THE PALAEOENVIRONMENT OF THE ABBOTSBURY IRONSTONE (UPPER JURASSIC) OF DORSET

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ABSTRACT. The Abbotsbury Ironstone represents a rare sandy facies of the Lower Kimmeridgian in Britain. Palaeoecological studies show that it consists of three facies deposited in an offshore beach or barrier bar environment. The main control on the fauna is thought to be the degree of water agitation.

THE Abbotsbury Ironstone consists of a sequence of limonite-oolitic sandstones, about 8 m thick. It is restricted to a small area around the village of Abbotsbury, Dorset (text-fig. 1), and apparently passes rapidly into clays less than one mile east of Abbotsbury. The outcrop is bounded on the north and west by a fault, and to the south by a seaward-facing scarp. It is the most westerly outcrop (on land) of Kimmeridgian in England, being 13 km west of the nearest known outcrop at Weymouth.

The Abbotsbury Ironstone is underlain by a 7-m-thick sequence of ferruginous sandstones (Sandsfoot Grits of Arkell, 1936). The junction of these with the ironstone is transitional. Neither the upper boundary of the ironstone, nor the lower boundary of the sandstones have ever been recorded at Abbotsbury. However, 4 miles NNW. of Abbotsbury, at Litton Cheney, Cope (1971) recorded 6–7 ft of limonite oolite, lithologically identical to the Abbotsbury Ironstone. This was overlain by 'yellowish clayey glauconitic sand' containing a large nodule which yielded a rich bivalve, gastropod, brachiopod, and ammonite fauna. The ammonites, as at Abbotsbury, were *Rasenia* sp. and *Prorasenia* sp. indicative of the Cymodoce Zone (Cope *in litt.*, 1971). The nodule is lithologically identical to the ironstone below, suggesting that the 'glauconitic sand' is merely leached ironstone. The fauna suggests facies C_1 of the ironstone (see below) though containing a more diversified bivalve and gastropod assemblage.

The ironstone was initially considered to be Upper Oxfordian (Corallian) in age (Strahan 1898), but later work showed it to be Kimmeridgian (Arkell 1933, 1936). It represents a rare exposure in Britain of a sandy facies of the Lower Kimmeridgian. Ammonites, *Rasenia* spp. and *Prorasenia* sp., indicate that the ironstone is confined to the Cymodoce Zone.

The natural exposures are poor and few; but in late 1966 a sewer-pipe trench exposed an almost complete section of the ironstone (loc. A, text-figs. 1, 2). This and other shallower excavations provided fresher and more fossiliferous material than now available from the natural exposures. All fossils in the natural exposures, and most in the excavations are leached. Collections of material are at present deposited in the Sedimentology Research Laboratory, Reading.

The ironstone has formerly been described from a stratigraphic and economic aspect by Blake and Hudleston (1877), Strahan (1898), Arkell (1933, 1936, 1947),

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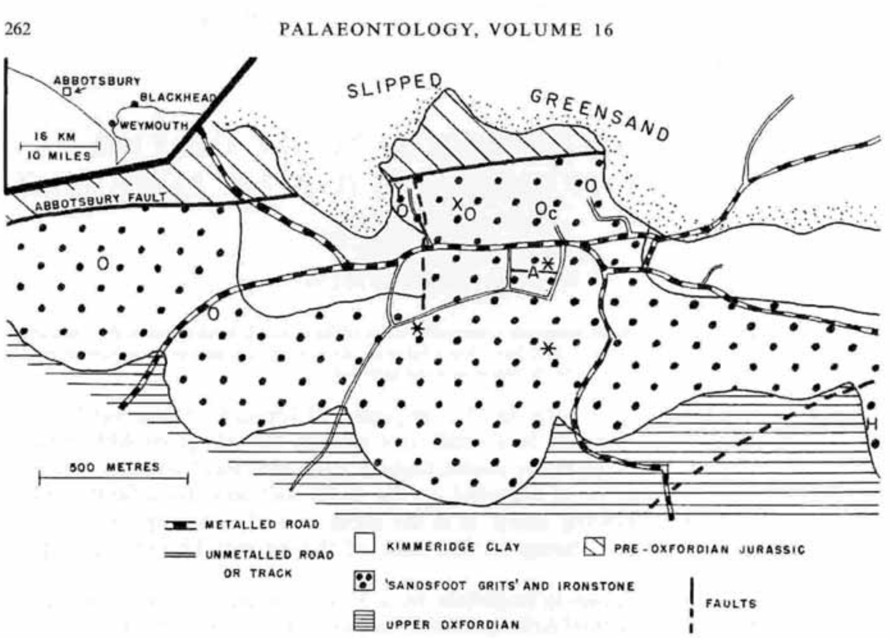


TEXT-FIG. 1. Geological map of the Abbotsbury area. Inset shows location and other exposures of Lower Kimmeridgian sediments. Letters, A, C, H, X, Y, are localities cited in text. Loc. A is in the centre of Abbotsbury village.
Open circles: areas with subfacies C_2.
Asterisks: areas with subfacies C_1.

Lamplugh *et al.* (1920), and Wilson *et al.* (1958). The purpose of this paper is to show the contribution that palaeoecological studies can make to the understanding of the depositional environment of oolitic ironstones; despite the wealth of sedimentological investigations on ironstones their faunas have been relatively neglected.

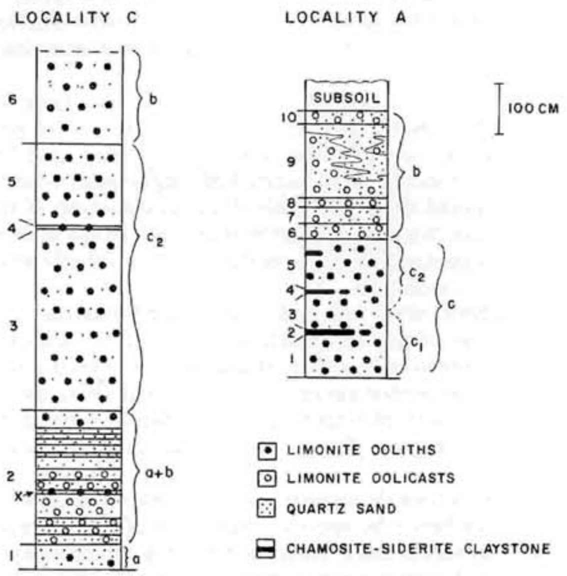
SEDIMENTS

The Abbotsbury Ironstone and associated Sandsfoot Grits can be divided into three main lithofacies, which are discussed in detail below.

A. Medium-bedded, moderately well sorted, bioturbated, fine-grained quartz sandstone.
B. Thin-bedded, poorly sorted to moderately well sorted, fine-grained quartz sandstone.
C. Massive, poorly sorted, limonite-oolitic fine-grained quartz sandstone.

The vertical distribution of these facies in the main exposures is shown on text-fig. 2.

The ironstone and underlying Sandsfoot Grits consist essentially of three constituents; chamosite clay, medium- to fine-grained quartz sand, and limonite ooliths. The differences in lithofacies are mainly due to differences in proportion of these



TEXT-FIG. 2. Sections of the Abbotsbury Ironstone. Bed nos. on left of columns, facies on right.

Loc. C

1. Reddish-purple, sparsely limonite-oolitic fine-grained quartz sandstone.
2. Irregularly thin-bedded, oolicast fine-medium-grained quartz sandstone. At X is the lowest stratigraphic occurrence of ammonites; *Rasenia* spp. and *Prorasenia* sp. of lower Cymodoce zone.
3. Massive, limonite oolitic fine-grained sandstone.
4. Thin parting as 3, with abundant *Aulacothyris dorsetensis*.
5. As 3, but getting less oolitic towards top.
6. Limonite-oolitic fine-grained quartz sandstone (less oolitic than 3) passing up into non-oolitic leached sand.

Loc. A

1. Reddish-purple limonite oolitic fine-grained sandstone.
2. Hard concretionary chamosite-siderite mudstone with sparse limonite ooliths.
3. As 1.
4. As 2.
5. As 1, oolith content variable.
6. Limonite-oolicast fine-grained sandstone, with concretionary limonite veins.
7. Limonite oolicast fine-grained sandstone, with abundant fossils.
8. As 7, with abundant ammonites.
9. Sparsely oolicast sandstone and leached, non-oolitic sand.
10. Limonite oolicast, fine-grained sandstone. Highest stratigraphic occurrence of ammonites, *Rasenia* spp. (transitional to *Aulacostephanus*), of upper Cymodoce zone.

three constituents. The sand grains are dominantly of sub-angular to sub-rounded strained quartz (always greater than 80% of the quartz sand fraction). A few sand grains show sutured grain contacts characteristic of metamorphic textures. Silt-sized particles are rare.

The most obvious diagenetic change is oxidation and leaching of the ironstone, probably at outcrop. This, however, has not altered the relative proportion of the major primary sedimentary constituents, quartz sand, clay, and limonite ooliths. The preservation of fossil moulds and uncrushed empty inner whorls of ammonites with their lappets preserved show that little if any compaction of the sediment has occurred. Even in the rare chamositic sideritic mudstone bands of facies C uncrushed shells indicate little compaction, and thus early growth of siderite and ferroan calcite cements in these bands is indicated.

Heavy mineral analysis, after hot hydrochloric acid treatment, of five samples from the base to the top of the composite Sandsfoot Grit–Abbotsbury Ironstone sequence showed the following in order of abundance: zoned zircon, tourmaline, staurolite, and garnet; with minor amounts of rutile, epidote, tremolite, and kyanite. Only zircon, a brown variety of tourmaline and epidote showed much rounding. All others were distinctly angular. There is no obvious variation in the heavy minerals between samples.

Both light and heavy minerals suggest that the sediments have not been extensively recycled, and can hence be used as indicators of the original source of the sediments. The light minerals show derivation from a tectonically deformed area. The heavy minerals indicate a source including metamorphic rocks. The most likely source is north-west France (Boswell 1924; Neaverson 1925), the sediments being carried from this area by a river occupying the western approaches of the English Channel (cf. Davies 1969; Wilson 1968). Despite the evidence from clay mineral studies (Cosgrove and Salter 1966), there is no evidence from the light and heavy minerals of derivation from south-west England (and the clay mineral distributions, at least in the Upper Oxfordian–Lower Kimmeridgian, are not as simple as Cosgrove and Salter indicate). This could either be due to lack of drainage from south-west England, or more likely, in view of the occurrence of Oxfordian and Kimmeridgian sediments in the Bristol Channel (Donovan 1971), the south-west England area was covered by a shallow sea. If the interpretation of the Abbotsbury sediments as subtidal barrier bar deposits is correct, they would separate a deeper basin towards the south-east from a hypothetical lagoonal area to the north-west.

FAUNA

The Abbotsbury Ironstone fauna (Table 1) is taxonomically dominated by bivalves, though in facies C brachiopods are numerically more abundant. The fauna can be closely compared ecologically with that of the Frodingham Ironstone (Hallam 1963).

Arkell (1936) stated that the Abbotsbury Ironstone had a specialized fauna. However, most of the bivalves and gastropod species are the same as those found in the equivalent Cymodoce Zone strata at Weymouth, and are either identical or allied to species of the underlying Upper Oxfordian. The brachiopods *Aulacothyris*

TABLE 1. Invertebrate fauna of Abbotsbury Ironstone, inferred feeding and ecological type, and facies distribution.

SPECIES	ECOLOGY	FACIES
Brachiopoda		
?*Septaliphoria hudlestoni* (Rollier)	ATTACHED EPIFAUNAL	c
'*Terebratula*' *subsella* (Leymerie)	SUSPENSION	c
Ornithella lampas (J. Sowerby)	,,	c
Aulacothyris dorsetensis (Davidson)	,,	bc
Lingula sp.	INFAUNAL SUSPENSION (1)	abc
Echinodermata		
Nucleolites scutatus (Lamarck)	SHALLOW INFAUNAL (2)	b
Bivalvia (3)		
Ostrea grypheata De Loriol	ATTACHED EPIFAUNAL (4)	b
Exogyra nana (J. Sowerby)	SUSPENSION	bc
Modiolus sp.	,,	b
Gervillia ?aviculoides (J. Sowerby)	,,	bc
Trigonia reticulata Agassiz	,,	b
Anisocardia globosa (Roemer)	SHALLOW INFAUNAL SUSPENSION	ab
Astarte ovata (Wm. Smith)	,,	b
Pholadidea abbreviatus (Blake and Hudleston) (5)	,,	b
Isodonta triangularis (Phillips)	?	b
Opis (*Trigonopis*) *corallina* Damon	?	b
Pleuromya uniformis (J. Sowerby)	DEEP INFAUNAL SUSPENSION	abc
Goniomya literata (J. Sowerby)	,,	a
Pholadomya canaliculata Roemer	,,	b
Entolium corneolum (Young and Bird)	SWIMMING EPIFAUNAL SUSPENSION	bc
Camptonectes auritus (Schlotheim)	,,	bc
Chlamys aff. midas Damon	,,	ab
Velata sp.	EPIFAUNAL SUSPENSION	bc
Gastropoda		
Bathrotomaria spp.	EPIFAUNAL ?HERBIVOROUS (6)	bc
Dicroloma sp.	?	bc
Chemnitzia sp.	?	bc
'*Natica*' sp.	?	bc
Amberlya sp.	?	bc
Cephalopoda		
Rasenia spp.	NEKTONIC ?CARNIVORE	bc
Paracenoceras calloviense (Oppel)	,,	b
Annelida		
Serpula spp.	ATTACHED EPIFAUNAL SUSPENSION (7)	bc

References are as follows: (1) Craig 1966, (2) Durham 1966, (3) Purchon 1968, (4) Yonge 1960, (5) Turner 1954, (6) Morton 1967, (7) Dales 1967.

dorsetensis and *Ornithella lampas* have been recorded in a Cymodoce Zone limestone at Cambridge, as has '*Terebratula*' *subsella* under the genus *Loboidothyris* (uncatalogued material in Sedgwick Museum, Cambridge). The only species that is unique to the ironstone is ?*Septaliphoria hudlestoni*, whose asymmetric variants have often been mistakenly recorded as *Torquirhynchia* [*Rhactorhynchia*] *inconstans*.

No microfauna was detected, probably due to the post-depositional leaching, and trace fossils are mainly confined to vague mottlings seen in some mudstone beds.

Each facies has its own faunal assemblage, with little sign of intergradation.

Fossils are generally rare, except in certain beds of facies B and lenses in facies C (see p. 269). The individual facies faunas are considered to be dominantly life assemblages because:

1. Few shells are broken: those that are belong to fragile types, e.g. occasional *Entolium*, *Nucleolites*, tall-spired gastropods.
2. Most of the bivalves are still articulated.
3. None of the shells show signs of wear.
4. Many of the burrowing forms are in life position (e.g. *Pleuromya*) and in some cases even the epifauna is in place (brachiopod 'nests', serpulids, and oysters in facies C.
5. Individual facies faunas pass very rapidly laterally into each other, e.g. facies C into B over a distance of less than 30 m.

The above points indicate very little disturbance of the fauna. The main exception is the breakage of *Chlamys* valves in facies A, which is considered to represent the most turbulent environment.

The inferred mode of life of each member of the ironstone invertebrate fauna is shown in Table 1. The percentage distribution of types in each facies is shown in text-fig. 3.

DEPOSITIONAL ENVIRONMENT

All the facies accumulated in a somewhat restricted range of environments, in which the wave turbulence was sufficient to move fine- to medium-grained quartz sand and generally keep clay in suspension, but insufficient to move or wear shells much, and incompetent to move sediment coarser than medium-grained sand. This is shown by the general absence of penecontemporaneous pebbles, which are frequently common in ironstones. Small clay pebbles are confined to rare occurrences in facies A.

Within this environmental framework, several higher and lower energy environments can be distinguished. These are based mainly on the fauna, but in part on the proportion of clay to sand, and the sorting characteristics of the sediment. The differences between environments is ascribed to differences in mean turbulence, and

FACIES	(a)	(b)	(c)	
SUBFACIES			2.	1.
NUMBER OF PRESERVED BENTHIC SPECIES	5	21	12	6
% EPIFAUNA	20	42	50	100
% INFAUNA	80	29	17	0
% UNKNOWN	0	29	33	0

TEXT-FIG. 3. Percentage of each ecological type in each facies.

thus by implication, depth. Variations in salinity and temperature as environmental controls are unlikely in view of the rapid lateral facies transitions. At least in facies C faunal differences cannot be attributed to substrate differences, and the range in grain size is insufficient to account for the pronounced faunal differences between facies.

Facies A. Medium-bedded, moderately well-sorted, bioturbated, fine-grained quartz sandstone.

This forms the major part of the ferruginous sandstones (Sandsfoot Grits) below the ironstone at localities H and C (text-fig. 1). The bedding units are of the order of 1 m. The sandstones are fine- to medium-grained and contain up to 5% of limonite ooliths, from which the iron is usually leached forming oolicasts (Pettijohn 1957: although oolimoulds would be a more accurate term). Where the sparse interstitial matrix has survived leaching and oxidation it is a chloritic, chamositic, and/or sideritic clay. Extensive bioturbation is present in most beds.

Considering the evidence for a turbulent environment (see below), much of the clay may have been introduced by bioturbation after relatively rare periods of clay deposition.

The macrofauna is sparse, consisting of deep and shallow burrowing suspension feeders and epifaunal suspension feeders (Table 1). In some beds the bioturbation takes the form of indistinct mottling indicating extensive biogenic reworking by deposit feeders. No recognizable ichnogenera occur. This bioturbation does not disturb the deep burrowing macrofauna, nor a few ½-cm-diameter tubes which, in one bed, penetrate to 25 cm from the top of the bed: this possibly represents an additional non-preservable suspension feeder. Thus deposit feeding apparently predated suspension feeding in these beds. No adjustment of the burrowers to erosion and deposition can be traced, due to the lack of any preserved primary sedimentary structures (though this was not confirmed with X-ray studies).

The thick sedimentary units of this facies (average 1 m) appear to have been deposited fairly rapidly; there are no identifiable fossil fragments in the lower parts of the beds; bioturbation is often extensive throughout with no sign of internal partings; identifiable trace fossils all extend down from the tops of the beds; and the deep-burrowing bivalves (*Pleuromya*) are *in situ* and at a constant horizon below the tops of the beds. The shallow burrowing and surface-living species (*Chlamys*, *Anisocardia*) are disarticulated, but only *Chlamys* is usually damaged: this indicates merely reworking of the top few centimetres of the bed, with little transport. The presence of epifaunal bivalves possibly capable of swimming (*Chlamys*) in the tops of the beds shows that these were the only forms capable of surviving the movement of sand at the sediment-water interface, probably by migration from one temporarily stable area to another. Simple washing in is unlikely as one would then expect them to be scattered through the beds and not consistently recur at the top of each bed.

The faunal characteristics of this facies are those of beaches or shallow subtidal areas (Rhoads 1967), where attached surface living is impossible and animals form deep burrows, both to avoid reworking and on beaches to avoid desiccation. In its grain size, heavy bioturbation, and fauna of dominantly deep burrowers this facies closely resembles the tidal sand flats of the Solway estuary, Scotland (personal observations; see also Wilson 1967). They differ from them in the intensity of bioturbation—usually some lamination survives in the Solway, and in the type of deep burrower—the Solway species consist of motile deep burrowers, whereas the Abbotsbury species (*Pleuromya*) is a sessile deep burrower. These differences may be related to slower rate of deposition of facies A. Facies A also lacks evidence for tidal channels: however, east of the map area (text-fig. 1) an isolated exposure at Rodden (Grid. Ref. SY 590846) shows a fragmental shelly sand with reworked *Pinna* sp. which may possibly represent a basal channel lag. A possibly closer analogy is with the middle shoreface sands of Galveston Island, Texas (Davies *et al.* 1971; Bernard *et al.* 1962), which consist of fine grained, structureless, bioturbated sands deposited in 5–30 ft (1·7–9 m) of water. Thus facies A could represent either tidal or subtidal sands: a decision between these is not possible. The absence of evidence of exposure is not significant, as the Solway sediments, although continuously exposed at each low tide, also show no evidence of exposure in sections.

Facies B. Thin-bedded, poor- to moderately well-sorted, fine-grained quartz sandstone.

This forms the upper beds of the ironstone in all exposures, and also some of the upper beds of the Sandsfoot Grits at locality C (text-fig. 2). Individual bed units are less than 5 cm thick and contain up to 5% of limonite oolicasts. The sparse matrix is oxidized chamosite–siderite clay. No bioturbation can usually be seen.

This facies contains the most diversified fauna, both in terms of species abundance and ecological type (Table 1). The fauna consists dominantly of abundant bivalves, gastropods, and ammonites: none of these show signs of wear and the ammonites have their lappets preserved. The ecological types include deep and shallow burrowing suspension feeders, epifaunal suspension feeders and nektonic forms. Carnivores and scavengers, not recorded in Table 1, are represented by rare ichthyosaur fragments and arthropods (*Eryma* sp.).

This facies represents a quieter water environment than facies A. This is indicated by the presence of a large diverse fauna, including all the major feeding types except deposit feeders, and by the abundance of shallow burrowing and epifaunal forms. The fauna is, however, still dominated by suspension feeders. The sedimentary units are thinner, and the deep burrowers in life position are scattered vertically throughout this facies, indicating that thick units were not deposited rapidly, but that sedimentation was slow enough to allow adjustment of the burrowers to erosion and deposition, or to allow renewed colonization. Some beds show features, such as impoverished fauna and thicker bedding, transitional to facies A.

The presence of common attached epifaunal suspension feeders (*Exogyra*, *Serpula*) and motile surface feeders (? some of the gastropods) indicate a greater stability of the sediment surface than facies A. The presence of oysters and serpulids also indicate periods of non-deposition and absence of movement of the sediment surface, in order to allow colonization by these forms; although the oysters are of the cupped type enabling them to cope with a certain amount of sedimentation on reaching maturity.

It is uncertain whether the increased stability of the sediment surface was due to decreased turbulence or whether the surface was stabilized by a vegetation cover.

Some of the attachment areas of the oysters seem to indicate attachment to vegetation. The type of vegetation indicated is round, whip-like stems, approximately 2–3 mm in diameter, probably algae. Marine grasses had not evolved by the Jurassic.

The physical conditions of this facies can be summarized as: turbulence sufficient to keep clay in suspension, but insufficient to move the sand surface continually and insufficient to move shells much; deposition of thin units of sand separated by periods of non-deposition. This fits in with the poorer sorting of the sediments relative to facies A. Modern analogues of this facies are those of shallow shelf regions (Newell *et al.* 1959; Parker 1964; Purdy 1964). In view of the vertical alternation (text-fig. 2), facies B may be considered as a deeper equivalent of facies A.

Facies C. Massive, poorly sorted, limonite-oolitic, fine-grained quartz sandstone.

This forms the main ironstone beds. Limonite ooliths make up 40–50% of the rock by volume, with fine- to medium-grained quartz sand about 40%. The matrix is chamosite-siderite clay, up to 20%, but in several beds in the trench (loc. A, text-fig. 2) the percentage rises to 60%, and the consequent decreased porosity has preserved the clay in its original unoxidized state. Bedding is apparently absent, except for the intercalation of the clay bands.

The macrofauna is sparse and confined to a few species of brachiopods and bivalves, and occasional gastropods and serpulids (Table 1). The brachiopods tend to be concentrated in 'nests' or lenticles. 'Nests' are globose clusters of brachiopod shells, usually monotypic, and thought to be original colonial associations (Hallam 1962; Ager 1967). The Abbotsbury 'nests' consist of only one species, *Aulacothyris dorsetensis*. 'Nests' indicate that attachment areas were rare and utilized to their full potential (cf. brachiopods on New Zealand boulders, Rudwick 1962). The lack of preserved growth rings on the brachiopods, due to cast preservation, makes stunting difficult to detect: but other species, such as ?*Septaliphoria hudlestoni* and '*Terebratula*' *subsella* have typically mature commissures. (Perhaps it should be noted here that *Ornithella lampas* and '*Terebratula*' *subsella* could be simply different growth stages of the same species, as the characteristic commissure of '*T.*' *subsella* does not develop until about 2 cm size, and below this their range of variation is very similar to *O. lampas*.) The reason for the small size of brachiopods forming 'nests' is probably the low food supply in a given volume of water. A large colony of small brachiopods could live in an area whose food supply was insufficient for even a small colony of large brachiopods. This correlation of size with 'nests' also disproves the idea that 'nests' are storm accumulates, as there is no reason why storm accumulates should consist only of small species.

Lenticles can be divided into two types: monotypic lenticles, and lenticles with several invertebrate species. Monotypic lenticles may represent either collapsed 'nests' or original colonial associations on the sediment surface. The latter is probably the mode of life of the curious species ?*S. hudlestoni*. This never forms 'nests' but occurs in monotypic lenticles. It is much larger than *A. dorsetensis* and shows a curious variation in symmetry of the commissure. This varies from asymmetrical to the left, through symmetrical, to asymmetrical to the right. This may be a direct phenotypic response to interference with the inhalent currents consequent on a colonial mode of life. It can be contrasted with genotypic asymmetrical brachiopods, such as *Torquirhynchia inconstans*, which is always asymmetrical either to left or right but shows no intermediate stages (cf. Ager 1967).

Lenticles with several species may either represent original colonial associations with a few exotic species, or more likely current accumulations of shells in irregularities in the sediment surface. 'Nests' and lenticles with several species are characteristic of different sub-environments of facies C.

All other faunal elements of facies C occur randomly, and are rare, except where they occur in lenticles. However, they are rarely damaged or worn and Pectinids are frequently articulated. The fauna can be used to distinguish two sub-facies.

Sub-facies 1. This occurs at the base of the ironstone in the trench (loc. A, text-figs. 1, 2) and elsewhere is restricted to the exposures shown on text-fig. 1. It passes very rapidly laterally into the second sub-facies.

The fauna consists of the brachiopods '*Terebratula*' *subsella*, *A. dorsetensis*, *O. lampas*, and ?*S. hudlestoni*; the bivalves *Entolium corneolum*, and *Exogyra* sp., and several species of serpulid worms (Table 1). The brachiopods are distributed in 'nests' (*A. dorsetensis*), monotypic lenticles (*A. dorsetensis*, ?*S. hudlestoni*), or isolated (all). Disarticulated shells are very rare. The serpulids grew on the brachiopod shells, or used them as initial attachment points. The bivalves are frequently articulated with both valves closed: the oysters, *Exogyra* sp., always have both valves together and closed. All the fossils, except where they occur in 'nests' and lenticles are rare. All forms are epifaunal suspension feeders and most are attached forms indicating breaks in sedimentation and cessation of movement of the sediment surface during which the fauna could colonize the sea floor.

This represents the environment of quietest conditions, as shown by the dominance of attached epifauna on a soft bottom. It is abnormal in that it contains no preserved infauna (even traces of burrowers) or any epifauna that contacted the sediment with their soft parts (e.g. gastropods). This is in direct contrast to the usual case in recent deposits, where an increase in mud content, related to the organic content of the sediments, allows an increase in the number of infaunal and deposit feeders. The absence of infauna could be attributed to removal of aragonitic forms by solution. This would bias the preserved fauna in favour of calcitic forms, and certainly the forms found are all calcitic, with the exception of the ammonites. But aragonitic forms are found in the lithologically identical sub-facies 2, and aragonitic forms should be detectable in sub-facies 1, if originally present, since sediment compaction is virtually absent.

The lack of infauna is associated with the presence of the brachiopod 'nests', whose formation has been ascribed to attachment of brachiopods to seaweed or sponges (Rudwick 1961; Ager 1965). The epifauna indicates normal oxidizing conditions at and above the sediment-water interface, so the infaunal absence must be due to chemical or mechanical factors within the sediment, or to faunal interactions with the epifauna. Chemical control seems unlikely, as the only signs of reducing conditions within the sediment is post-depositional pyrite within shell material; none is developed outside in the matrix, and limonite ooliths have not been altered to a more reduced form or replaced by siderite or pyrite. This also does not explain the absence of such epifauna as gastropods.

Faunal interactions are possible. Zenkevitch (1963) found that in certain cases bottom deposits were suitable for colonization by infauna but that the epifauna had taken all the food supplied.

Another possibility is that mechanical factors made the bottom unfit for colonization by infauna. In view of the absence of gastropods, this is more likely. If the brachiopod 'nests' were formed by attachment to sponges, the absence of infauna can be explained. Ager and Evamy (1964, p. 334) commented on the common association of the rhynconellid *Lacunosella* and sponges in the Upper Jurassic of the French Jura (confirmed by Childs 1966). Ager (1967) figured a sponge (from Ijima 1902) with no less than sixty-nine individual brachiopods attached. Zenkevitch (1963) noted that in the Barents Sea, the bottom may contain large amounts of sponge spicules and owing to mechanical factors may become unfit for benthos. This occurs on the Kildin bank, where finely cartilaginous and sufficiently silted floors give refuge to a rich epifauna, and are almost devoid of infauna. Sponges and brachiopods are predominant in these regions. The development of other members of the epifauna are also restricted by the mass growth of sponges, since these powerful filters take all the nutrients out of the water.

This would explain the dominance of brachiopods in this sub-facies, with only a few other forms. It can also explain the curious lack of lamination without evidence for bioturbation, as decay of cartilaginous sponge spicules could cause loss of any lamination prior to shell solution. The absence of sponge spicules in the sediments is against this interpretation, but the spicules may have been leached out together with the microfauna, or the sponges may have been entirely cartilaginous.

Sub-facies 2. This lies to the north and west of sub-facies 1 and vertically above it in the trench (loc. A, text-fig. 2). It is lithologically identical to sub-facies 1. It forms the main ironstone where sub-facies 1 is absent. Faunally it is distinguished by the presence of gastropods and rarity of all brachiopods with the exception of *A. dorsetensis*. Ecologically the fauna shows an increase compared to sub-facies 1 of motile epifaunal feeders, the gastropod *Bathrotomaria*, and perhaps some of the other gastropods. In this sub-facies all the brachiopods are spread out into lenticles of the predominantly mixed type and there are no 'nests'. Gastropods of the genera *Bathrotomaria* and *Nerinea* are common. In most exposures the bivalve fauna is restricted to *Exogyra* and Pectinids (*Chlamys*, *Entolium*) with occasional *Pleuromya*, but there is a slight increase in diversity of the bivalves towards the north-west (locs. X and Y, text-fig. 1), where *Trigonia* and *Astarte* are found in this sub-facies. This may indicate a gradation in that direction into facies B.

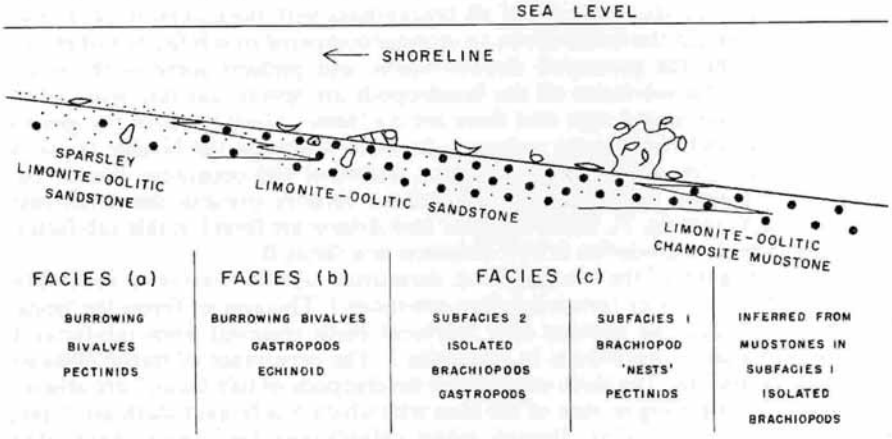
The spreading out of the brachiopod *A. dorsetensis* together with other shells into lenticles indicates greater turbulence than sub-facies 1. This species forms the 'nests' in sub-facies 1 and the lenticles may represent shells removed from sub-facies 1 and concentrated in depressions in sub-facies 2. The occurrence of mixed lenticles tends to confirm this. The three other larger brachiopods of sub-facies 1 are absent. This is rather surprising in view of the ease with which brachiopod shells are transported (Boucot *et al.* 1958). Though others (Middlemiss 1962) have shown that brachiopods are not likely to be transported far without comminution, the absence of transport over as short a distance as 30 m indicates some sort of baffle preventing transport—such as the sponges mentioned in sub-facies 1. *A. dorsetensis* could be transported, as it lived attached to the sponges, and thus could be lifted off them.

The mode of deposition of the two sub-facies can be treated together. Both were apparently formed in an environment transitional between sand and clay deposition, thus probably at greater depth than either of the other facies.

Conditions envisaged are fairly rapid periods of deposition separated by periods of non-deposition. There was little movement of the surface after deposition, and these stable substrates were colonized by a variety of attached epifauna, intolerant of surface movement. This colonization could not occur in an environment of continual deposition: slow deposition could not account for the burial of whole colonies and lenticles of brachiopods in life position. Thicknesses of up to 30 cm of sediment must have been rapidly deposited in order to preserve the brachiopod 'nests'.

Recent analogues of such a specialized environment are difficult to find. The poor sorting, presence of clay bands, and evidence of lateral passage into facies B indicates a quieter water equivalent for facies C. Whether this was due to increased depth, or to baffling by organisms such as sponges or algae is not known.

Environmental summary. As noted above, the faunal and lithological characteristics of the Abbotsbury Ironstone seem to fit best a nearshore environment, or one marginal to an offshore (barrier) bar (text-fig. 4). An offshore (barrier) bar is preferred, due to the absence of any shoreline or strand indications, such as shell hashes, and strand line shell and fish accumulations; and the lack of any sediment derived from south-west England. The reconstruction indicated is of a barrier bar, facing south-east. This is similar to the reconstruction of Davies (1969) for the Upper Lias sands, with the difference that no land is thought to have existed in south-west England.



TEXT-FIG. 4. Reconstruction of the facies distributions of the Abbotsbury Ironstone, with characteristic faunal elements. 'Shoreline' refers to beach or top of bar.

The vertical sequence and indications of lateral passage between environments suggests a gradual deepening during the course of deposition, until facies C_1, with shallowing again above this. The nearest analogue of the Abbotsbury environment appears to be the barrier bar environments of the Gulf of Mexico, discussed by Bernard *et al.* (1962). If the Cymodoce Zone sediments on the Dorset coast at Weymouth are considered, the comparison can be strengthened. These consist of a series of clays, siltstones, and fine-grained sandstones (Blake's, 1875, Transition Beds). Palaeoenvironmental studies (unpublished) indicate that these sediments can be interpreted as open bay, topset, prodelta deposits comparable to those of the Gulf of Mexico region (Shepard 1956; Parker 1956), with marine fining upward cycles interpreted as distal barrier bar inlet deposits. The Recent sediments of the northern Gulf of Mexico are the result of a Holocene transgression, punctuated by periods of stillstand (Bernard and Leblanc 1965): the Lower Kimmeridgian sediments in Dorset also show transgressive sedimentation, with evidence for stillstand in the Cymodoce Zone. The depositional episode of the Abbotsbury Ironstone was apparently terminated by a marine transgression bringing the relatively quiet water black clays of the Mutabilis Zone westwards over the former barrier bar environment.

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