

Wolf, K.H. and Chilingarian, G.V., (eds.) 1976. Compactional diagenesis of carbonate sediments and rocks. *In Compaction of coarse-grained sediments*, (Amsterdam: Elsevier), 2, 740–768.

M.A. Mostaghel, B.Sc., M.Sc., Ph.D.,
219, Edgebank Place,
Calgary, Alberta, T3A 3E7,
Canada.

T.D. Ford, B.Sc., Ph.D., F.G.S.,
Department of Geology,
University of Leicester,
U.K.

EXCURSION REPORT

THE GLACIAL GEOLOGY OF THE CHESHIRE-SHROPSHIRE PLAIN

Leader Peter Worsley — Sunday September 1st 1985

A party of 24 members distributed between a Land Rover and a minibus departed from Nottingham and headed north-west via Leek to the first stop on a minor road (SJ 901639) some 4 km east of Congleton just below the summit of The Cloud. Here the leader outlined the rationale of the days campaign, namely an examination of evidence relating to the Devensian cold stage in the Cheshire-Shropshire lowlands. This would consist of glacial and periglacial sediments and landforms. He remarked that from the vicinity of Leek until shortly after the last locality to be visited the journey would be entirely over ground covered by the Late Devensian ice sheet only 20,000 or so years ago. The glacial limit was not readily observable in the field.

From the vantage point below The Cloud the sharp topographic contrast between the western Pennine front (corresponding roughly to the Red Rock Fault) and the Triassic floored Cheshire Plain was clearly seen. Unfortunately, the overall visibility was poor in marked contrast to that 13 weeks previously on Dr Lloyd Boardman's excursion to the North Staffordshire coalfield when at Mow Cop, 6 km to the south-west, the Welsh Borderlands were clearly visible 60 km to the west. However, 12 km to the north-west the unmistakable dish profile of the University of Manchester's radio telescope at Jodrell Bank was evident and this served as a very useful locational marker, for the next locality to be visited—Chelford, was close by. From The Cloud the party proceeded via Congleton to Lapwing Lane a minor road east of Withington Hall on which the entrance to the current sand quarry was located.

Chelford-Oakwood Quarry (East) SJ 825718 is one of the more important Quaternary localities in Britain. In the Chelford area the land surface forms a rather featureless plain developed on the products of the Late Devensian glaciation, now known as the Dimlington Stadial. These products consist of a glacigenic complex—tills, sand and gravels, lacustrine silts, etc., which are grouped into the Stockport Formation. At the time of the visit this formation, as exposed uniformly around the quarry margins, was only 2 m thick. Beneath lay the Chelford Sands Formation, a suite of alluvial sands of exceptional purity and high degree of sorting with a dominant near-horizontal stratification.

The precise location of sand workings at Chelford has inevitably changed over the years. The present quarry at Oakwood had only been under development for two years or so and consequently it was not, as yet, very extensive. However, a view was taken of the now abandoned Oakwood (West) Quarry on the opposite side of the access road enabling some appreciation of the sand-body geometry to be made. The sands infill and bury a palaeovalley which falls to the north-west—the original workings at Farm Wood lying in its 'downstream' extension. This valley is cut into the Mercia Mudstone, but in places a thin glacigenic sequence overlying biogenic rich sills and gravels occurs between the basal sands and the bedrock. Unfortunately, exposures of these older sediments were no longer available due to flooding.

In the new quarry it was remarked that the ground water abstraction pump was situated close to the palaeovalley axis. Approximately in the middle of the Chelford Sands a thin succession consisting of peat, organic muds and macro plant material was exposed. This was the lateral equivalent of the bed originally exposed in the Farm Wood Quarry (1.5 km to the north-west) during the 1950–60's and hence a representative of the Chelford Interstadial type succession. Analysis of the plant macro and micro fossils along with the Coleoptera suggest the former presence of a boreal forest with birch, pine and spruce. Exposures in the Oakwood Quarry (West) showed convincingly that the biogenic material occurred within a palaeochannel cut within the main sand body. It was possible for the party to see that the organics at Oakwood (East) were restricted in distribution and that the outcrop limit on the east face was consistent with a drape on the bank of an incised channel. Dumped masses of the peat enabled members to closely examine the organic material and collect examples of pine and spruce cones. Most of the smaller-diameter woody fragments (especially birch branches) showed major compression when viewed in cross section. Conventional wisdom assigns the Chelford Interstadial to the Brörup Interstadial of Denmark which is of early Weichselian (Devensian) age. However, at Chelford itself we have no firm stratigraphic control on its age other than it ante-dates the Late Devensian glacial advance and post-dates an earlier glaciation.

Mercian Geologist, vol. 10, no. 3,
pp. 225–228, 1 fig.

After leaving Chelford the route was via Middlewich and Nantwich to Whitchurch where lunch-break was made. Then the road leading to Oswestry was taken and as Ellesmere was approached the terrain character changed dramatically from an essentially featureless landscape to one of pronounced hills and depressions. The Ellesmere district has long attracted the attention of glacial geologists and the American H. Carville Lewis in the last century commented on the 'fine hummocks and large billowy hills' and stated 'this is a magnificent moraine'.

Sand and gravel extraction at the Wood Lane Quarry (SJ 422325) has been operative for several decades. Unfortunately its relative remoteness from higher education centres has discouraged long-term systematic logging of the faces and, as a result, there is currently no consensus as to its precise significance.

Members were able to examine three main lithofacies, tills, sands and sandy gravels, in exposures at the south end of the quarry, away from a pronounced ridge feature along the northern boundary. Former sections on the north side revealed major tectonic elements. Opinions on the mechanism of deformation differ, one school of thought favours subsidence deformation in association with buried ice wastage whereas the other prefers glacial thrusting.

The current workings were cut into hummocky terrain which has no obvious morphological trend. The exposed succession consisted of:-

6 m	Gravels—horizontally stratified
3 m	Pebbly sand with two tills of varying thickness and extent
4 m	Sands—base not seen

The leader explained that this basic tripartite succession had persisted throughout much of the quarry area south of the ridge. The most impressive unit was the middle one for this contained till bodies of very variable geometry. These were interpreted as the products of sediment flows [flow tills] which were emplaced subaerially upon an aggrading proglacial fluvial surface. Subsequent fluvial activity had partially eroded the tops of some flow units and, in addition, limited deformation had occurred through load displacements. Sometimes flat-lying recumbent folds were evident immediately below the base of the flow units.

It was suggested that the landforms and sediments should be assigned to a superficial depositional environment which may originally have had a low relief. Subsequent melt of buried ice had extensively deformed the initial depositional surface. Interestingly Richard Sanderson (aged 12) was asked to comment on his impressions on the relationship between the sediments and landform as the active quarry was approached and, without prompting, he remarked on the low amplitude flexuring of the extensive planar stratification structures and their concordance with the land surface.

Upon leaving Ellesmere the party was behind schedule, due in part to a group of visitors (prearranged) having found their car locked in the quarry, the main party fortuitously having avoided this hazard by walking in and out. It had been intended to pay a quick visit to the Mousecroft Lane Quarry at Shrewsbury where the Irish Sea glacigenic sediments could be seen overlain by similar materials of Welsh provenance. Unfortunately during the previous weeks the main exposures had been landscaped after many decades of availability so, in order to gain some time, Shrewsbury was avoided and, shortly after the A5 was attained at Atcham, the B4380 was followed passing the excavations at the former Roman town of Uriconium (Wroxeter) to the next stop at Leighton.

The River Severn, the longest river in Britain, has a very curious course since, after crossing the southern margins of the Cheshire-Shropshire Plain, it cuts through an upland area which originally formed part of the main English watershed. In doing so the Severn forsakes the 'easy' route northwards across the plain to the Irish Sea. There is almost universal agreement that this anomaly is the product of a glacially influenced diversion of drainage. The paradox is that the current understanding of the stratigraphy suggests that the diversion is as recent as Late Devensian in age and earlier glaciations do not appear to have achieved such an effect on the drainage. It was suggested that this may be due to Welsh ice having been more forceful in previous glaciations.

The main diversionary course extends in an arc for some 11 km from Coalbrookdale, immediately west of Iron Bridge, to some 3 km north of Bridgnorth. Within this section of the river an incised gorge some 100 m deep is largely the result of the drainage diversion rather than the adaptation of a pre-existing valley.

A detailed history of the gorge formation has yet to be convincingly demonstrated. The instability of the valley sides has erased any fluvial depositional terrace features which may have existed. A totally buried feature of comparable dimensions to the modern gorge exists beneath the plateau surface lying to the east and, immediately west of the modern gorge intake, a major buried channel occurs below the modern floodplain. At least an element of subglacial meltwater erosion appears to have been involved in its cutting although the classic interpretation involves simple ice-impounded lake overflow across the pre-existing watershed. Within the river valley downstream of the gorge proper, close to Bridgnorth, glacigenic materials are associated with a major terrace feature and their altitude suggests that at least a significant element of the erosion had been achieved prior to the final phase of ice marginal withdrawal.

From a view point by the B4380 west of the gorge (SJ 618048) members were able to enjoy a fine view. To the east of the diversionary valley was seen to be clearly discordant in form to the general upland plateau. Below, to the south, the modern River Severn had developed a set of classical meander loops and the various elements of the meandering river depositional environment were evident, except an example of an ox-bow lake cut-off.

A short drive led to Iron Bridge itself and a brief stop was made in order to marvel at the oldest iron bridge in the world. Then the route lay east closely following the north bank of the Severn to a point just before Coalport. In this sector of the valley abundant evidence of valley side instability was seen, a testimony to the relatively recent cutting of the valley. From Coalport the road climbing steeply past the major industrial archaeological site at Blists Hill was taken and soon the plateau surface was attained. After negotiating the complex Telford new town road network, the simpler Roman routeway was soon joined north of Shifnal and a drive east along Watling Street soon brought the party to Gailey Corner where the A449 was taken southwards for the short distance to Four Ashes.

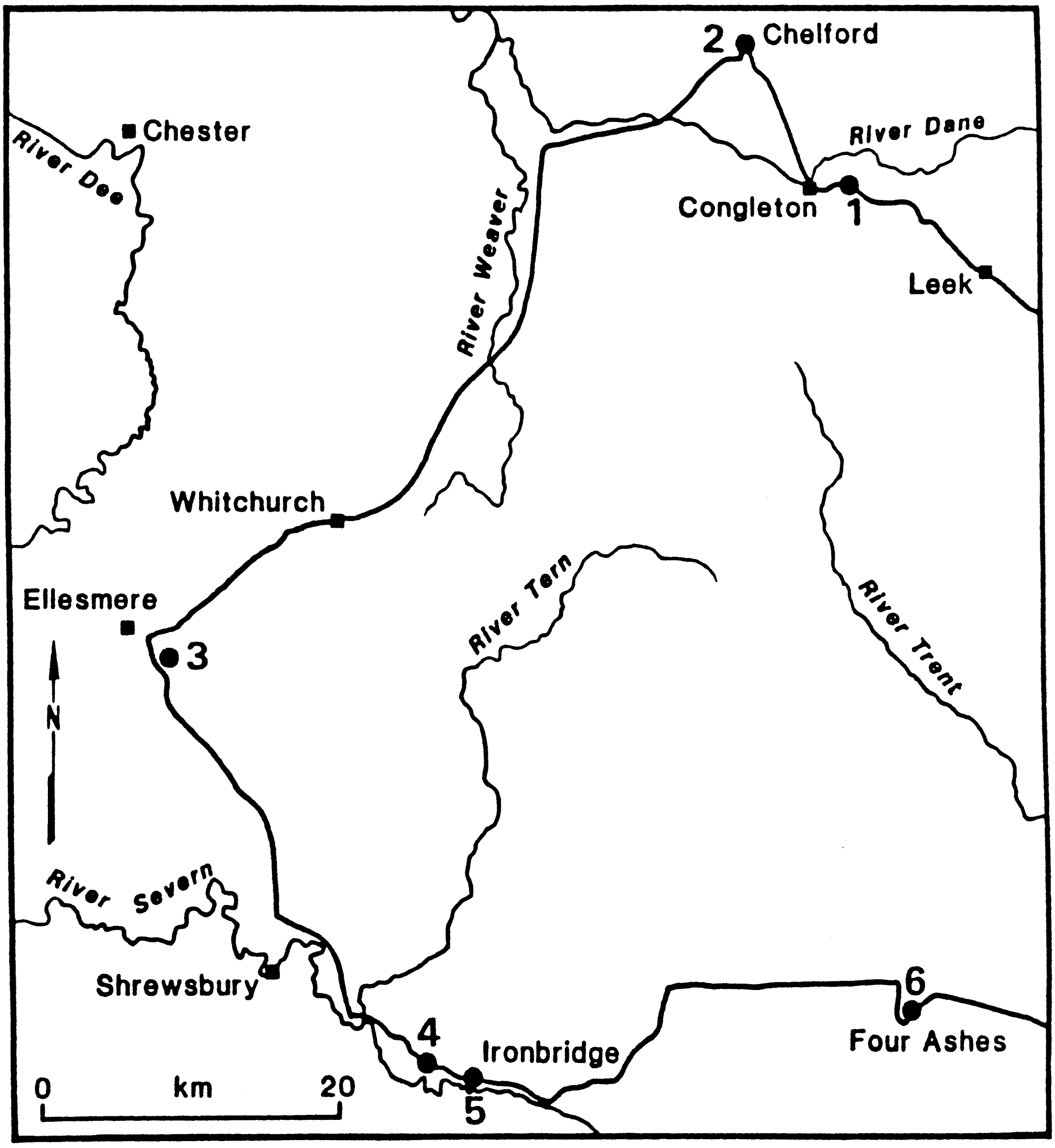


Fig. 1. Locality map.

Although the leader did not recommend a stop at Four Ashes (SJ 913084) the consensus view was in favour, despite the late hour and lack of any significant exposure. Having parked behind the Four Ashes public house it was suggested that the pub sign, a landscape of rural midland England, was as informative as the site itself! However, the party did penetrate the undergrowth and woodland to view the restored field which now occupies the site of the former quarry which in the 1960's yielded an astonishing abundance of organic rich lenses in a thin gravel succession overlain by Late Devensian till. An almost totally grassed bank did reveal some pebbly gravels and, towards the top, a silty clay material which with 'the eye of faith', could be taken to be the till. This bank is the sole remaining field representative of the type succession of the last British cold stage—the Devensian—and this historic fact appeared to justify the pilgrimage in the opinion of members, even though the main evidence has long since been quarried away. It can now be reported that in the near future the Nature conservancy will be excavating a clean section at the site down to the Triassic surface. Thereafter a direct return to Nottingham was made with a one-and-a-half hour late arrival for which the leader apologised.

Acknowledgements

Grateful thanks are extended to British Industrial Sands (Mr. C.N.K. Tizard) and Ellesmere Sand and Gravel (Mr. T. Jones) for permission to enter their quarries and to Martin Degg who drove the minibus.

Peter Worsley,
Department of Geography,
University of Nottingham,
Nottingham, NG7 2RD.

BOOK REVIEWS

VOGEL, J.C., (Ed.) *Late Cainozoic palaeoclimates of the Southern Hemisphere* 1984. A.A. Balkema, Rotterdam. 536pp., £27.50, Hardcover. ISBN 90 6191 554 6.

Never having had the opportunity to visit the Southern Hemisphere, the reviewer was initially a little doubtful over the intrinsic interest to be generated by this volume amongst those whose primary perspectives are oriented towards the north. This feeling was not lessened by the discovery that it constituted the proceedings of a symposium, for past experience has been that products of this nature are often patchy in their quality. In the event these factors have proved to be largely unfounded and a volume of some quality has been compiled by the editor and his assistants, plus of course, the contributors themselves.

It is often not realised by those geologists who tend to switch off when post-Cretaceous topics are under discussion, that a revolution comparable in its magnitude to that arising from the plate tectonic theory has occurred in Cainozoic geology. The Cainozoic revolution has been due in large measure to the successful abstraction from the deep ocean basins of cores registering long records of sedimentation. Examination of these cores has yielded abundant data on palaeoenvironmental parameters from over two thirds of the earth's surface where previously knowledge had been effectively zero. A major benchmark event occurred about a decade ago when for the first time it was possible to publish a detailed map of global surface character at a specific time in the past. This was the CLIMAP (Climate, long-range investigation, mapping and prediction) reconstruction of the world eighteen thousand years ago showing the distribution of land, snow, ice, vegetation types and sea surface temperatures. Since then it has become increasingly realistic to model former atmospheric circulation patterns. The fact that successful attempts at understanding climatic change must adopt a global viewpoint, has been highlighted and this necessarily means examining both hemispheres in equal detail. However, the concentration of workers in the northern hemisphere has meant that the task of southern hemispheric investigation has fallen upon the shoulders of a relative few. "Late Cainozoic Palaeoclimates" is a milestone on the path towards a fuller appreciation of the pattern of global climatic change and its effects of landforms, sediments and biota.

The volume is organised into six parts and within these the non-specialist is naturally going to be attracted to the overview type of contribution. An initial section (3 papers) is titled palaeoclimatology and the keynote opening paper by H. Flohn reviews equatorial and Southern Hemisphere climatic evolution from an atmospheric standpoint. S.P. Harrison *et al.* examined the last glacial-interglacial stage transition by predicting circulation patterns 18, 9, and 8 thousand years ago and the testing against the palaeohydrological responses. South America (6 papers) features J.H. Mercer's excellent review of the record of glacial variations since the Mio-Pliocene transition. Australasia (7 papers) includes M.J. Salinger's account of New Zealand's climates over the last 5 M.a. and J.M. Bowler and R.J. Wasson on glacial age environments of inland Australia. Southern Africa, the venue of the symposium, naturally has the most material (14 papers) and of these that by K.W. Butzer presenting a fine synthesis of the South African Late Quaternary is noteworthy. The fifth part (6 papers) has the southern deserts as its theme and the first three by Thomas and Goudie, Wasson and Lancaster discuss aspects of the palaedune fields. Finally, there is a part (6 papers) devoted to the African faunal record and those who have read the admirable 'thriller' by Johanson and Edey on "Lucy—the beginnings of humankind" will appreciate H.B.S. Cooke's account of horses, elephants and pigs.

The text format, apart from title pages, is camera ready copy and is entirely satisfactory. Numerous maps and diagrams have been prepared to full publication standards and their reproduction is first rate. Unfortunately, there is no index but no doubt it could be argued that the impressively short period between the symposium and publication (less than a year) made this difficult. Perhaps the major omissions is any substantial account of Antarctica, it is only featured in one paper. This is at variance with the publishers dust jacket comment 'Antarctica and the surrounding oceans play the major role in regulating atmospheric circulation patterns even across the equator'. In view of the adopted title this omission is anomalous although it has to be noted that there is a rich recent literature on Antarctica.

Peter Worsley,
Department of Geography,
University of Nottingham,
Nottingham, NG7 2RD.

DERCOURT, J. and PAQUET, J. *Geology: Principles and Methods*, 1985 (French edition published 1983). Graham & Trotman Ltd., i-xxi + 384pp., 462 figs., selective bibliography (72 refs.) and index, £27.95 (hardback edition) or £13.95 (paperback). ISBN 0 86010 484 2 or ISBN 0 860 10 489 Pbk.

The publishers in their advertising material lead with the comment that "Geology: Principles and Methods" is an important new textbook. Further claims include it being ideal teaching material for undergraduate level courses. At the outset let me make it clear that in no way can this book be considered to be a textbook. The publicity material, the various forewords, and a quick scan through the book whetted my appetite but before page 100 I nearly gave up in frustration and despair. The prefatory fanfares talked of a refreshing readable text but the reality is very different.

Organisation is very much a problem. Brian Windley made a point of the fact that the chapters in his "Evolving Continents" could be read in any order the reader chose which is fine for a text aimed at third year students and senior learners. "Geology: Principles and Methods" is introductory in its style (and intent) yet Chapters 4, 5 and 6 (igneous and metamorphic rocks) require quite an overview of the subject for understanding. Much of the material discussed fairly freely in these chapters is not formally introduced in the book until later. The problem lies in using a case history approach which, at a very early stage, requires the reader to possess a sophisticated level of geological appreciation. After formal discussions on mineralogy and igneous-rock classifications, the unfortunate tyro would be thrown into an analysis of ophiolites, aspects of gross-scale structures in orogenic belts, and complex deformational, metamorphic, and stratigraphic aspects with no groundwork having been done. The continual reference to pages further along in the book is disconcerting and would be hard to cope with for one starting out in geology. Similar problems in the case histories of "Granites and Associated Rocks" which follow immediately on the heels of the basic rocks, lead to a heightened feeling of disjointedness. It seems very unreasonable so early in an introductory text to ask readers to cope with the intricacies of a high-grade terrain, with complex migmatite, metamorphic, and granitic histories; particularly when metamorphism is dealt with in the *next* chapter. To break away from the standard oft-repeated format of introductory texts is a fine ideal but in this case it does not work. The attempts to integrate and synthesise come far too early in the build up of the subject.

Having severely criticised the book as an introductory text, what does it offer the more established reader? For them the problems outlined above may well turn into bonuses as they could cope with the level of knowledge required when reading the case histories. The emphasis on examples from mainland Europe will broaden the scope of most readers and perhaps provide encouragement to pursue foreign language literature further. Several other positive features may be mentioned. A chapter on continental erosion and one on the marine environment does away with the normal very traditional treatment of landforms which dominates many North American and British textbooks. A section on deformation mechanisms explains how rocks respond to stress difference and accommodate shape changes; unfortunately the attempt is not fully successful because of an idiosyncratic approach. This is a disappointment because French researchers have been world leaders in studying microscopic deformation processes which sum to allow plate motion, mountain building, and similar global scale processes. The Applied Geology section is good but not as new as claimed by the publicists: several texts clearly show the economic implications of geology and justify study of the subject in economic terms.

A major disappointment, and one which showed the somewhat dated nature of the work, is the treatment of the tectonics of the Canadian Cordillera. Some branches of geology are expanding rapidly and none more so than the understanding of the tectonics of the continents. Besides new techniques (e.g. COCORP and similar applications of reflection profiling) the study of the western cordillera of North America has been the most influential in the upsurge of interest in continental tectonics. An appreciation of the far-travelled nature of many terranes in the cordillera has led to a new model of orogenesis which is now being over-enthusiastically applied in true band-wagon fashion. Nonetheless it is an important concept that is totally absent in a new book that devotes a significant part of a chapter to the virtual type area for these ideas.

Final comments must relate to the many many problems with the translation which is distractingly poor on a large number of pages and several passages are opaque. In my opinion it is not in a fit condition to be released on the English market. Problems with the translation further reinforce my comments in relation to the book being clearly not an introductory text. Students would pick up some disastrously odd ideas from reading this book. If I had paid for the book I would have seriously considered the Graham & Trotman "money-back guarantee". As the book now stands it needs a moderate amount of work to make it the equal of the best English texts which it has the potential to emulate.

N.B. This book may be obtained at the prices given above, plus postage, directly from Graham & Trotman Ltd., Sterling House, 66 Wilton Road, London SW1V 1DE. Telephone 01 821 1123. Telex. 298878 Gramco G.

C.A. Boulter,
Department of Geology,
University of Nottingham,
Nottingham, NG7 2RD.

MAALOE, S., *Principles of Igneous Petrology*, 1985. Springer-Verlag: Berlin-Heidelberg-New York. 291 figs. XIV, 374pp. Hardcover DM 138. ISBN 3 540 13520 0.

Modern igneous petrology has become a very diverse topic, encompassing such features as geochemical modelling, experimental petrology and isotopic systematics. It is therefore encouraging to find a publication which attempts a synthesis of these new developments. The first seven chapters of this book are concerned with phase diagrams, the murals of the experimental petrologist. Although such diagrams can appear daunting, Maaloe's explanations are clear and concise even for a novice of this topic. Throughout these chapters the reader is gradually introduced to more and more complex systems without being overawed by the phase diagrams.

The remaining chapters of the book deal with partial melting, fractional crystallisation, oxygen fugacity, magma kinetics, magma dynamics and isotope geology. Of these topics the sections concerning magma kinetics and magma dynamics are extremely useful, since they are not normally discussed is such a text. In all of these chapters many of the more modern developments in the field of igneous petrology are well explained.

All of the chapters are well structured, which makes for an interesting and easy read. However, it should be noted that the entire book represents a discussion of the theoretical aspects of igneous petrology and as such represents a good text for final year undergraduates and research workers. Although any enthusiast of igneous petrology may gleam much information from this book.

Judging from the price quoted by Springer-Verlag (DM138) this will not be a cheap book for British readers but this reviewer hopes that they will produce a cheaper soft-back edition.

T.S. Brewer,
Dept. of Geology,
University of Nottingham,
Nottingham, NG7 2RD.

ERRATA

1. Due to an oversight which resulted in the author not receiving proofs, a number of printing errors crept into the letter to the editor entitled *Lithostratigraphy of the Peel Sandstones* in Vol. 10, No. 1, pp. 73–76 by S.F. Crowley (Dept. of Geology, University of Liverpool). The editor offers his apologies for these errors, the corrected versions of which, as supplied by the author, are given below.

Page 73. Line 24–29. This well developed inverted clast stratigraphy is most obviously defined by the restricted occurrence of Wenlock faunas to The Stack conglomerates (supported by the work of Lewis, 1934 and my own recent collection of approximately 70 fossiliferous clasts, a small number of which were examined by Dr. C.T. Scrutton) and Ashgillian faunas to the Whitestrand conglomerates (supported by Gill, 1903; Lewis, 1934 and the presence of Ordovician related crinoid ossicles identified in one derived limestone clast by Dr. S.K. Donovan).

Page 74. Line 7–8. 2. Prior to the uplift and erosion of the Cambro-Ordovician Manx Massif, as defined by the predominance of Manx Slate clasts in the Manx Carboniferous (Arundian) basal, red bed conglomerates exposed at Langness (south IOM) and their complete absence from the Peel Sandstone conglomerates.

Page 75. Line 18. Ford, T.D., 1984. Field excursion to the Isle of Man. *Mercian Geol.* 9. 243–244.

2. In Vol. 10, No. 2 Table 1, p. 116 in the paper by *M.A. Moss* the analyses for Acid Leach (1b) and Residue Calculations (1c) for BD2 and BD3 were inadvertently transposed by the author when preparing this table. The resulting descrepancy between Fig. 5 b and c and Table 1 was unfortunately not detected until after the journal had gone to press. The editor and author apologise to those readers who attempted to correlate Table 1 with Fig. 5.

In this same paper there are, in spite of proof reading by both the author and editor, different spellings of Sprotbrough. The spelling favoured by the Ordnance Survey and used by geologists for stratigraphical purposes is ‘Sprotbrough’.

EAST MIDLANDS GEOLOGICAL SOCIETY

SECRETARY'S REPORT FOR 1984/85

This was the Society's 21st year with, as usual, a variety of subjects for the Indoor Meetings and locations for the Field Excursions. These consisted of 7 indoor, 4 field days, 2 week-end, 1 week and a Joint day with the Matlock Field Club, with the leaders and speakers providing their services freely.

After the Annual General Meeting in March, a Collectors' Meeting was held and was master-minded by the late Jim Sykes who sadly died only a few weeks later. The April Meeting was on Portuguese Trilobites given by Dr. M. Romano of Sheffield University. On a Thursday evening in May Professor Wayne Ahr from Texas talked on Uniformitarian Sedimentology—he was spending a few months at Leicester University.

A week-end in the Ingleton area in May was led by Paul Smith, aided by Ian Bryant, both at that time at Nottingham University. The President, Dr. T.D. Ford, ably led the Isle of Man week-end at the end of May. The June Excursion to Nuneaton was with Dr. M.J. le Bas of Leicester University. As far as numbers were concerned, the most successful excursion, was in celebration of the Society's 20 years. This was a repeat of one made in its 1st year to Dudley, with a barge trip on the Canal in the morning and a leisurely stroll around the Black Country Museum in the afternoon, the pace being dictated by the very hot weather which ended up as a thunderstorm just as we were to leave for Nottingham again.

The Eastern Lake District was the venue for the week's excursion with Dr. A.J. Wadge spending the whole week with the group and later assisted by Dr. M. Nutt both from the British Geological Survey at Keyworth. Unfortunately one of the members broke her ankle on the second day and spent the next few weeks in hospital, but I am pleased to report she has now completely recovered.

September's Excursion, to the Charnwood Area was led by Dr. R.A. Old of British Geological Survey at Keyworth, and at the end of September a small coach party visited Chatterley Whitfield Mining Museum and afterwards in complete contrast, the very modern City Museum and Art Gallery at Hanley where members listened to a talk on the work of the Curators by Mr. I. Steward.

The Joint Meeting with the Matlock Field Club was again a full day, Wendy Emmett, a Nature Conservancy Council Warden, talking on the Water Resources and Drainage Systems of Lathkil Dale and in the afternoon leading a visit to the area.

The indoor meeting in November was a very descriptive talk on Decorative Stone, Rock as a Status Symbol given by Mr. R. Roberts of the Geological Museum in London, and for the December meeting we travelled the Solar System with Dr. R.W. Jotham of the Adult Education Department, Nottingham, the following wine and buffet reflecting the journey through space. There were no promises for a follow-up excursion!

In January Professor Worsley of Nottingham University spoke of Ice Age Cheshire before Glaciation comparing this with his work in the High Arctic and the final meeting was the Presidential Address on the Evolution of Castleton Caves. So ended the year with its very varied programme. All indoor meetings except one had had full lecture halls but the day excursions were not nearly as well patronised. To encourage members to attend during the summer season, Council had decided to keep the coach fares to £3.00 or below during the 1985 period.

This previous point was one of the problems discussed during the 5 Council Meetings held in 1984, as were the Society's affairs, arranging the programme and any ideas put forward by members. These are always welcome and should be sent to the Secretary.

Eleven circulars had been produced reminding everyone of the forthcoming programme. The Society is most grateful to those members who every year willingly hand deliver them to those within their area, as they also do the Mercian Geologist, thus saving us at least £12 per circular and considerably more on the Journal.

The Society Exhibit, which publicises our publications and activities, had spent time in the Chesterfield Tourist Board, exhibited at the Association of Teacher's of Geology Conference at Leicester University, then to Arnold Library, Nottingham and finished up at Derbyshire College of Higher Education.

In 1984 members had been asked to sign Deed of Covenant forms to enable the Society to recover money they had paid in Income Tax to which around 25 had responded. These forms are available from the Secretary on request.

The Society Archives, consisting of masters for the Journal, which had been held by the late Jim Sykes (another debt we owed to him), were now housed with the Treasurer who had kindly taken over the responsibility for them.

In 1984 the Society purchased various sets of books which were then sold to members at a reduced rate where possible. Geological Howlers which was a second buy did not sell as well as before, but the Geologists' Association Guides sold very well indeed at only 50p per guide.

Again a slight drop in membership with a total of 471:–

Honorary	Ordinary	Joint	Junior	Institutional
3	235	122	4	107

Dr. R.J. Firman had taken over as Editor in September but had encountered problems all the way. Volume 9 No. 4 was ready before Christmas, but with typists doing Exam Papers and trouble in actually getting it printed with numerous errors when it was, the Journal with a December date was not available until March 1985. He wished to thank Dr. F.M. Taylor for still organizing the sale and delivery of the Mercian Geologist to both members and Exchange Libraries.

Again our thanks to Professor P.E. Baker and the University of Nottingham for readily allowing the Society the use of the Department of Geology for our activities, and my thanks to everyone, especially Council, Speakers and Leaders for making the job of Secretary such a pleasure, with all your support 1984 has been another successful year.

W. Madge Wright

THE MERCIAN GEOLOGIST

Journal of the East Midlands Geological Society

The journal first appeared in December 1964 and since that time 38 parts, comprising 10 volumes have been issued; the last, Vol. 10 No. 2 in Mar., 1986. The Mercian Geologist publishes articles especially on the geology of the Midlands of England, but other articles have been published which are of current interest to geology generally. Contents include original papers, review articles, biographies, bibliographies, excursion reports, book reviews and the Secretary's report on Society activities.

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 × 0.75. Thus the optimum size for the original diagram, including space for caption, index and explanation if required on the diagram, should be 285×190 mm (285×380 mm with a single fold). Greater reduction is possible but care must be taken with the original to ensure that at the final reduced size (230×155 mm; or 230×310 mm) the smallest letters are no smaller than 1 mm and that there is a similar minimum spacing between letters and lines. Bar scales (metric) should be provided as the exact reduction cannot be guaranteed.

Half-tone plates are reproduced at the original size, and should not exceed 230×155 mm. The quality of the published photograph depends initially on the quality of the original and it follows that the photographs submitted should be exactly as the author would wish them to appear in the journal—good contrast, in focus, adequate magnification and without distortion.

If there are any points of difficulty, please do not hesitate to contact the editor during the production of the manuscript. The editor's sole concern is to produce excellent quality papers to be enjoyed by all readers. Please send completed manuscripts to the editor.

For Readers:

All parts of the journal are available for purchase and a detailed contents list will be sent on request. Current numbers of the journal are usually obtained by subscription: [37 parts issued in 21 years].

Year 1986

Ordinary Members	£6.00	Joint Member	£6.50
Institutional Members	£6.00		

Single copies £3.50 (£3.00 Institutional Members; Others Members £2.50)
Complete volumes, 4 parts; £13.00 (£12.00 Institutions; Other Members £10.00).

Librarians in overseas libraries and geological institutions may take part in an exchange scheme organised by the Science Library of the University of Nottingham. About 200 institutions throughout the world receive the Mercian Geologist by sending in exchange, original geological periodicals.

Address: Editorial matters, manuscripts, exchanges, orders for back numbers

The Editor, Mercian Geologist, Department of Geology,
The University, Nottingham, NG7 2RD, England.

CONTENTS

Excursion Report

Reviews

Errata

Secretary's Report

Mercian Geologist, vol. 10, no. 3,
September, 1986, pp. 151–234,
plates 9–14.