THE SEDIMENTOLOGY AND PALAEOECOLOGY OF THE CORALLINE CRAG (PLIOCENE) OF SUFFOLK

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To Margaret

Frontispiece

Top : Coralline Crag phosphorite deposit resting on irregular London Clay surface. Ramsholt Cliff. Scale is 25cm long.
Bottom : Coralline Crag exposed at Crag Farm showing large-scale cross-stratification and ochreous yellow coloration. Scale is 1m long.

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The Sedimentology and Palaeoecology of the Coralline Crag (Pliocene) of Suffolk

Peter S. Balson

ABSTRACT

The Coralline Crag is a Pliocene, shallow marine, bioclastic sand formation with an outcrop restricted to south-east Suffolk. Four distinct sedimentary facies have been recognised which indicate that the Coralline Crag was deposited during a single marine transgression. The stratigraphically lowest facies is a nodular phosphorite horizon resting on an eroded surface of London Clay (Eocene). The components of the phosphorite deposit include phosphatic pebbles and cobbles and assorted phosphatised fossils which were derived from a variety of sources including a Miocene sand formation which was broken up during the transgression. The composition of the phosphorite mineral has been examined using electron microprobe, X-ray diffraction and X-ray fluorescence techniques and found to be francolite (carbonate fluorapatite). The phosphorite is overlain by a bioturbated, bioclastic silty sand facies deposited in shallow marine conditions at an early stage during the transgression. This facies is succeeded laterally and is overstepped by a sandwave facies of cross-stratified, comminuted and abraded bioclastic sand. The sandwave facies is succeeded laterally north and eastwards by a facies of coarse skeletal sands with a relatively small terrigenous sediment content.

The sedimentary and faunal characteristics of these facies and their vertical and lateral distribution indicate the former presence of a linear sandbank (sandwave facies) possibly parallel to the Pliocene shoreline. Sediment travelled along a transport path from the north-east, along the bank and was deposited in the nearshore zone.

Subsequent meteoric diagenesis led to widespread dissolution of aragonitic grains. Dissolution was restricted to facies with high primary porosity which were preferentially preserved from erosion by the concomitant cementation. Calcitic bryozoans are proved to be useful environmental indicators when studied in conjunction with sedimentary evidence. The unusual large cyclostome Bryozoa, characteristic of the Coralline Crag, are shown to have varying growth morphology dependant on substrate type.

Chapter 1

Introduction

1.1 'Coralline Crag'

1.2 Outcrop of the Coralline Crag

1.3 Thickness of the Coralline Crag

1.4 History of research of the Coralline Crag

1.5 Commercial exploitation of the Coralline Crag

1.6 Aims of this study

Chapter 1 Introduction

1.1 'Coralline Crag'

The word 'Crag' is a local East Anglian term used to denote any dominantly shelly sand. The word has found its way into many local place names eg. Crag Farm, Crag Pit Nursery, Crag Path etc. These shelly sands have been worked and their fossils collected for hundreds of years, but it was not until 1835 that it was realised that at least two distinct deposits of different ages were included under this name (Wood in Charlesworth, 1835a p.85). Until this time most observers thought that the lower deposit was the undisturbed portion of the upper deposit.

> "Beneath the common stratum of shells and pebbles is a bed of sand devoid of that peculiar deep tinge which so generally accompanies the crag-formation: this bed is in contact with the London Clay, and contains a great assemblage of organic remains; but these exhibit so novel a character, and the circumstances under which they were deposited were evidently of so different a nature from those of the superior stratum, as at once to strike the attention of the most casual observer". (extract from Charlesworth, 1835a, p.83)

Charlesworth (1835a) thus divided the "crag-formation" into an upper division, which he termed the 'Red Crag' after its distinctive reddish coloration, and a lower division which he termed the 'Coralline Crag' after the abundant 'corals' found in that deposit. These 'corals' were later shown to be the skeletal remains of Bryozoa (Wood, 1844, Milne Edwards and Haime, 1850). It is interesting to note that Charlesworth in this paper used the term 'coral' and not 'coralline' as misquoted by many later authors. He wrote (p.87) "These corals sometimes occur in a loose sandy grit, from which they are readily attached: but it frequently happens that the stratum is almost wholly constituted by them......." He later refers (p.93) to these as the remains of 'zoophytes' but nowhere was the term "coralline" used to describe the organisms.

His separation of the Coralline Crag as a distinct and older deposit to the Red Crag was not without critics. Woodward (1835) in an acrimonious reply to Charlesworths paper wrote "... his [Charlesworth's] term 'Coralline Crag' is not appropriate, as it leads us to suppose that it is composed of corallines, when in fact there are none in the Ramsholt bed, which is chiefly adverted to". If Woodward meant bryozoans when he used the term 'coralline' he was certainly mistaken, bryozoans being very numerous at Ramsholt (= thesis locality 3). The argument continued for several years with Charlesworth (1835b, 1836, 1837), Fitch (1835) and Lyell (1839) supporting the validity of the Coralline Crag as a division and Woodward (1836) and Desnoyers (1838) opposing it. The erroneous use of the word 'coralline' by Charlesworth led to a plethora of alternative names including 'Bryozoan Crag', 'Polyzoan Crag', 'White Crag', 'Lower Crag', 'Lowest Crag' and 'Suffolk Crag' (Jones and Parker, 1864; Bell and Bell 1871, 1872; Dalton and Whitaker, 1886; Burrows, 1895b). For one reason or another these terms never found lasting favour and Charlesworth's original name has been retained.

1.2 Outcrop of the Coralline Crag

The known, present day, surface outcrop of the Coralline Crag consists of a series of small disjunct outcrops aligned roughly NE-SW which lie to the east and north-east of Ipswich in south-east Suffolk (fig. 2). The main body of the Coralline Crag lies between Aldeburgh in the north and Gedgrave in the south but is cut just south of Aldeburgh by the course of the River Alde (fig. 3). This main body is roughly 13 km long and 3.5 km across at its maximum width and generally forms a slightly elevated ridge relative to the surrounding area. This is due to the slightly greater resistance to weathering of the indurated Coralline Crag (see Chapter 8) relative to the less well cemented, younger deposits which surround it. The subsurface extent of this body is poorly known but extends as far north as Sizewell and thence offshore. (Lyell, 1839., Lees, 1980). It extends southwards probably as far as Boyton Marshes (Whitaker, 1885) which lie to the south of the Butley River. A small, discrete body of Coralline Crag is situated at Rockhall Wood,9 km to the south-west of the main outcrop. This small outlier is surrounded by the outcrop of the stratigraphically younger Red Crag and is therefore an inlier with respect to the overlying Pleistocene. (see Prestwich 1871a for detailed map and sections through the Rockhall Wood outcrop). A further small,discrete body of Coralline Crag is found 1.5 km south of Rockhall Wood at

Figure 1

Geological map of the East Anglia region (after Chatwin, 1937). Thesis study area shown by heavy rectangle.

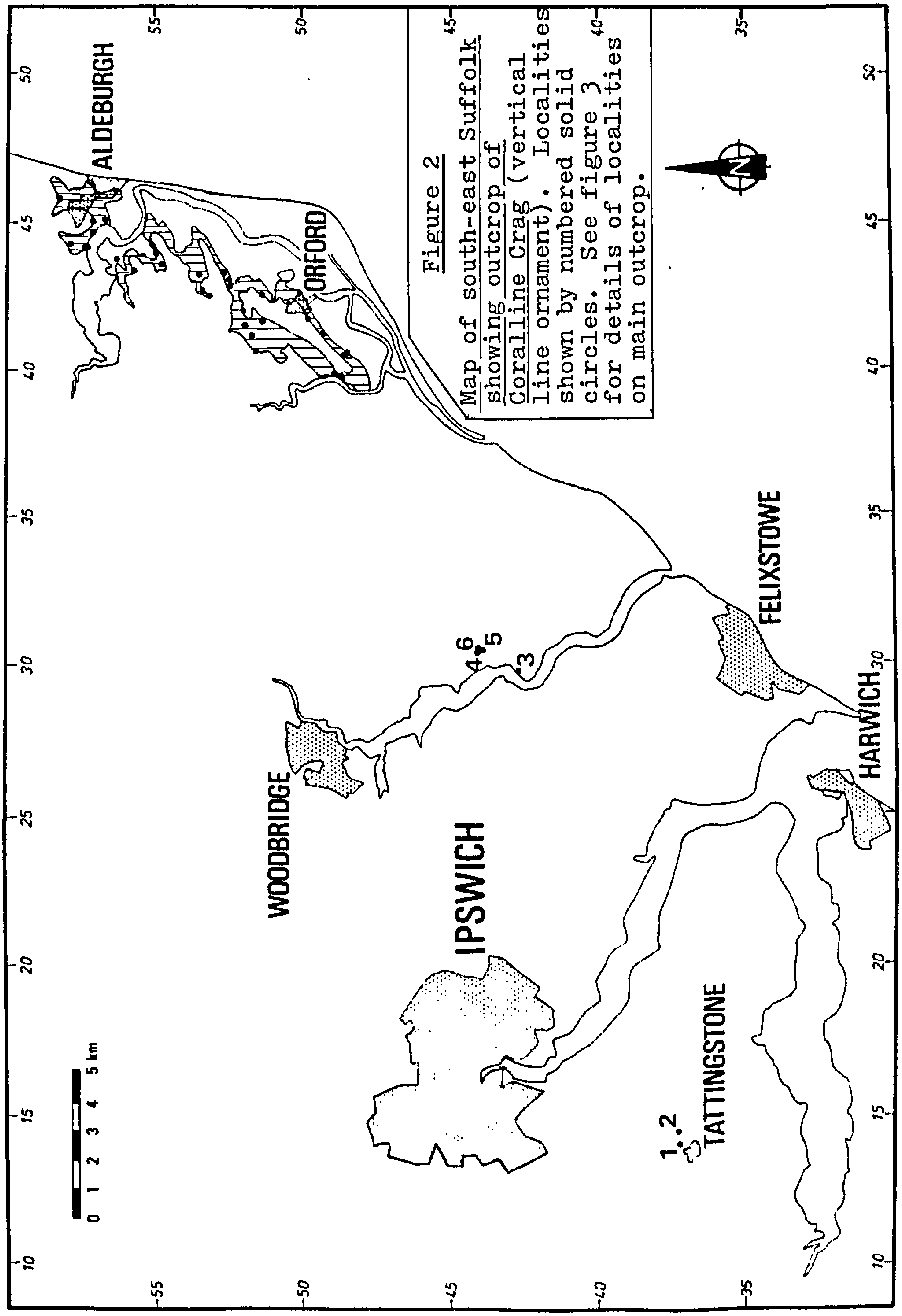


Figure 2

Map of south-east Suffolk showing outcrop of Coralline Crag (vertical line ornament). Localities shown by numbered solid circles. See figure 3 for details of localities on main outcrop.

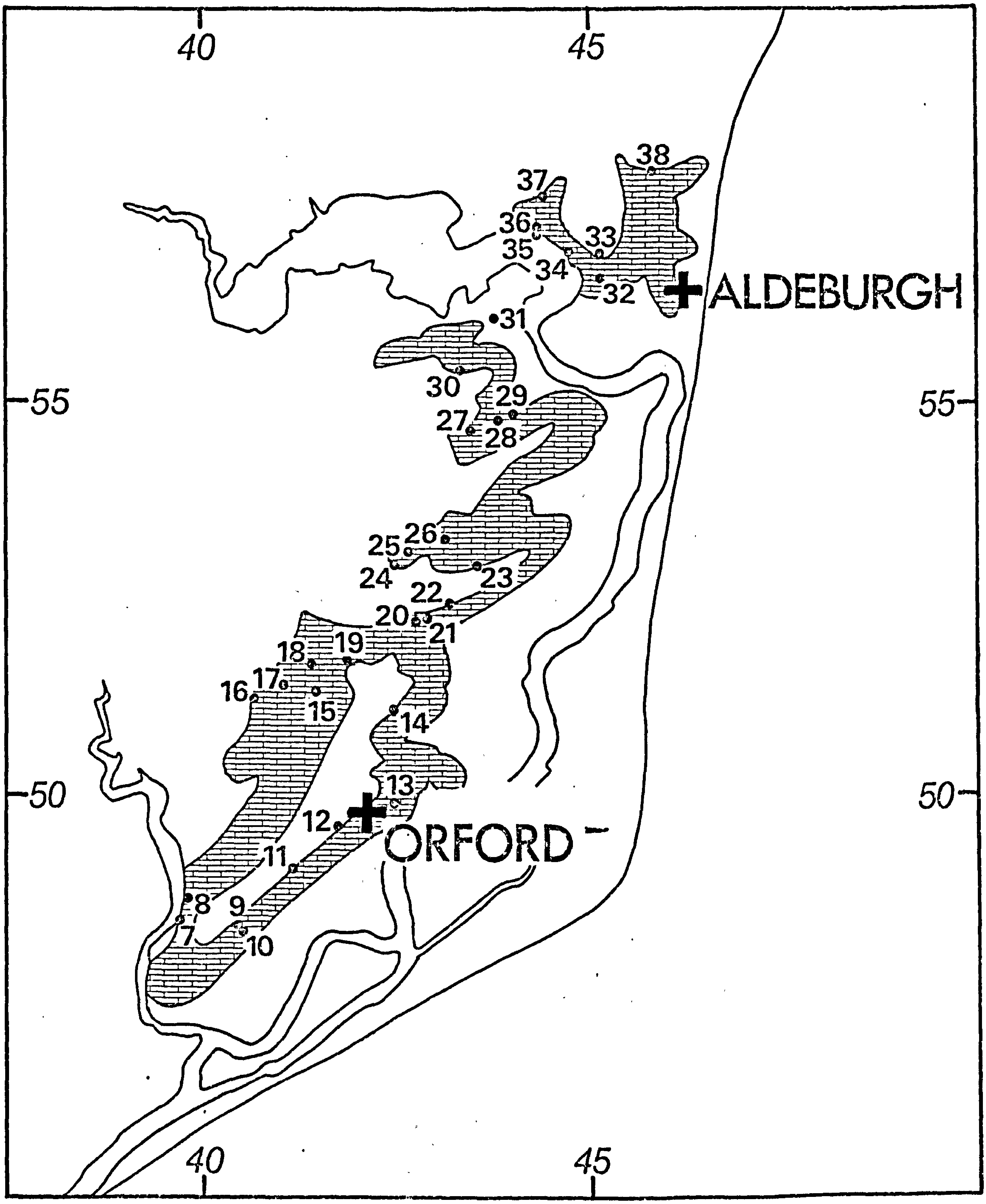


Figure 3

Map showing main outcrop of Coralline Crag (brick ornament). Localities shown by numbered solid circles. (cf. figure 4)

National grid references of localities are listed in Appendix 4.

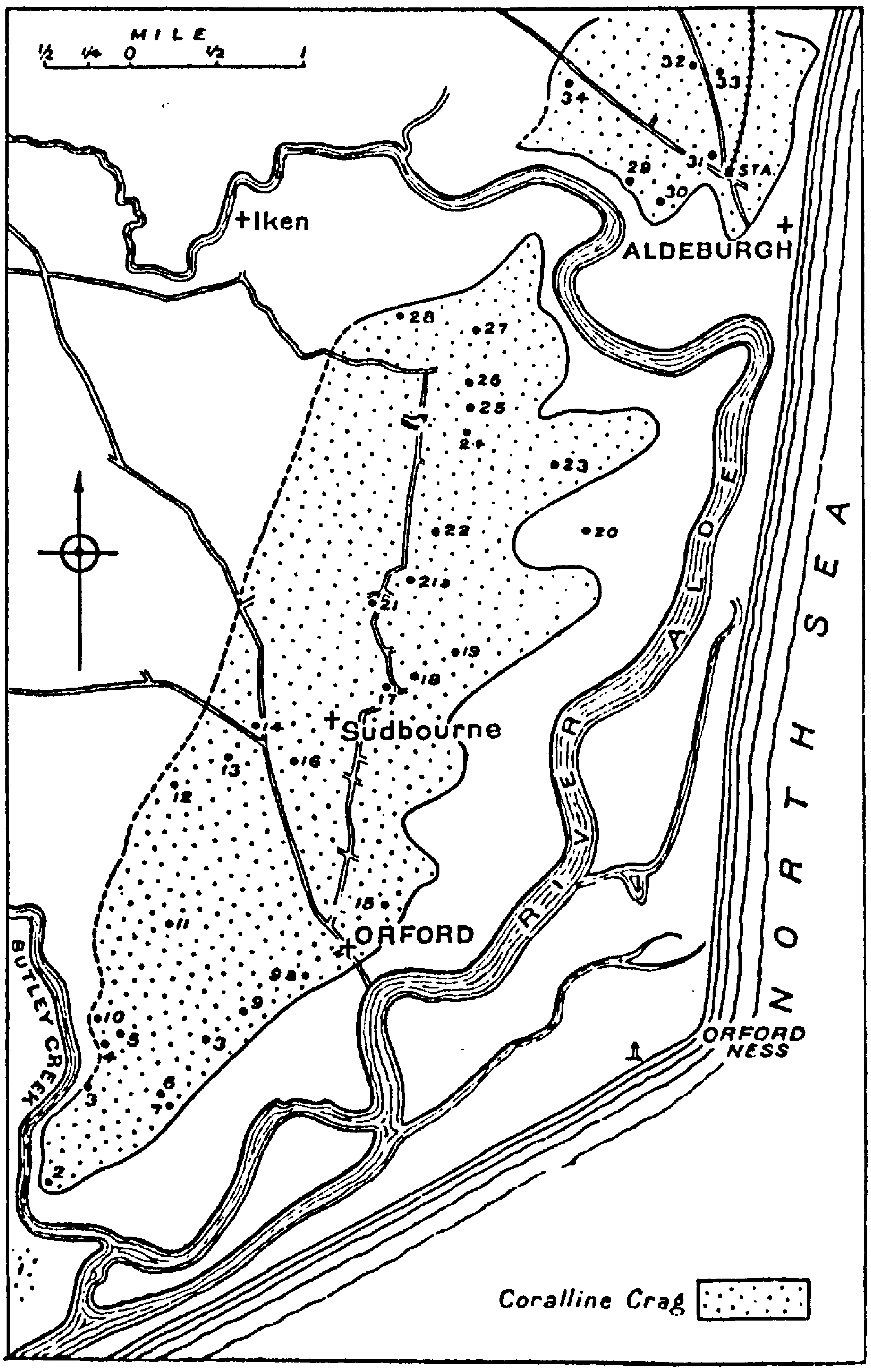


Figure 4

Map showing main outcrop of Coralline Crag and localities described by Harmer (1898) (after Boswell, 1928).

Ramsholt Cliff on the bank of a meander of the River Deben. The precise extent of this small outcrop is unknown but small exposures can be followed for about 200 m along the densely overgrown river bank. The most southern outcrop of the Coralline Crag is found in a valley to the east of the village of Tattingstone 16 km to the south west of Ramsholt Cliff. The known extent of this outcrop is discussed in Chapter 7.

The outcrop of the Coralline Crag thus consists of a main outcrop, bisected by the R. Alde, and at least three much smaller outcrops. Occurrences of Coralline Crag beyond the limits of the known surface outcrop have often been mentioned in the past.

The former exposure on Boyton Marshes has already been mentioned. The other most frequently mentioned former occurrence is that at Sizewell to the north of Aldeburgh. Lyell (1839, p.127) seems to have been the first to notice the Sizewell occurrence, writing "The most northern point to which the coralline crag (sic) has been traced, is Sizewell Gap, several miles north of Thorpe". He also observed that the Norwich Crag was exposed "...along the coast, at Thorpe, near Aldborough, where it may be seen at low-water resting on the coralline crag (sic)". This record was apparently overlooked by later authors. Later records appear to stem from Mr. C.P. Ogilvie of Sizewell who stated that the Coralline Crag "...forms dangerous sunken rocks off Thorpe and Sizewell" (in Dalton and Whitaker, 1886, p.11). This observation formed the basis of the records by Reid (1890, p.26) and Harmer (1898, p.320) of submarine "rocks" off Sizewell. Reid (1890, p.27) also mentioned that the Coralline Crag had once been exposed on the beach at 'Aldborough' (early version of Aldeburgh). However, the Sizewell occurrence of Coralline Crag has rarely been confirmed in more recent times (ie. since 1886). Lees (1980) in a study of the offshore Sizewell-Dunwich Banks described an occurrence of <u>in situ</u> Coralline Crag in a vibrocore taken 3 km east of Sizewell and thus confirms the early record of Lyell (1839). It should be remembered that the coastline has suffered considerable erosion at this point since 1839 (Carr, 1980) and that therefore much of the present day offshore outcrop may have constituted part of the onshore outcrop in historical times.

An occurrence of Coralline Crag at Waldringfield, east of Ipswich, was recorded by Whitaker (1885, p.65). A large quarry dug for the exploitation of the Red Crag phosphorite deposit north-east of Waldringfield church had shown "...some six inches [15 cm] of Coralline Crag...beneath the nodule-bed..." at a depth of about 40 feet (12.2 m) in the workings. Wood and Harmer (1872,p.iii) recorded "...a trace... of Coralline Crag ... at Trimley [near Felixstowe] , where it was observed in the digging of a ditch by the late Mr. Acton". These two records have never been subsequently confirmed but it seems not unreasonable to suppose that many such small traces of Coralline Crag might exist in the area.

1.3 Thickness of the Coralline Crag

Prestwich (1871a)believed the Coralline Crag to be 83 feet (25.3 m) thick. He arrived at this figure by the summation of the individual thicknesses for each of his 'zones' (see fig. 6) and made the assumption that all of these zones would be present in a complete vertical section through the most complete part of the outcrop. He later (Prestwich 1871c, p.496) amended this estimate to a total of 76 feet (23.2 m). Wood and Harmer (1872) thought that Prestwich's figure was excessive and believed a figure of 60 feet (18.3 m) to be closer to the true thickness. The Coralline Crag rests on a very uneven erosional surface of Eocene London Clay. The primary thickness of the formation is dependent on the distribution of the ridges and troughs of this lower contact. The upper surface of the Coralline Crag has also been much eroded. Thus it is difficult to accurately determine the maximum thickness of the Coralline Crag.

Utilising the contour map of the London Clay surface produced by Carr (1967, fig. 2; 1971, fig. 2) and Carr and Baker (1968, fig. 4) in conjunction with the outline of the known surface outcrop of Coralline Crag an estimate of the total thickness of the Coralline Crag can be obtained (fig. 5). By overlaying the topographic contours of the area over this map a thickness of around 80 feet (24.4 m) for the Coralline Crag to the north of Sudbourne is obtained. This estimate is based, on two assumptions.

1) That the contour map of the London Clay surface is accurate as the data points for this area of the map are based on resistivity studies and not on direct borehole evidence (Carr and Baker, 1968, fig. 2a)
2) That the entire thickness of sediment from the erosional top of the London Clay to the surface exposure of Coralline Crag consists only of Coralline Crag with no intervening deposits between these two Formations.

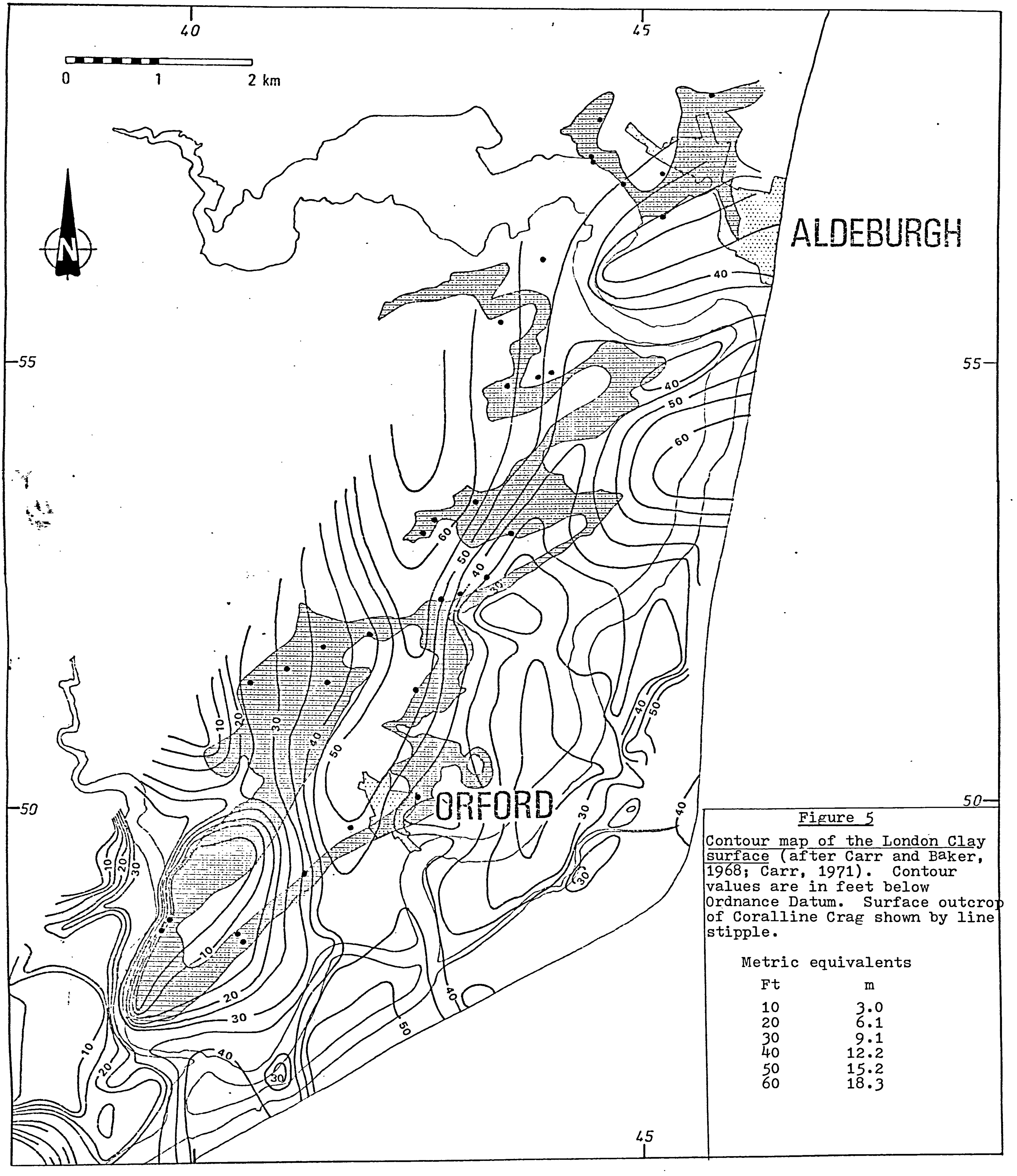


Figure 5

Contour map of the London Clay surface (after Carr and Baker, 1968; Carr, 1971). Contour values are in feet below Ordnance Datum. Surface outcrop of Coralline Crag shown by line stipple.

Metric equivalents

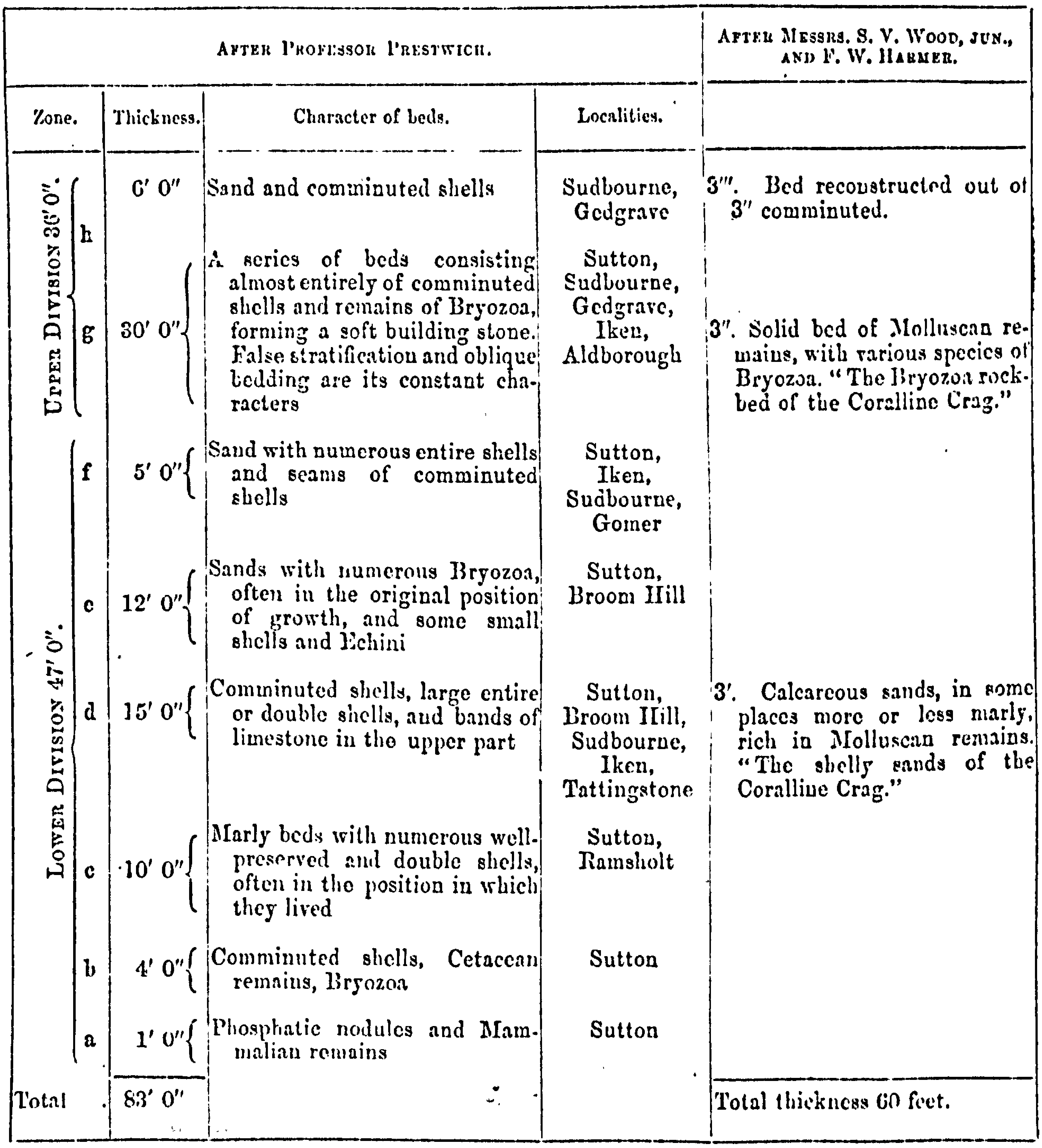
Ft	m
10	3.0
20	6.1
30	9.1
40	12.2
50	15.2
60	18.3

The confirmation of the maximum thickness of the Coralline Crag awaits a detailed borehole investigation.

1.4 History of Research on the Coralline Crag

Since Charlesworth (1835a) first described the Coralline Crag as a distinct formation it has been the subject of many studies. Many of the early studies centred on arguments over the determination of relative age of the Coralline Crag by application of the "percentage method" of Lyell on the molluscan faunas. (eg. Charlesworth, 1835b, 1836, 1837; Desnoyers, 1838; Lyell, 1839). From 1848 onwards numerous monographs were produced on different fossil taxa from the Crag (see Chapter 9) but these studies were mostly intent on increasing already voluminous lists of fossil species found in the Crag without consideration of the sedimentology or palaeoecology of the Formation. During the mid 19th century when the exploitation of the Crag phosphorite deposits for phosphate fertilisers was at a peak many papers discussed these basal conglomeratic deposits. Most of the exploitation, and therefore most papers, related to the deposit at the base of the Red Crag, the Coralline Crag deposit being only rarely mentioned (eg. Lankester, 1865a, 1868; Prestwich 1871a) (See Chapter 2).

Perhaps the first major paper to be produced on the Coralline Crag subsequent to 1835 was that of Prestwich (1871a) who proposed one of the first palaeoenvironmental models for the deposition of this Formation. He proposed that the Coralline Crag was divisible into a vertical series of 'zones' and that these zones were distinguishable on the basis of their sedimentary structures and faunas. Prestwich's division of the Coralline Crag is illustrated in figure 6. He proposed a model of deposition which involved an initial



After Professor Prestwich.					After Messrs. S. V. Wood, Jun., and F. W. Harmer.
Zone.		Thickness.	Character of beds.	Localities.	
Upper Division 36' 0".	h	6' 0"	Sand and comminuted shells	Sudbourne, Gedgrave	3'''. Bed reconstructed out of 3'' comminuted.
	g	30' 0"	A series of beds consisting almost entirely of comminuted shells and remains of Bryozoa, forming a soft building stone. False stratification and oblique bedding are its constant characters	Sutton, Sudbourne, Gedgrave, Iken, Aldborough	3''. Solid bed of Molluscan remains, with various species of Bryozoa. "The Bryozoa rock-bed of the Coralline Crag."
Lower Division 47' 0".	f	5' 0"	Sand with numerous entire shells and seams of comminuted shells	Sutton, Iken, Sudbourne, Gomer	
	c	12' 0"	Sands with numerous Bryozoa, often in the original position of growth, and some small shells and Echini	Sutton, Broom Hill	
	d	15' 0"	Comminuted shells, large entire or double shells, and bands of limestone in the upper part	Sutton, Broom Hill, Sudbourne, Iken, Tattingstone	3'. Calcareous sands, in some places more or less marly, rich in Molluscan remains. "The shelly sands of the Coralline Crag."
	c	10' 0"	Marly beds with numerous well-preserved and double shells, often in the position in which they lived	Sutton, Ramsholt	
	b	4' 0"	Comminuted shells, Cetacean remains, Bryozoa	Sutton	
	a	1' 0"	Phosphatic nodules and Mammalian remains	Sutton	
Total		83' 0"			Total thickness 60 feet.

Figure 6 Vertical subdivisions of the Coralline Crag proposed by Prestwich (1871a) and Wood and Harmer (1872) (after Burrows, 1895a)

period of subsidence and marine transgression depositing the lower beds reaching a maximum in zone "e", which was thought to indicate deposition in water depths of 500-1000 feet (152-305 m). Deposition of zone "e" was thought to have been followed by a period of uplift until the top of the Coralline Crag became emergent. Prestwich's attempt at a zonation of the Coralline Crag was criticized by Wood and Harmer (1872) and later by Harmer (1898). Wood and Harmer (1872, p.iii) wrote "We doubt the constancy or determinability of such horizons", and believed that no distinct faunal facies could be recognised anywhere in the Coralline Crag. They also disagreed with Prestwich's interpretation of maximum water depth during Coralline Crag deposition. They preferred to divide the Coralline Crag into 3 zones (see fig. 6) where bed 3" and 3"' represented altered conditions of the original sediment. Whitaker (1885) and Dalton and Whitaker (1886) produced the first Geological Survey sheet memoirs covering the area of the Coralline Crag outcrop.

Reid (1890) produced a useful summary of the literature of the 19th century and cited an extensive bibliography of Crag references.

Harmer (1900a) proposed that the Coralline Crag be assigned to a new Pliocene stage, the Gedgravian (see Chapter 13). He also (Harmer, 1898, 1902, 1910), criticised Prestwich's model for the deposition of the Coralline Crag and said that the Formation represented submarine shell banks "under the influence of tidal currents from the south-west (sic)... in a sea of moderate depth, probably at no great distance from the then existing shore, and parallel to it", Harmer's model represents the most recent attempt to explain the deposition of the Coralline Crag, subsequent authors being mostly content to reiterate his ideas.

Since Harmer's work in the early part of the 20th century published papers on the Coralline Crag have been infrequent. Boswell (1927, 1928) wrote two memoirs for the Geological Survey which covered the area of the Coralline Crag outcrop but in these he only reviewed former literature without advancing new ideas. Carter (1951) in a study of a section at Rockhall Wood attempted to distinguish between in situ and transported assemblages of Foraminifera. He noticed that the foraminiferid assemblages often showed a size distribution which was similar to the grain-size distribution of the sediment. Species whose size distribution did not reflect the sediment grain-size distribution were considered to have been unaffected by post-mortal transportation and to represent in situ fossils. Unfortunately this potentially valuable study was based on only a single locality (? = thesis locality 6) and the work was never extended to include other localities. Baden-Powell in a series of papers (1953, 1955a, 1955b, 1960) reviewed the early literature regarding the palaeoenvironment of the Coralline Crag and proposed correlation with the Astian of the Mediterranean (see Chapter 13 for discussion on correlation). Cambridge (1977) briefly mentioned the Coralline Crag and reviewed recent ideas on correlation with the Belgian Neogene (see Chapter 13). Since this thesis was written Wilkinson (1980) has described ostracod assemblages from several Coralline Crag sections.

1.5 Commericial exploitation of the Coralline Crag

The Coralline Crag has had many economic uses locally in the past. The shelly sediments were formerly used as a land dressing to restore deficient lime-content in the soil (Whitaker, 1885, p.110). A large quarry near Red House Farm (= locality 25 of Harmer; see fig. 4: close to locality 27 (this study)) was opened specifically for this purpose (Boswell, 1928 p.63) but is now infilled.

The sediments were also, and still are, used in some areas for the making of farm roads and paths (Boswell, 1928, p.65). Where the Coralline Crag is sufficiently lithified blocks of it have been used as a building material. Blocks of Coralline Crag can be seen in the tower of Chillesford church, and farm walls and buildings on Sutton Hall Farm at Pettistree Hall. The buildings at Pettistree Hall include a small cottage constructed of Coralline Crag blocks which is the only dwelling so constructed known to the author. Excavations into the Coralline Crag are still used as paddocks for farm animals as described by Boswell (1928, p.64) (eg. at Crag Farm, locality 21).

Orford Castle

The exploitation of the phosphorite deposits at the base of the Crags during the mid 19th century led to a profusion of pits being opened in the study area. However, exploitation was concentrated on the Red Crag phosphorite deposit with only the pit at Rockhall Wood (see Chapter 2) known to have been opened in the Coralline Crag for this purpose. This industry commenced in 1847 but began to die out in 1854 when the Cambridge Greensand deposits were discovered. Despite this, 5000 tons (c.5000 tonnes) of phosphorite per annum were extracted as late as 1889 (Reid, 1890, p.16-18).

1.6 Aims of this study

A study of the Coralline Crag particularly lends itself to comparison with modern skeletal carbonate deposits. Present-day carbonate sedimentation is traditionally regarded as being confined to low latitudes (30°S - 30°N) but many studies have now been made on carbonate sediments from continental shelves of much higher latitudes. (eg. Hoskin and Nelson, 1969, 1971; Lees and Buller, 1972; Milliman, 1974; Wilson, 1979; Scoffin et al, 1980). Lees and Buller (1972) compared and contrasted the carbonate sediments of high and low latitude areas and came to the conclusion that sediments of "warm-water" and "temperate-water" areas could be distinguished on the basis of the types of carbonate grains present. Sediments with high proportions of molluscan, barnacle and bryozoan skeletal material, as for instance the Coralline Crag, were thought to be typical of "temperate-water" areas. The preservation potential of present-day deposits has been discussed (eg. Scoffin et al p. 353) but little is known of the internal structure of these deposits or of how their composition and facies may have changed during the Holocene transgression. Study of fossil deposits such as the Coralline Crag should contribute to a better understanding of the formation of modern temperate-water carbonate deposits.

Many factors have contributed to the lack of significant progress in the study of the Coralline Crag in recent times. Much of this is due to the failure to appreciate the nature of the complexities involved in transgressive shallow marine environments. Rapid facies changes must be expected within a relatively small geographical area. Within this type of marginal marine environment the processes of reworking and transportation assume a great importance in any study of shelly faunas. These factors must be understood before any interpretation based on skeletal analysis of fossil material can be attempted. The subaerial diagenesis with its concomitant removal of aragonitic skeletal material serves as a further complication to the study of fauna (see Chapter 8). Fortunately this study has been able to concentrate on the extremely abundant, and environmentally sensitive, bryozoan faunas, most bryozoan skeletons consisting wholly of calcite (see Chapter 10,11). Present day exposures of Coralline Crag are very much poorer than during the heyday of Coralline Crag research. However a total of 38 localities were located for study (figs. 2,3) (cf. Harmers localities: fig. 4). Three of these were temporary exposures (localities 26, 28 and 29) and 3 others have been lost since the beginning of this study (1976) (localities 1,2 and 33). Other sites will inevitably be lost in the near future unless moves are taken for their conservation.

Thus, this study represents the first attempt for many years to relate faunas and sedimentary facies to a proposed model for the deposition of the Coralline Crag (summarised in Chapter 12). In situ fossil assemblages have been identified and analysed. Sedimentary facies have been recognised and correlation aided by a detailed survey of the relative elevations of all known exposures. Finally the broader implications of Coralline Crag deposition within the stratigraphic framework and evolution of the North Sea basin are explored in Chapters 13 and 14.

Chapter 2

The Crag phosphorite deposits. Part I: Description

2.1 General occurrence

2.2 Coralline Crag phosphorite deposit

2.3 Nomenclature of Crag phosphorite deposits

2.4 Commercial exploitation

2.5 Basis of this study

2.6 Components of the Phosphorite deposits

A. Phosphatic components
  - i) Phosphatic nodules (concretions)
  - ii) Phosphatised fossils
    - (a) Fossils derived from Mesozoic formations
    - (b) Fossils derived from the London Clay (Eocene)
    - (c) Fossils derived from a Miocene formation
  - iii) Arenaceous phosphorite ('Boxstones')

B. Non-phosphatic components
  - i) Non-phosphatised fossils
  - ii) Miscellaneous rock fragments

Chapter 2

The Crag phosphorite deposits. Part I: Description

At the base of both the Coralline Crag and Red Crag deposits, conglomeratic remanié material can often be found lying unconformably on the erosional surface of the London Clay. A large proportion of the conglomeratic material consists of rounded and abraded phosphorite nodules (concretions) and other derived phosphatic debris including vertebrate teeth and bones. Antia (1979) defines a phosphorite deposit as a phosphate-rich bed ($>$ 4.5% by weight of apatite) with less than 30% vertebrate material. By this definition these basal conglomeratic deposits can be considered as phosphorite deposits. Although the constituents of these deposits are demonstrably of greater age than the Crag sediments with which they are intermingled, they form an important source for detrital minerals of the Crag deposits (chapter 6) and should be considered in any study of Crag sedimentology.

In general the components of the phosphorite deposit are concentrated into the lowermost Crag sediments where they overlie the London Clay. The deposit has also been found in the lowermost Red Crag sediments where they overlie the Coralline Crag at Ramsholt Cliff (locality 3) and Tattingstone Hall Farm (locality 2) (this study) and at Rockhall Wood (Prestwich, 1871b). The 'thickness' of this horizon, i.e. the thickness of the zone in which the conglomeratic material is concentrated, can reach 18 inches (45 cm) (Reid, 1890). More commonly the deposit consists of a single layer of pebble-sized detritus resting on the plane of unconformity.

Although the majority of phosphatic material is found in the basal few centimetres, scattered nodules occur throughout both the Coralline and Red Crags. Small phosphorite grains (< 2 mm) are a widespread minor component of the Crag sediments. Bell (1911, 1912, 1915) believed that physical downward 'sifting' of these relatively dense phosphatic components led to their concentration at the base of the Crags. He therefore believed that the phosphatic components were continuously supplied from an outside source into the Crag sediments. Although there is no evidence to suggest this 'sifting' mechanism for the basal concentration, there is evidence to suggest that material may have been supplied during deposition of the Coralline Crag. At Red House Farm (locality 28) there is a concentration of phosphorite nodules which is believed to be several metres above the London Clay surface. This material may have been transported from the basin margins during deposition of the Coralline Crag. Winnowing of associated sediments may have been important in concentrating the phosphatic material as a lag deposit on an unconformity plane within the body of the Coralline Crag (see Chapter 12).

2.2 Coralline Crag Phosphorite Deposit

Much of the contact between the Coralline Crag and the London Clay is below Ordnance Datum. Exposures of the contact are therefore rare. The lack of exposure in recent years has led to the erroneous belief that the phosphorite deposit is absent from the base of the Coralline Crag (Cambridge, 1977). The present study confirms the occurrence of this deposit at Ramsholt Cliff (locality 3) (frontispiece and Plate 1) and at Tattingstone Hall Farm (Chapter 7). The Coralline Crag phosphorite deposit was also seen during an INQUA meeting excavation at Rockhall Wood (locality 5) (R. Markham pers. comm. 1979). The latter observation confirms the first record of this deposit by Lankester (1865a, p.222; 1868).

2.3 Nomenclature of Crag Phosphorite Deposits

The Crag phosphorite deposits were first noted by Henslow (1843) who described the occurrence of phosphatic concretions in the Red Crag at Felixstowe. He initially thought that the concretions were coprolitic in origin (Henslow, 1846). This was later realised to be incorrect and they were variously termed pseudo-coprolites or false coprolites (Buckland, 1849, Herapath 1851). Despite this, the term 'coprolite bed' became widely used for the Crag phosphorite deposits (e.g. Prestwich 1871a). When Lankester (1868) proved the existence of concentrations of phosphatic material at the base of both the Red and Coralline Crags he discarded the misleading term 'coprolite bed' and termed the two deposits collectively as the 'Suffolk Bone-Bed'. As bones are relatively rare and phosphorite concretions are the dominant phosphatic component it is proposed that the Crag basal conglomeratic concentrations be termed collectively as the 'Crag phosphorite deposit' using the definitions of Antia (1979) for bone-beds and phosphorite deposits. This term can then be qualified according to the Crag sediments in which the deposit is found e.g.

'Coralline Crag phosphorite deposit'.

2.4 Commercial exploitation

Henslow's discovery led to the exploitation of the Crag phosphorite deposits (mostly from the Red Crag) for use as phosphate fertilisers. This extraction commenced in 1847 and reached a peak around 1854, during which year an estimated 12,000 tons (c. 12,000 tonnes) of phosphate was obtained (Reid, 1890). Fears were expressed at the time that the Red Crag might be completely destroyed within a relatively short period by the extent of the excavations (Charlesworth, 1868).

2.5 Basis for this study

The many pits which were opened during this time provided a wealth of material for collections and resulted in a profusion of literature. However, only one pit (Rockhall Wood:? = locality 5) is known to have worked the deposit at the base of the Coralline Crag (Prestwich, 1871a;p.116). Therefore in any study of museum material (often inadequately labelled) there will be a natural bias towards material derived from Red Crag sources. It seems unlikely, however, that the material will vary significantly between the two deposits except in minor details as demonstrated later in this chapter.

Thus, much of the evidence for this current study is, by necessity, derived from museum collections although examination in the field of both Red Crag and Coralline Crag deposits has also been carried out.

2.6 Components of the Phosphorite deposits

The conglomeratic deposit contains both phosphatic and non-phosphatic components which vary in their relative importance at different localities and between the Coralline and Red Crag deposits.

A. Phosphatic components

i) Phosphatic nodules (concretions)

Variously shaped, commonly spheroid or ellipsoid, nodules dominantly composed of fine-grained carbonate fluorapatite (francolite) (see appendix 1) (Plate 2,A). These nodules evidently developed as concretions which were later derived into the Crag phosphorite deposits (see Chapter 4).

Pettijohn (1975) recommends that the term 'concretion' be used only for regular forms and that the term 'nodule' be used only for irregular forms. This terminology is followed by Hudson (1978). In this study it is proposed that the term 'concretions' be applied only to complete in-situ bodies whether they be regular or irregular in form. The term 'nodule' will be applied to derived phosphatic concretions, parts of concretions or other phosphatised material which is not of organic origin (viz teeth & bones), where the original form of the complete concretion has been altered by derivation and abrasion. Therefore a phosphorite 'concretion' from the London Clay, which may have a regular or irregular form, can be broken up by processes of erosion and derivation to form a number of smaller phosphorite 'nodules'.

This scheme thus avoids problems arising from variously-shaped bodies in which the shape may be the original form or have been subsequently altered, or where the original concretionary nature of the body is uncertain. The size of the nodules varies widely but they are commonly between 1 and 10 cm long. A specimen seen in the Ipswich Museum was 25 cm long. The size distribution appears to vary locally. The outer surface of the nodules is usually dark-brown, smooth and polished but sometimes the surface is dull and buff coloured with only projecting angularities showing a polished appearance. The surface of the nodules is often pitted with small depressions between 0.3 and 1.0 cm in diameter resulting from the action of marine boring organisms. Sometimes the surface is seen to be covered with yellowish dendritic and vermiform markings (Plate 2, B). These markings are thought to be due to contact by modern tree rootlets which penetrate the Crag at some localities (R.G. Bromley, pers. comm. 1979).

Most of the nodules have no easily discernible nucleus in section. Some, however, have clearly originated as concretions within the carapaces of decapod crustacea (Plate 3, A-B). Other organic nuclei include the roots of shark teeth (Plate 3, C) and ?crustacean burrow fills (Plate 4, A-B). Some spiral nodules (Plate 5, B) were previously thought to be the fossilised faeces of sharks (e.g. Spencer, 1971). These nodules are between 2.5 and 11 cm long with a roughly equal division into dextrally and sinistrally coiled forms. Siliceous concretions form or have been subsequently altered, or where the original concretionary nature of the body is uncertain. The size of the nodules varies widely but they are commonly between 1 and 10 cm long. A specimen seen in the Ipswich Museum was 25 cm long. The size distribution appears to vary locally. The outer surface of the nodules is usually dark-brown, smooth and polished but sometimes the surface is dull and buff coloured with only projecting angularities showing a polished appearance. The surface of the nodules is often pitted with small depressions between 0.3 and 1.0 cm in diameter resulting from the action of marine boring organisms. Sometimes the surface is seen to be covered with yellowish dendritic and vermiform markings (Plate 2, B). These markings are thought to be due to contact by modern tree rootlets which penetrate the Crag at some localities (R.G. Bromley, pers. comm. 1979).

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Wetherell (1859) described concretions which formed around the axes of the Pennatulacean Graphularia wetherelli from the London Clay of North London. Similar concretions from the Crag are also described. Indeed many other comparisons can be made between concretions from the London Clay and those found in the Crag phosphorite deposits (Plates 3, 4). It seems likely that the great majority of the phosphatic claystone nodules (with the possible exception of the spiral nodules which have yet to be found in the London Clay and may prove to be Mesozoic in age) were derived from London Clay beds which contained a similar fauna to that found at Sheppey today as noted by Bell (1918) (see Chapter 4). Only in rare instances are nodules found to contain moulds of molluscan shells. The moulds are hollow but Bell (1915) claimed that on rare occasions the shell may be pseudomorphed by phosphate.

ii) Phosphatised fossils

In addition to those organisms which acted as a nucleus for concretionary growth of carbonate apatite described above, a wide variety of other phosphatised fossils are found. These fall into three groups.

(a) Fossils derived from Mesozoic formations:

These include phosphatised casts of ammonite chambers of Jurassic or Cretaceous age (Plate 5,A).

(b) Fossils derived from the London Clay (Eocene):

These include phosphatised teeth of Striatolamia (= Odontaspis), 'Lamna', Myliobatis and various other selachians. Phosphatised wood (Plate 11), often bored by Teredo, and various fish, reptile and mammal bones are also found. The fossils which acted as a nucleus for concretionary growth of carbonate apatite and which are found in nodules of phosphate-rich claystone were derived from the London Clay. The carapaces of decapod crustacea such as Xanthilites and Hoploparia are common examples in this category (Plate 3, A-B). Phosphatised casts of the chambers of Nautilus are also found.

(c) Fossils derived from a Miocene formation:

These include phosphatised teeth of Carcharodon megalodon (Plate 9, A) and the bones of various cetacea including Balaenodon and Hoplocetus (Plate 10). C. megalodon*is a Miocene shark which is believed to have reached lengths of greater that 84 feet (25.6 m) (Bowerbank, 1852). Details and species lists of derived fossil material found within the Crag phosphorite deposits can be found in Wood (1859), Lankester (1865a), Bell (1915) and Spencer (1971).

iii) Arenaceous phosphorite ('Boxstones')

Rounded cobbles of quartz-wacke, variable in size but most having a long axis dimension of between 8 and 25 cm. The matrix comprises between 20 and 80% of the sediment and is composed dominantly of francolite, but with a large proportion of limonite cement.

The petrology of the 'boxstones' is fully described by Boswell (1915). These sandstone cobbles were first recorded and described by Clarke (1851) and given the name 'Boxstones' by Lankester (1870) referring to the fact that on being broken the cobbles often reveal moulds of large bivalves or gastropods. Occasionally they enclose cetacean teeth or pieces of cetacean bone. Rarely the sandstone may be found adhering in small quantities to tooth and bone material as noted by Lankester (1868, 1869).

Details and species lists of the fauna found within 'boxstones' can be found in Wood (1859) and Bell (1911, 1915, 1917, 1918).

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* C. megalodon is now placed in the genus Procarcharodon (A. Longbottom, pers. comm., 1981)

B. Non-phosphatic components

In addition to the phosphatic components described above, a variety of non-phosphatic components are an important constituent of the Crag phosphorite deposits.

i) Non-phosphatised fossils

These include silicified belemnite rostra where the calcite has been replaced by beekite. Unmineralised teeth and bones of terrestrial vertebrates of possible Pliocene age are recorded (Spencer, 1964, 1971).

ii) Miscellaneous rock fragments

By far the commonest non-phosphatic rock types found in the Crag phosphorite deposits are rounded fragments of London Clay carbonate septarian concretions and large flints derived from the Chalk. Other rock types recorded include:-

> Quartzite, Lower Greensand chert, granite, porphyry, mica-schist, Rhaxella chert, Liassic marlstone and fragments of Kellaways Rock. The variety of the exotic rock content of the Crags has been summarised by Bell (1915), Double (1924) and more recently by Spencer (1971) and Hey (1976).

Chapter 3

The Crag phosphorite deposits. Part II: Factors affecting Phosphorite formation.

Chapter 3

The Crag Phosphorite Deposits. Part II: Factors affecting Phosphorite formation

Before proposing a model for Crag phosphorite evolution current views on phosphorite genesis will be examined. Most interpretations of ancient phosphorite deposits are based on studies of Recent occurrences. However, the present need not necessarily be the key to the past.

3.1 Recent sea-floor phosphorite deposits

Only two sea-floor phosphorite deposits have been shown by radiometric dating to be geologically Recent. The first is off South-West Africa (Baturin et al, 1972) and the other is off the Peru-Chile coast (Veeh et al, 1973). All other modern sea-floor deposits have been shown to have been reworked from geologically older formations. The observed association between these two areas of phosphorite formation and oceanic upwelling currents has led to the conclusion of a cause-effect relationship (McKelvey 1967). Kazakov (1937) proposed that phosphate minerals transported in solution by deep ocean waters would be precipitated when these cold benthic currents moved over continental shelves. The phosphate mineral is thus precipitated inorganically. Bushinskii (1966) called this "the chemical hypothesis" and refutes it completely in a detailed discussion. Riggs (1979) reviewed the case against a cause-effect relationship with oceanic upwellings and noted that "...the correlation of the distribution of known occurrences of sea-floor phosphatic sediments with known upwellings appears to be somewhat fortuitous. Some upwellings are associated with no apparent phosphatic sediments, some have minor concentrations of modern phosphate disseminated through the sediments, while many occur in conjunction with major concentrations of lithochemical phosphorites (i.e. reworked from older pre-existing phosphorite sediments...)". Bushinskii (1966) pointed out that many ancient phosphorite deposits are found in areas which have probably never been directly affected by oceanic upwelling currents, as for example the Mediterranean Miocene deposits and those in the North Sea basin (this study).

Moreover those deposits currently associated with upwelling currents are very poor nodular phosphorites and totally unlike rich deposits such as those of Florida (Riggs, 1979). Thus although upwellings are an important process in supplying phosphates to surface waters they are not a mechanism which necessarily results in the production of a phosphorite deposit. In this case the Recent examples represent minor occurrences at a time when conditions necessary for a major phosphogenic episode, whatever they may be, do not exist.

3.2 Mode of formation of phosphorite deposits

Bushinskii (1966) thought that a far more important source of phosphate was from river water derived from humid highland regions, but considered that upwelling currents, and to a much lesser extent, hydrothermal waters, also contribute phosphate to shallow marine waters. He proposed a model for the formation of a phosphorite deposit in five stages:

1. The influx of river waters with a high phosphate content. Locally this may also have occurred by upwelling currents in shallow regions (5-100 m deep).

2. Concentration of dissolved phosphorus by organisms, which use the phosphorus to build their skeletons and the soft parts of their bodies.
3. Precipitation of dead organisms to the bottom of the sea and their disintegration, resulting in supersaturated phosphate solutions being formed in the ooze. In shallow regions, precipitation of dead organisms to the bottom and their disintegration only occurred during quiescent periods.
4. Precipitation of phosphates from supersaturated interstitial solutions. During this stage, phosphorite nodules, oolites, cement, various pseudomorphs, as well as phosphatised coprolites or grains of phosphates were formed in the ooze.
5. Rewashing of the ooze by waves during storms, accompanied simultaneously by an enrichment of the phosphorite bed as the result of the removal of fine, non-phosphatic constituents.

He termed this model the "biochemical hypothesis". A high organic production is required. The organic material must then be allowed to break down in the sediment to release the organic phosphates. Thus the input of organic material into the sediment must be greater than the material removed by scavengers and other organisms. If saturation in the interstitial waters with respect to phosphate is to occur it is therefore perhaps more important that areas of upwelling ocean currents are areas of high organic productivity as all the phosphate from the upwelling waters is completely utilised by phytoplankton (Baturin & Bezrukov, 1979) and therefore cannot be precipitated directly into the sediment.

Another mechanism which may result in the formation of phosphate- rich rocks arises from the deposition of avian guano. The guano deposits themselves probably do not have a high preservation potential in the geological record but solution of the guano under subaerial weathering processes may yield phosphate-rich solutions which can precipitate as phosphorite cements in underlying rocks (Braithwaite, 1980).

It seems most likely that as stressed by Riggs (1979) there is no one mechanism for the formation of a phosphorite deposit and that the mechanism for production of pelletal phosphorites like those of Florida may indeed prove to be totally different to that which produced concretionary phosphorite development like that seen in the East of England Tertiary.

3.3 Precipitation of apatite

Kazakov's (1937) suggestion that apatite precipitates inorganically from marine waters leads to a number of problems. The ascension of cold carbonate-enriched water into a warm shallow shelf sea, with loss of CO_2 and a rise in pH favours the precipitation of both apatite and calcium carbonate. As the concentration of carbonate is several orders of magnitude higher than the concentration of phosphate in sea water any precipitation of apatite would be completely overwhelmed by the precipitation of calcium carbonate. "In order for large quantities of apatite to form with only negligible amounts of calcite present, it is necessary that the dissolved phosphate content be raised high enough so that the calcium ion is being controlled by apatite rather than by carbonate equilibria" (Burnett, 1977). This situation can occur in anoxic pore waters. Sholkovitz (1973) has shown that the dissolved phosphate content of these pore waters reaches a maximum 15 cm below the sediment interface. Thus a high phosphate concentration can occur in anoxic sediments after the mobilisation of phosphates derived from the decay of organisms. Once supersaturation occurs precipitation can commence on suitable nucleation centres. Baturin and Bezrukov (1979) wrote: "The probable reason why phosphate is.. precipitated, irrespective of the mineral nature of nucleation centres, consists in the patchy structure of the microenvironment, particularly the pH value that may fluctuate due to bacterial action, local ammonia concentration, or dissolution of carbonates".

It is not clear what exactly constitutes a suitable nucleation centre as different workers have reached different conclusions. It is often thought that apatite replacement of carbonate is the most important mechanism in the formation of a phosphorite deposit (e.g. Ames, 1959, Parker & Siesser 1972). Kennedy and Garrison (1975) have described phosphatic nodules from the Cretaceous Glauconitic Marl which appear to have formed by replacement of carbonate. However, Riggs (1979)
15 commented "Phosphate does replace carbonate, but this is only one of numerous processes of formation in a complex system of authigenic sediments and is not <u>the</u> origin of phosphorite sediments".

Certainly Burnett (1977) described phosphorite precipitation as epitaxial growths <u>on</u> carbonate nuclei rather than replacing them. The conclusions drawn from this study on preferred nucleation centres will be discussed later.

The last and perhaps the most important factor in the formation of some phosphorite deposits is the reworking of the phosphatic material and winnowing of the sediments in which the apatite was precipitated. Cycles of phosphorite formation followed by periods of erosion during times of reduced sea level as described by Baturin (1971) will be seen later to be an important factor in the evolution of the Crag phosphorite deposit.

Chapter 4 The Crag phosphorite deposits. Part III: Origin and Evolution

4.1 Introduction

4.2 Source of phosphorite nodules

4.3 Eocene events

4.4 Miocene events

4.5 Plio-Pleistocene events

4.6 Age of the 'Trimley Formation' ('boxstones')

4.7 Stimulus for phosphorite formation in the East of England

4.8 Conclusions

Chapter 4 The Crag phosphorite deposits. Part III: Origin and Evolution

4.1 Introduction

> "We may fancy their [large mammals] first entombment, when probably numbers fell a sacrifice to some geological vicissitude during the convulsions of Nature in her throes to give birth to the world we live in...Then again we see the deposit in which they were enclosed - 'the great mammoth burial-ground' - broken up, becoming the sport of ocean, the bones torn from their resting-place and dashed to fragments on the shore, the harder portions resisting the action of the waves, and fighting for mastery inch by inch, until the waters, vanquished at least, have spent their fury, perhaps shutting themselves out by their own turbulence, or else the land has risen in its defence. Thus again the osseous fragments are found entombed - the diminished but not totally destroyed, remains of noble forms.
>
> Ages again roll on, and the Red Crag protects them, but not for ever, - the sea returns to the attack, and man, more ruthless than the waves, seizes upon them, and carries them away from their resting-place..."
> (extract from Dennis (1857))

One of the earliest published models for the formation of the Crag phosphorite deposit is that given by Dennis (1857) above. Clearly he recognised the derivative nature of the mammalian remains of the deposit but described only the last stage in a complex sequence of reworking during transgressive/regressive cycles which led to the formation of the Red Crag phosphorite deposit. Earlier, Buckland (1849) described how London Clay phosphorite concretions were formed and how they were exhumed to be included within the Crag phosphorite deposit.

More recently Antia (1979), in an attempt to explain the formation of the phosphorite deposit, proposed a model in which he stated that some of the phosphatised components were contemporaneous with the deposition of the Crags themselves. There is, however, a large hiatus between the formation of the phosphorite deposits and the deposition of the overlying Crag sediments.

In the following model an attempt will be made to explain the observed facts by transgressive/regressive cycles and two phosphogenic episodes during the Tertiary in the East of England.

4.2 Source of phosphorite nodules

The fact that phosphatic concretions occurred in the London Clay and that the Crag phosphorite nodules were derived examples of these concretions was first recognised by Henslow (1848). This fact was largely ignored by many later authors who attempted to explain the formation of the nodules by the phosphatisation of derived pieces of London Clay (e.g. Lankester, 1869). Buckland (1849) and Herapath (1851) described the formation of the concretions within the London Clay sediment as a response to organic decay. Charlesworth (1868) described concretion growth around the roots of shark teeth in the London Clay and believed that the Crag nodules originated by removal of the protruding tooth crown from such concretions.

There is no doubt that phosphorite concretions are commonly found in the London Clay as noted by Spencer (1971) and that this is the source of the great majority of the phosphorite nodules found in the Crag deposits. London Clay phosphorite concretions used in this study are from Warden Point, Sheppey, Kent and from an I.G.S. borehole at Crystal Palace.

4.3 Eocene events

X-Ray diffraction (X.R.D.) (Fig.45) and X-ray fluorescence (X.R.F.) analyses show the London Clay concretions to be dominantly composed of francolite (See appendix 1). Most of the concretions are spheroid to ellipsoid in shape with a buff coloured exterior and a harder, darker brown interior. They formed as early diagenetic concretions of primary carbonate apatite at a shallow depth within the anoxic sediment. Pyrite, which is also precipitated at shallow depths (Curtis, 1978) can often be found in septarian veins sometimes cutting existing structures within the concretions (Plate 6, B & E) Pyrite formation must therefore post-date the precipitation of carbonate apatite. Concretions often contain structureless pellets of amorphous carbonate apatite, 0.5 - 2.0 mm in diameter, (Plate 6, E-G). The abundance of these pellets in some concretions could indicate that the concretions frequently developed around animal burrows. Some concretions formed as a response to an organic nucleus, particularly crustacean carapaces, the roots of shark teeth and other skeletal remains of fish. These nuclei all have a high primary phosphate content. However, many phosphate-rich skeletal remains from the London Clay show no associated concretion growth; e.g. the majority of shark teeth.

Concretions of calcium carbonate or pyrite are often found around material which was originally calcite or aragonite.

For apatite to be precipitated the dissolved phosphate content must be raised high enough so that the calcium ion is being controlled by apatite rather than by carbonate equilibria (Burnett, 1977). Organic phosphorus from decaying organisms is a primary source of phosphorus in interstitial pore waters. This provides a 'patchy structure of the microenvironment' which Baturin and Bezrukov (1979) believed to be the probable reason why phosphate is precipitated irrespective of the mineral nature of the nucleation centre. Organic decay seems to be the most important factor in concretion growth in the London Clay although apatite precipitation does show a degree of substrate specificity.

Teeth of sharks probably had only a small organic content when they were incorporated into the anoxic sediment. Where organic material was still present this would be expected to be dominantly concentrated in the porous roots of the tooth and indeed this is the site where concretion growth occasionally occurs. Concretion growth has not been found around tooth enamel which has a comparatively insignificant organic content (McConnell, 1973).

The phosphatic concretions are associated with the magnesium-rich clay mineral, montmorillonite, and fine-grained dolomite in the London Clay. The association between apatite precipitation, magnesium-rich clays and dolomite is well known (Bushinskii, 1966; Riggs, 1979) although the significance of this relationship is not fully understood. Scattered grains of glauconite are also found in the concretions.

A period of regression followed the deposition of the London Clay in Eastern England. During this time large amounts of London Clay were probably eroded. Phosphorite concretions form at shallow depths in unconsolidated sediments, thus large numbers would be derived from even superficial erosion. The concretions have a high specific gravity (S.G. 2.77) and would thus be readily concentrated as a lag deposit on the erosional surface.

During the initial stages of regression when the concretions were exposed on the sediment/water interface' boring marine bivalves could penetrate the softer outer portion of the concretions, their crypts terminating against the harder core. In the absence of any associated bivalve body fossils it is safest to refer the borings to the ichnogenus <u>Teredolites</u> ' (Leymerie), this name referring to flask-shaped structures with constricted apertures which are normally but not necessarily attributable to bivalve activity in lithified substrates (S.R.A.Kelly personal communication, 1980). Concretions are often bored on all surfaces indicating that they were not enclosed in the sediment and that they were periodically overturned (Plate 4, C). Abrasion removed the softer exterior leaving a polished surface pitted with small depressions representing the distal extremities of the crypts.

During the regressive phase oxidation of pyrite led to the break-up of concretions with septarian veins of that mineral. This resulted in the formation of fragments of phosphorite with a rather angular cross-section. Such fragments are commonly found in the Crag phosphorite deposit. Occasionally the concretion did not break-up (Plate 6, A & C) and the vein cavities have become partly filled with limonite although some small crystals of pyrite remain. Carbonate concretions were undoubtedly exhumed during this period but were probably destroyed by subaerial weathering. This period of exposure and concentration was followed by a renewed transgression in the Neogene probably during the Miocene.

4.4 Miocene events

The Miocene transgression resulted in the deposition of a formation of mud-rich quartz sands. The remnants of this Miocene formation, the 'boxstones', are found as a component of the Crag phosphorite deposit in a small area of Suffolk. The percentage of matrix in the sand varies between about 20 and 80% (Boswell, 1915) but is commonly found to comprise about 50% in thin section point counts (Plate 7, A & B). The matrix was found by X.R.D. (Fig.46) and electron microprobe analyses to be dominantly a mixture of francolite and limonite. The limonite cement may have been derived from the breakdown of glauconite grains which are rare in studied thin sections of 'boxstones'. This was a later, diagenetic process probably occurring in conjunction with the solution of calcareous mollusc shells as small amounts of limonite are often found precipitated in the cavities formed by the removal of these shells. Limonite was therefore not the primary cement in the formation of 'boxstones'. These moulds of gastropods and articulated bivalves are generally found at the centre of the sandstone cobbles (Plate 8). The 'boxstones' clearly originated as concretions around these calcareous nuclei, as first noted by Clarke (1851). Teall (1900, p. 383) proposed a model for the formation of 'boxstones' which involves precipitation of apatite as a response to saturation of pore-waters with carbonate from the solution of the molluscan shells themselves. Growth is only rarely found around vertebrate, i.e. phosphatic, material (Plate 9, B-E: Plate 10, C). This is the converse of most London Clay concretions. This apparent difference may be due to a difference in the diagenetic sequence in which apatite was not the primary cement. The possibility that the 'boxstones' matrix was originally calcium carbonate which was later replaced by apatite was investigated.

Electron microprobe analysis was used by Parker (1971) to obtain a CaO/P_2O_5 ratio of 2.30 for replaced limestones from Agulhas Bank, South West Africa. The CaO/P_2O_5 ratio for the 'boxstone' matrix is 1.56 (Table 1). This figure accords more closely with the value of 1.50 quoted by Burnett (1977) for phosphorite nodules from the Peru-Chile shelf. As this figure is only slightly higher than that expected for a pure carbonate fluorapatite, Burnett used this result as an indication that there were no "unreplaced residuals" that might have been present if apatite had formed by replacement of calcite.

However, in the case of the 'boxstones' the molluscan shell moulds are evidence of the subsequent removal of calcite and aragonite. A late diagenetic carbonate cement is often

Table 1: Partial analyses (electron microprobe) of phosphorite concretions expressed as weight percent of oxides. 1. London Clay phosphorite concretion. 2. Crag phosphorite nodule. 3. 'Boxstone' matrix.

	1	2	3
Na_2O	0.38	0.65	0.63
MgO	0.48	0.22	0.33
Al_2O_3	2.38	2.00	1.27
SiO_2	8.02	5.88	3.98
P_2O_5	29.03	30.98	30.89
K_2O	0.43	0.23	0.22
CaO	45.31	46.49	48.15
Fe_2O_3	1.58	2.72	2.08
Total oxides	87.61	89.17	87.55
CaO/P_2O_5	1.56	1.50	1.56

found infilling small spaces between the early diagenetic apatite rim cement of quartz grains. The carbonate has a high ferroan content, and a lowest refractive index equal to or greater than balsam. Rims of apatite around mineral grains are another criterion thought by Burnett to indicate primary precipitation of apatite. Parker and Siesser (1972) observed a decrease in P_2O_5 content from the surface to the centre of replaced limestone blocks. Electron microprobe traverses from the surface to the centre of 'boxstones' revealed no significant variations in the P_2O_5 content of the matrix. Additionally, no pseudomorphism of calcareous shells and microfossils by apatite has been observed although this may be due to a preference for finer grained carbonate by the replacement process, as described by Birch (1979). Although carbonate replacement by phosphate cannot be entirely ruled out as a mechanism for the formation of the 'boxstones', it is considered more likely that apatite was precipitated directly from solution as a primary cement.

In common with the London Clay concretions, apatite precipitation was in response to organic decay. Some 'boxstones' with no body fossil nucleus are seen to consist of extensively bioturbated sediment. Pellets of francolite ½ - 1 mm in length are fairly common (Plate 7, C). These pellets are not concentrically layered and are probably the faecal pellets of burrowing organisms. Precipitation of apatite is often quoted as being a response to local fluctuations of pH in the microenvironment (Burnett, 1977., Baturin and Bezrukov 1979). Increases in pH may result from the liberation of NH_4^+ into the interstitial porewaters around decaying animals. Xylem, however, decomposes giving acid conditions (Bushinskii, 1966). The phosphatisation of wood (phosphatised wood of London Clay age is found in the Crag phosphorite deposit) is thus difficult to explain if pH is an important factor. As in the London Clay, supersaturation of porewaters with respect to phosphate is probably the most important single factor in concretion growth. Where large amounts of organic phosphate are liberated in the surrounding porewaters due to the decay of animal tissue, supersaturation with respect to phosphate will occur and apatite will be precipitated. This is the mechanism for concretion formation around calcareous molluscs and burrows with faecal pellet concentrations. As in the London Clay, teeth may have a small organic content in rare cases, and a concretion may form around the root.

The abundant teeth and bones of sharks and marine mammals derived from this deposit are characteristically phosphatised. They show evidence of marine boring and extensive abrasion. This is probably an indication of the prolonged transport subsequent to the death of the animal in the deeper waters of the basin until they were incorporated into the muddy sands at the basin margin. While above the sediment/water interface the organic content of the teeth and bones would be greatly reduced by scavengers and bacteria. In this case where organic phosphate was not liberated by decay within the anoxic sediment apatite was precipitated within existing structures as a replacement process. This is the mechanism by which the dahllite of teeth and bones was phosphatised in this deposit. Derived teeth of London Clay sharks and rays were also phosphatised in this way during the Miocene. In the London Clay this second type of process only seems to occur in the phosphatisation of wood tissue (Plate 11).

X.R.F. analysis shows that phosphatic concretions from the Crag phosphorite have a slightly higher content of P_2O_5 than London Clay concretions (Table 2). This is probably enrichment due to further apatite precipitation during the Miocene in a similar replacement process to that which phosphatised the teeth and bones. This possibility was first mentioned by Buckland (1849) who wrote that the nodules "...may have absorbed a larger dose of phosphorus than they contained before they were washed out of their matrix in London Clay...". However, he thought that the source of this additional phosphate was from the decomposition of molluscs within the sediments of the Crag.

Deposition of this Miocene formation was followed by another regression. This resulted in the winnowing of the unconsolidated sand. Freshly exhumed concretions were bored by marine bivalves. Again, borings are often on all sides, indicating exposure on the sediment surface and periodic overturning. Finally all the unlithified sediment was winnowed away leaving the 'boxstones' behind on the London Clay erosional surface. Due to the large size of the 'boxstones' and their limited distribution ("It should be noted that they occur almost entirely in one part of the Crag district": Harmer, 1898) within the Crag phosphorite deposit

Table 2: Partial analyses (X.R.F.) of phosphorite concretions expressed as weight percent of oxides. 1. London Clay phosphorite concretion. 2. Crag phosphorite nodule.

	1	2
Na_2O	0.84	1.27
MgO	2.74	0.31
Al_2O_3	1.44	2.83
SiO_2	13.82	6.71
P_2O_5	21.67	26.07
K_2O	0.85	0.49
CaO	37.37	43.47
Fe_2O_3	3.10	3.80
Total oxides	81.83	84.95

it is not believed that they have been transported any appreciable distance, contrary to Harmer (1898) who considered them to have been transported and concentrated by 'littoral drift'. Bell (1911, 1912) believed they were derived and transported from a Diestien deposit to the south-west of the Crag basin but later seems to have changed his opinion to derivation from deposits within the Suffolk area (Bell, 1915, 1918).

Lankester (1868, 1870) observed some large flag-like slabs of this phosphatic sandstone near Trimley, Suffolk. Taylor (1874) wrote:- "...it is not uncommon to find slabs... which appear to have undergone little abrasion and to be in nearly the same condition they were in when the formation to which they orginally belonged was broken up" (In Bell 1917). It seems clear therefore, that rather than the'boxstones'being transported into the area they represent the remnants of a previously existing formation which was broken up 'in situ' with perhaps the unconsolidated parts of the sediment being winnowed away. This formation of muddy sands can perhaps be usefully termed the "Trimley Formation" after its occurrence in the area of Trimley (See Appendix 2). Usage of this term removes the ambiguity resulting from the term 'boxstone' which has been applied to various concretions from many different deposits.

4.5 Plio-Pleistocene events

The various components of the phosphorite deposit were then covered by bioclastic sands during a further transgression during the Pliocene which deposited the Coralline Crag. During the transgression pieces of London Clay carbonate septaria were incorporated into the deposit. After a further brief regression the Red Crag transgression overstepped the Coralline Crag onto the Cretaceous outcrop further inland.

It is difficult to state with confidence at which stage in the evolution of the Crag phosphorite deposit the Mesozoic components and other miscellaneous rock types were incorporated. As the Coralline Crag deposit was rarely quarried and present day exposures are poor it is not known if only some or all of these components are present and were therefore derived before its deposition or whether it was not until the more extensive Red Crag transgression that they were incorporated. Certainly Chalk flints are very common in the Red Crag phosphorite deposit but not in the Coralline Crag deposit. The various phosphatised Mesozoic fossils were probably mineralised before the Tertiary and derived directly into the Crags from a deposit like the Cambridge Greensand. Spencer (1971) believed that transport by ice was responsible for the presence of Jurassic ichthyosaur coprolites in the phosphorite deposit.

Terrestrial vertebrate remains of an age more recent than Miocene are also found in the Red Crag phosphorite deposit. These are largely unmineralised and are probably contemporary with the Plio-Pleistocene marine deposits. There is therefore no evidence of a further phosphogenic episode occurring since the Miocene in the East of England.

4.6 Age of the 'Trimley Formation' ('boxstones')

There seems no doubt that the molluscan fauna found within 'boxstones' and most of the phosphatised vertebrate remains, which on rare occasions show adherent arenaceous phosphorite, are contemporary. The problems involved in stratigraphic correlation of the invertebrate and vertebrate faunas of this Formation are discussed more fully in Chapter 13. Further work is required if accurate correlation is to be achieved but at this stage it is probably safe to conclude that the 'boxstones' are the remnants of a formation of muddy sands of Miocene possibly Anversien age.

4.7 Stimulus for phosphorite formation in the East of England

As stressed before (Chapter 3) oceanic upwellings may play an important role in supplying phosphates to shallow marine environments but they are not necessarily the mechanism which is required for the formation of a phosphorite deposit. Indeed it is difficult to see how deep oceanic upwellings could have directly affected the East of England during Tertiary times. One interesting observation is that phosphorite deposits tend to occur at the same stratigraphic horizons in widely differing parts of the world. This would imply that the conditions necessary to create a phosphogenic system were globally controlled. During the Tertiary, phosphorite deposits are particularly numerous in the Eocene and Miocene and these are the very horizons where the two phosphogenic episodes affecting the East of England are seen to occur.

The initiation of phosphogenic episodes may be associated with global warm periods which might affect the rates of decomposition of organic material and thus accelerate apatite precipitation. Piper and Codispoti (1975) suggested that a significant change in global nutrient budgets may be required. They suggested that an increase in marine denitrification, with a consequent lowering of productivity, will allow excess phosphorus to accumulate in sea water until it precipitates out as carbonate fluorapatite.

Carter (1978) thought that global eustatic regression during the Miocene might account for the worldwide occurrence of phosphorite deposits of that age. This regression would result in a net increase in dissolved phosphate in deep water in all oceans, creating a situation in which increased phosphate precipitation could have occurred in areas of upwelling. Apart from the lack of association with upwelling currents, the East of England phosphorites were formed during periods of transgression rather than regression.

Whatever the stimulus for phosphogenic episodes one interesting correlation is found between phosphorite formation in the London Clay and volcanic activity. Bushinskii (1966) thought that volcanic processes may be a source of phosphorus in a phosphogenic system. Knox and Ellison (1979) have described ash bands in the London Clay of Essex and Suffolk. These ashes have mostly undergone total alteration to montmorillonite, often associated with phosphorite formation. These ashes are related to widespread volcanic activity in N.W. Europe during Lower Eocene times. Thus a volcanogenic source of phosphorus may also have been involved in the production of the London Clay phosphorite concretions.

4.8 Conclusions

1. In the Eocene of Eastern England phosphorite concretions were formed by the precipitation of carbonate fluorapatite in microenvironments of organic decay. The

dominant mechanism involved precipitation from interstitial porewaters supersaturated with respect to phosphate. The preferred nucleation centres were rich in organic material and usually also rich in inorganic phosphates e.g. crustacean carapaces. Material with a high inorganic phosphate content but only a low organic content e.g. teeth, rarely acted as nucleation centres.

2. During a Miocene transgression muddy quartz sands were deposited over a small area of East Suffolk. Apatite was similarly precipitated as a concretionary growth in interstitial porewaters surrounding centres of organic decay. However, these centres were generally associated with molluscs or patches of bioturbated sediment. Concretion formation was rare around centres primarily rich in inorganic phosphate, but with a low organic content. These centres formed sites for the precipitation of apatite by replacement.

3. Although these differences exist between phosphorite formation in the Eocene and Miocene of Eastern England the major factor influencing the formation of a phosphorite concretion was the availability of high local concentrations of organic phosphate in interstitial porewaters. The mineral nature of nucleation centres seems less important.

4. Phosphorite formation in the East of England appears to be related to transgressive episodes while regressive episodes are important in the concentration of phosphatic

material in a remanié deposit.

Chapter 5 Sedimentary Structures and Facies

Chapter 5. Sedimentary Structures and Facies

5.1 Introduction

The Coralline Crag is by no means a uniform deposit in terms of sedimentary facies as thought by Harmer (1898, p.308). A number of distinct facies can be recognised which in part correspond to the 'zones' described by Prestwich (1871a) (see figure 6). In the present study 3 major facies are distinguished and are described as facies A, B and C. Each of these facies was found to have a distinct, geographical and, to some extent, vertical distribution (see chapter 12). Facies A is further subdivided into 3 subfacies which are here referred to as facies A1, A2 and A3. Facies A1 and A2 are characterised by their general lack of recognisable sedimentary structures while facies A3 is thought to be intermediate between facies A and B. Using the classification of Selley (1976) the sedimentary structures can be divided into primary (physical) structures and secondary (chemical) structures. The primary structures are subdivided into inorganically and organically formed structures. The secondary structures are not considered in this chapter but are described in Chapter 8 on diagenesis.

5.2 Inorganic Primary Sedimentary Structures

These structures include the common larger-scale forms which are typical of unidirectional flow over sand-sized sediments i.e. large-scale cross-stratification and horizontal stratification, and some smaller-scale features associated with these larger-scale bedforms e.g. silt bands, shell orientation.

a) Cross-stratification

The cross-stratification observed in the Coralline Crag can be divided into 2 types.

(i) Type I

Description

This type characterises facies B and consists of sets of cross-strata generally between 1 and 2 m thick. A set of 2.3 m thickness was observed at Crag Farm (locality 20). The sets generally have straight horizontal to sloping contacts and may thus be termed tabular rather than trough cross-stratification. Sections at right angles to the direction of dip of foresets may show large-scale trough-shaped lower contacts to the sets, (Plate 13, C) or more or less horizontal parallel lamination in small sections (Plate 13, E). The foresets themselves are generally concave with tangential lower contacts and truncated tops. Individual foreset laminae are indistinct without the obvious vertical grading of sediment within each lamina noted by Allen and Narayan (1964) in the quartz sands of the Folkestone Beds. This may in part be due to the coarse bioclastic nature of the Coralline Crag sediment which would allow finer grains of sediment from successive avalanche events to infiltrate previously deposited coarse sediment. Further work using sediment peels may reveal whether grading within the foreset laminae can be identified. Longitudinal grading of coarser elements, mostly bryozoan skeletal fragments, can be observed with larger fragments often found to be concentrated at the base of the foresets and within the bottomsets. Silt drapes which are characteristic of type II cross-stratification in the Coralline Crag are notably absent from type I bedding. The maximum foreset dip is generally between 24 and 28° although dips of up to 30° were observed.

Interpretation

Each individual foreset layer was deposited from an avalanche of carbonate sand down the steeper face, or lee-side of a subaqueous sandwave (see section 5.2 a) (v) for discussion of bedform terminology). Many features of the bedding may be useful for the determination of the precise conditions under which these sandwaves formed. Allen (1965) found strongly developed longitudinal grading in avalanche layers only when flow over large-scale ripple bedforms was relatively slow, and avalanching from the crest therefore relatively infrequent. These gradients became less well marked when current strength was greater.

Another feature, which Allen and Narayan (1964) thought could be indicative of lower velocity flows, was absence of well developed bottomset structures resulting from flow separation over the sandwave crest and a resulting region of backflow in the region of the toe of the sandwave lee slope. This backflow gives rise to small asymmetrical ripples and cross stratification which opposes the foreset dip on the larger bedform. The fact that the Coralline Crag cross-stratification appears to lack these features, but that they are commonly found in the Red Crag as at Bawdsey is notable. There are evidently differences between the environmental conditions involved in the formation of large scale cross-stratification in the two deposits. Allen and Narayan (1964) came to the conclusion that silt bands in the Folkestone Beds were deposited during periods of normal tidal current flow (cf. McCave, 1970) and inferred that large-scale bedload transportation occurred only during periods when currents were enhanced by storm activity where silt bands were present. Conversely they concluded that where silt bands were absent and sequences of foresets were unbroken, bedload transportation was more continuous under the action of normal tidal flows. Thus by comparison with the work of Allen and Narayan (1964) and Allen (1965) it would appear that the cross-stratification observed in facies B of the Coralline Crag can be explained by the migration of subaqueous sandwaves in response to normal tidal flows where the currents were relatively slow and avalanching relatively infrequent. Jopling (1965) studied the shape of foreset laminae related to current strength in laboratory flume experiments. At low velocities sediment particles crept along the stream bed and were deposited on the upper foreset slope. The transport rate was minimal and all transport took place by bed-load movement. Sediment accumulated on the upper foreset slope where it was distributed downslope by gravitative slip. This meant that the foreset slope was essentially a planar slip-face which abutted the floor of the channel with an angular contact. With increasing velocity a greater proportion of the sediment was taken into suspension and was carried beyond the crest of the bedform and the angular contact was replaced with a tangential contact. With a further increase of current strength the foreset became concave. Whilst it should be remembered that Jopling's experiments were conducted in a laboratory flume, his results would imply that the concave foresets of the Coralline Crag which generally have tangential lower contacts were indicative of relatively strong currents and not weak currents as implied by the work of Allen and Narayan (1964) and Allen (1965). The Red Crag cross-stratification also generally has concave foresets with tangential lower contacts but may additionally show bottomset backflow bedding. It would therefore appear that other factors than current strength such as sediment type and sediment supply may be important in the production of observed cross-stratification features. Indeed, ripple bedding (ripple height less than 4 cm: Allen 1968 a) has not been observed anywhere in the Coralline Crag. Under steady and uniform equilibrium conditions, current ripples are restricted to mineral-density sands less than 0.7 mm in diameter (Allen,1980 p.283). The Coralline Crag with its high bioclastic content is probably too coarse, therefore, for ripples to occur. Figure 7 shows that, for coarse-grained deposits, with increasing current velocities there will be a transition from plane beds directly to large-scale ripples with no transition through the small-scale ripple field.

Leeder (1980) explained the absence of ripples in coarse sands by the inhibition of flow separation over bed defects due to enhanced vertical mixing of boundary layer fluid over transitional to rough boundaries.

(ii) Type II

Description

This type of cross-stratification is characteristic of facies A3 at Rockhall Wood (localities 4,6) but may also be found elsewhere (e.g. Valley Farm, locality 23). The sets of cross-strata are variable in thickness but are generally around 0.5 m thick. The sets have trough-shaped upper and lower contacts and may therefore be termed, trough cross-stratification. The troughs are small, generally of only a few metres length, and appear trough-shaped in sections of differing orientations. The individual laminae are concave

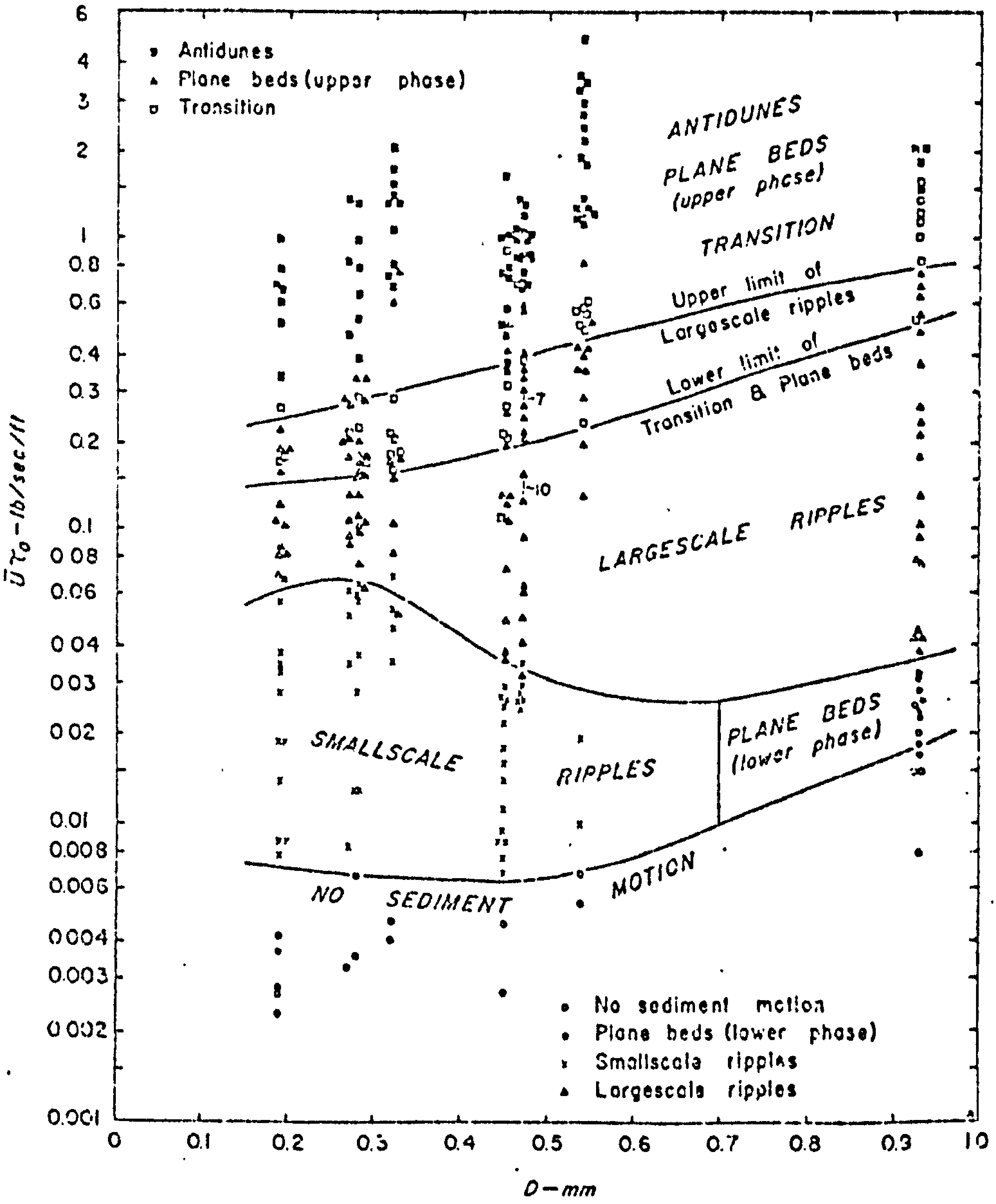


Figure 7 Bed form as a function of flow power and sediment size (after Allen, 1968a)

with tangential lower contacts. The laminae are not well defined, again possibly due to the coarse-grained bioclastic nature of the sediment. Typical trough cross-stratification of this type is illustrated in Harms et al (1975; p.46). Each trough-shaped set represents an elongate, concave erosional scour filled with curved laminae. The long axes of the elliptical scours are generally parallel to local flow conditons. The fill of the troughs is asymmetrical with the laminations having a greater thickness at the upcurrent end. The foreset laminations are occasionally draped with silt laminae usually between 1 and 2 cm thick.

Interpretation

The smaller scale trough cross-stratification is the result of the migration of small sinuous mega-ripples or dunes. The nomenclature of large-scale transverse bedforms is discussed later in this section. In contrast to type I cross-stratification, the foresets are frequently draped with thick laminae of fine sediment. The significance of these drapes and those found in facies C is discussed in section 5.2 (c). Cross-stratification of this type is best developed in facies A3 at Rockhall Wood (localities 4 and 6) where it unconformably overlies the siltier bioturbated sediments of facies A2. Derivation of fine-grained sediment from the erosion of this underlying facies may be an important factor in the production of the silt drapes at this locality as it is likely that supply of silt rather than environmental conditions was more important in the production of silt laminae.

(iii) Large-scale transverse bedforms as depth indicators

Allen (1968b) proposed that ripple height and wavelength could be correlated with flow depth. From a compilation of data he arrived at the relationship:

$$H = 0.086d^{1.19}$$

where H is the height of the large-scale ripple and d is the depth of flow. He also proposed an equation:

$$\lambda_D = 1.16d^{1.55}$$

where λ_D is the wavelength of the large-scale ripple, to describe the relationship between wavelength and flow depth. It is often felt desirable to be able to determine a palaeo-water depth for a fossil formation. It is for this reason that Allen's empirical approach has found favour with many workers (e.g. Dixon, 1979). The validity of the results of indiscriminate applications of these formulae must be brought into question after consideration of the following points:-

1) Allen's (1968 b p.170) data, by his own admission, shows a considerable scatter. Grain size is thought to have an effect on λ_D which appears to decrease with increase of sediment size. Other causes of scatter are thought to arise from the fact that 'dunes' observed in natural environments are rarely if ever in exact equil-

ibrium with prevailing conditions.

2) The formula is intended to derive the depth of flow which may or may not be equivalent to the water depth. For example the flow depth will be less than water depth where discrete surface or bottom currents are present.

3) Cross-stratification observed in fossil deposits almost invariably consists only of bottomsets and some portion of the foresets. It is often difficult to determine how much erosion of the top sets and upper part of the foresets has occurred and thus it is difficult to infer the original height of the bedform.

With these points in mind, if formulae are used on the best preserved sets of cross stratification in the Coralline Crag an estimate of the <u>minimum</u> flow depth may be determined. Therefore in facies B where the maximum value of set thickness is 2.3 m, d can be inferred to have had a minimum value of approximately 16 m. If we consider that the sandwave which produced this cross-stratification was probably nearer 3 m in height d becomes roughly equal to 20 m. The sandwave wavelength (λ_D') is approximately 120 m. In facies A3 where set thickness is around 50 cm, d has a value of about 4.5 m. Thus it may be tentatively inferred that water depth during deposition of facies B may have been about 20 m while facies A3 was deposited under about 4.5 m of water. Wavelength (λD) is approximately 33 m. Stride (1970) was also highly critical of such an empirical approach to the determination of palaeo-water depths and presents a plot (Stride 1970, fig 3) of sandwave height against water depth using data from around the British Isles. This plot shows an almost random scatter of data with no obvious correlation. Sandwaves of only 12 m height are quoted as occurring in water depths of about 165 m at the south-western edge of the Celtic Sea. Stride concludes that "sand waves, as known in present seas, show little prospect of being a useful indicator of water depth, even of the minimum water depth".

(iv) Inferred palaeo-current directions

Dip orientations of foreset beds were measured wherever exposure was large enough for foresets, as well as bottomsets, to be seen. Measurements were obtained for 16 localities showing type I cross-stratification and 2 localities showing type II cross-stratification.

Data for type I cross-stratification is shown in Table 3. The mean vector dip directions are also displayed in figure 8. From figure 8 it can be seen that the dip directions show only a small degree of scatter and trend SW - WSW more or less parallel to the trend of the present coastline.

Locality	No. of measurements	mean maximum foreset dip	mean vector dip direction
7	4	28°	210°
9	4	25°	198°
11	7	26°	233°
12	8	26°	240°
13	4	25°	204°
14	4	--	213°
18	10	27°	206°
19	6	19°	273°
20	16	24°	239°
21	4	25°	245°
22	1	16°	254°
23	4	28°	221°
24	4	19°	253°
25	2	27°	248°
27	4	19°	224°
30	4	22°	231°

Table 3

Foreset orientations of Type I cross-stratification for localities in facies B.

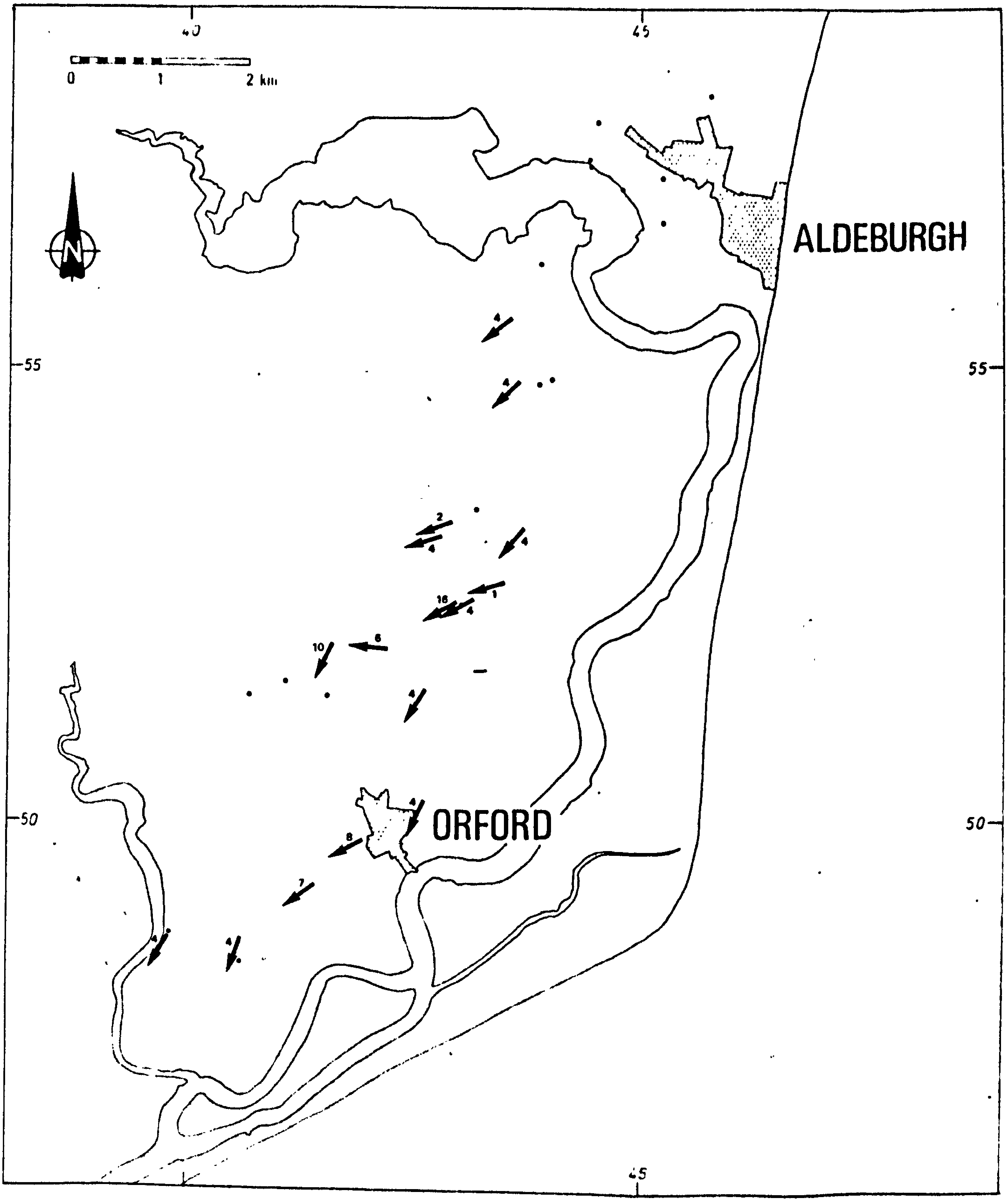


Figure 8 Map showing vector mean foreset dip direction measured at localities in the sandwave facies. Number of measurements shown alongside direction arrows.

Locality	No. of measurements	mean maximum foreset dip	mean vector dip direction
4	4	--	252°
6	4	--	256°

Table 4

Foreset orientations of Type II cross-stratification for localities in facies A3.

Data for type II cross-stratification is shown in Table 4. Type II cross-stratification was found to have a similar mean vector dip direction to that of Type I. Tidal currents are, of course, not linear but rotatory. Thus the direction of foreset dip indicates the net imbalance between flood and ebb currents. If the foreset dip directions do indicate the direction of net sediment transport and the dominant flow direction then it can be inferred that the palaeocurrent direction was very dominantly to the south-west with only small deviations from this trend. The localities around Aldeburgh therefore lie in a position which was up current from localities with large-scale sandwave cross-stratification which in turn lie up current from localities which show smaller-scale dune cross-stratification. The significance of sediment transport paths is discussed further in Chapter 12.

(v) Large-scale ripple nomenclature

A great deal of controversy surrounds the classification and nomenclature of large-scale ripple-shaped bedforms.

This has been concentrated on the definition of dunes, megaripples and sandwaves. The classifications have been based on a variety of parameters including bedform height (amplitude), wavelength, crest sinuosity and bedform stability. Allen (1980) defines sandwaves as "large flow-transverse bedforms in association with reversing tidal currents, where typically both ebb and flood flows are effective in transporting bed-material at least some of the time". He also states (p.281) that "Relatively asymmetrical currents shape sand waves with one side so steep that large-scale flow separation is inevitable". Many sandwaves in the southern North Sea have relatively gentle lee slopes with an inclination less than 5° (A.H. Stride pers. comm, 1980) which perhaps would not be termed 'sandwaves' by the definition of Allen. Allen (1980 p.283) used the term 'dune' to describe bedforms which are "similar in cross-section and plan to current ripples, the downstream slope again being constructed largely by avalanching... the wavelength exceeding 0.6 m and the height rising above 0.04 m". The major distinction that Allen makes between ripples, dunes and sandwaves relates to their stability within the flow; current ripples being able to travel greater distances within a tidal cycle due to their smaller volume than dunes or sandwaves. Ripples therefore lag only slightly behind changes in tidal flow. Dune forms probably persist throughout tidal cycles but are capable of reversal to an opposite facing to that possessed during the preceding tidal cycle. Sandwaves are altogether more stable structures persisting over long periods of time with relatively slow migration relative to wavelength.

This process-orientated attempt at classification may prove to be a more useful definition for the geologist than classifications based on bedform morphology alone. However, at the present time little is known of the internal structures of modern sandwaves or whether or not they are in equilibrium with present day shelf conditions. Most studies of fossil examples of large-scale cross-stratification are by necessity involved with classification based on internal morphology. Some aspects of bedform morphology are more easily deduced than others. Estimates of bedform amplitude are hindered by the general non-preservation of the crest of the bedform.

Swift _et_ _al_ (1979) used ripple spacing (wavelength) as their criterion for classification, ripples with a spacing of 5 - 150 cm, megaripples 1 - 40 m and sandwaves $>$40 m. Clearly such a classification is useless for preserved fossil examples. They also proposed that sandwaves are able to survive through successive seasons while megaripples are erased during the reduced current flows of the summer months and that this could be used to distinguish the two bedforms.

b) Horizontal and low-angle stratification

Facies C is characterised by horizontal and low-angle stratification. Large, infrequent, laterally extensive, horizontal silt laminae between 1 and 2 cm thick are also distinctive of this facies. The stratification is indistinct when examined closely, again possibly a result of the coarse-grained nature of the sediment or additionally due to bioturbation. The greatest angle of dip in facies C was seen at Aldeburgh Hall (locality 32) where the stratification dips at an angle of roughly 7° bearing 156°S (Plate 14,B). The explanation of these low angle bedding planes is rather difficult. They clearly represent primarily angled depositional surfaces which may possibly have been the lee slopes of very low profile sandwaves. Alternatively they may be the result of the preservation of sandwave stoss slopes in which sandwave migration was roughly northwards. An explanation involving flattening of existing seabed topography by periodic wave action is not consistent with the lack of internal truncation surfaces. Whatever the exact explanation of these bedding features they clearly result from deposition under a different regime than the cross-stratification described above. Occasionally small lenses, only a few centimetres in length, of silt-sized sediment were found associated with the horizontal stratification (e.g at Crag Pit Nursery, locality 38). It may be possible that these were originally draped over small bedform imperfections (? ripples) which were subsequently removed leaving only small lenses of silt.

c) Silt/clay drapes

Drapes of silt/clay sized sediment are found in facies A3 over foresets of trough cross-stratification and in facies C over low angle stratification and small ?scour troughs. The mechanism for deposition of fine-grained sediment from tidal currents was discussed by McCave (1970). He discovered that observed thicknesses of mud drapes could not be explained in terms of deposition during periods of slack water in tidal cycles, as the time available was inadequate. Houbolt (1968) shows mud layers from 0.2 to 1.0 cm in thickness interbedded with sands deposited on Well Bank in an area of strong tidal currents. McCave (1970;p.4157) proposed that this could be accounted for by an increase in fine-grained sediment concentration in the water, possibly caused by a storm, coupled with negligible wave activity and neap tides. The process of entrainment will be inhibited if sufficient fine-grained sediment is deposited around the time of slack tide to render the bed smooth. The succeeding tides could then deposit mud on this surface rather than entrain sand. McCave (1971) suggested that on most continental shelves where concentration of mud is low (generally ~ 1 mg/l) wave activity will be the major controlling factor in mud deposition but that where suspended sediment concentrations become high (order of 100 mg/l or more), mud deposits will result, irrespective of wave activity at the bed. Thus in the Coralline Crag where it is scarcely possible that deposition was below effective wavebase (particularly during deposition of facies A3) for even the majority of the time, it seems probable that increased sediment concentrations, possibly caused during storm events are the more likely cause of the formation of thick silt drapes.

d) Intraformational Mud clasts

Small mudclasts, mostly less than 1 cm across are locally common in the Coralline Crag. They are most frequent where facies A3 and B are seen to overlie the siltier sediments of facies A2. At Gedgrave Cliff (locality 7) small clasts of silty sediment are common within the large scale cross-stratification of facies B. These are presumably derived clasts of the finer grained sediment which lies beneath the unconformable base of facies B.

e) Orientation of shells

Where the shells of large bivalves are preserved they are generally disarticulated and orientated in a concave downwards orientation although this is by no means universal. Where moulds of large shells are found these also indicate a predominance of the concave-downwards orientation of these shells. Emery (1968) observed that a concave-down orientation of bivalve shells was found on wave washed beaches where currents were fast and there was a general absence of bioturbation whereas on the continental shelf most shells were orientated concave up due to the actions of carnivores and scavengers. Although his study mostly involved epifaunal molluscslike Mytilus, Placopecten and Arca a similar situation was observed for infaunal bivalves like Spisula and Arctica. Clifton (1971) made similar observations but made the important point that "The ultimate orientation of shells within the sediment may differ from the orientation of unburied shells" and that "Internal bioturbation, in particular, may tend to randomize pre-existing orientations". While random orientations of small shells and shell debris can be observed in the Coralline Crag sediments, larger shells are generally orientated parallel to bedding. Clifton and Boggs (1970) record a concave-up orientation for shells of the bivalve Psephidia in a wave zone (strong currents) which resulted from ripple transport of the shells. Although there is no doubt that shells orientated in a concave-downwards attitude are more stable to the actions of overturning by currents (Brenchley and Newall, 1970) the usefulness of shell orientation as a palaeoenvironmental indicator in fossil deposits may be limited.

5.3 Organic Primary Sedimentary structures

a) Burrows

Unwalled burrow structures may be locally common particularly within facies C but also to a lesser extent elsewhere. These generally consist of horizontal unbranched cylindrical structures approximately 1 cm in diameter which may be extremely common and bioturbate most of the sediment (Plate 14, E,F). The burrows were evidently unwalled and are probably attributable to the activites of crustaceans. In the cross-stratified sediments of facies B other types of burrow may be frequent. Many of these are thinner, longer and more sinuous than those described above and may be horizontal to subvertical.

b) Bioturbation

In addition to the clear burrow structures described above, sediments which show no recognisable sedimentary structures may have been affected by extensive bioturbation. It is interesting to note that all the well-defined burrows were observed within leached Crag sediments. The process of leaching and cementation may prove to be important in picking out these burrow structures. Some burrow structures were seen in the fine-grained sediments (unleached) at Rockhall Wood by the use of sediment peels. Presumed bioturbation structures include imbrication of patches of shell debris within the sediment (Plate 14,D). This may be due to the activities of infaunal echinoids or some other large infaunal burrower.

5.4 Summary

1. The Coralline Crag may be divided into distinct sedimentary facies which have characteristic suites of sedimentary structures.
2. Two types of cross-stratification can be recognised. The first (Type I) consists of large-scale tabular sets with a thickness generally between 1 and 2 metres. The second (Type II) consists of smaller trough sets with a thickness generally less than 1 metre. Type I cross-stratification is the result of the migration of subaqueous sandwaves while Type II may be attributed to smaller, more sinuous bedforms.
3. The Coralline Crag bedforms are indicative of the presence of

tidal currents. The absence of backflow structures and the small scatter of foreset dip vectors is inferred to be due to dominance of a single current direction within a full tidal cycle. This current direction may have been reinforced by wind generated waves during periods of storm activity.

4. Ripple bedding is absent from the Coralline Crag probably due to the coarseness of the sediment.
5. The set thicknesses have been used to infer a <u>minimum</u> flow depth of 16 metres for production of Type I cross-stratification and a flow depth of 4.5 metres for production of Type II cross-stratification.
6. The presence of silt drapes over bedforms may not be indicative of periods of reduced current activity but may reflect periods of increased fine sediment input and reduced wave-effectiveness on the sea-floor.
7. The orientation of bivalve shells in a concave-down or concave-up manner may not be a useful criterion for palaeoenvironmental reconstructions.

Chapter 6 The Coralline Crag Sediments

Chapter 6 The Coralline Crag Sediments

6.1 Introduction

The broad usage of the term 'Crag' to denote any shelly sand leads to confusion in the interpretation of borehole data where the presence of 'Crag' in the log may indicate either Pliocene or Pleistocene sediments. However, the selection of a more specific term for these sediments is by no means straightforward. Broadly speaking the Coralline Crag sediments consist of carbonate-rich skeletal sands which, once lithified, come under the category of clastic or detrital limestones. Carbonate grains generally comprise greater than 50% of the sediment. The quartz fraction and the majority of the carbonate fraction have grain sizes between $^{+}4$ and $^{-}1\phi$ diameter, although larger shells greater than $^{-}1\phi$ (2 mm) diameter are relatively common. The term 'skeletal calcarenite' (Pettijohn, 1975) seems to be a useful description of the Coralline Crag sediments as this term is based primarily on grain-size and not on the nature of the allochemical grains or on the type of cement as is the classification of Folk (1962). Using the classification of Dunham (1962) the Coralline Crag sediments would fall under the headings of Packstone (grain supported, $>$10% micrite) or Grainstone (grain supported, $<$ 10% micrite) depending on the content of micritic mud in the sediment. Both Folk's and Dunham's classifications will be affected by diagenetic changes in the sediment.

Identification of the grain mineralogy was accomplished by examination of thin sections obtained by vacuum impregnation of blocks of sediment with Araldite.

The various types of carbonate grain were examined in more detail by examination of disaggregated sediment under a binocular microscope (see Chapter 9).

6.2 Granulometric analysis

a) Methods

Sieving is the most widely used technique employed in the granulometric analysis of sediments. When sieving is used in the analysis of ancient bioclastic sediments several major drawbacks are encountered. Grain shape is a major factor influencing sieving results. Maiklem (1968) has shown that coarse-grained platy or rod-shaped particles can have fall velocities comparable with finer subspherical material, because of their complex settling paths. Thus, platy and rod-shaped grains will be retained on a sieve despite the fact that their weight is much less than more equant grains of the same material retained on a sieve mesh of the same size. Smaller grains of a denser material will not be retained on the same sieve mesh as larger grains which have the same weight and shape. The discrepancy between sieve analyses and hydraulic behaviour of sediments is well known (Sengupta and Veenstra, 1968; Channon, 1971; Braithwaite, 1973). Sieving of bioclastic sediments like the Coralline Crag which are mixtures of platy carbonate fragments and equant quartz grains results in grain-size distributions which often show large percentages of coarse grains represented by shell fragments despite the fact that during sedimentation these coarse grains may have been transported under similar hydraulic conditions as much smaller quartz grains. Channon (1971) termed this phenomenon "the shell anomaly". Sieve analyses of bioclastic sands thus often show bimodal grain-size distributions, the larger mode attributable to the bioclastic component while the smaller mode reflects the quartz sand component (e.g. Dixon, 1979).

This bimodality therefore results from the sieving method and not from any characteristic of the depositional regime. Large percentages of shell fragments may serve to obscure variations in the hydrodynamic character of the sediment. It is possible to correct this anomaly by using the quartz equivalent sphere diameter i.e. the diameter of a quartz sphere having the same terminal settling velocity as the particle. This lengthy procedure could only be used on a small number of particles. The settling velocity is often quoted as a more useful parameter than the size determined by sieving (e.g. Channon, 1971). However even determination of settling velocity has serious drawbacks. Most grades of sand presumably travel as bed load as well as in suspension thus an analyser should use the threshold stress of grain movement rather than settling velocity as a hydraulic criterion (Sanford and Swift, 1970). Additional problems are encountered when fossil sediments are analysed. It is often difficult to completely disaggregate a sediment where some form of post-depositional cementation has occurred. In the case of the Coralline Crag cementation by carbonate or limonite is common, generally resulting in small aggregates of grains in even the most carefully disaggregated samples. Aggregation thus causes an apparent increase in grain-size. Post-depositional compaction, on the other hand, causes a decrease in grain-size particularly with regard to platy skeletal fragments which are relatively easily fractured. Further complications in the granulometric analysis of skeletal sands arise from the possibility of in situ formation of carbonate grains, for instance by an infaunal bivalve which then remains in the sediment and never becomes part of the transported load of the bottom currents. Furthermore, as is particularly the case in the Coralline Crag, differential solution has often affected the sediment and removed aragonitic skeletal material while leaving calcitic skeletal material unaltered. The carbonate released by the solution of aragonite was reprecipitated in the form of sparite cement on the surfaces of calcite grains thus slightly increasing their overall dimensions (see Chapter 8).

So as to remove the effects on grain-size analysis of the shell anomaly, grain aggregation, compaction, in situ formation of carbonate grains, and selective solution and reprecipitation it was decided to remove all the carbonate fraction from sediment samples to leave only an acid insoluble fraction which consisted mainly of quartz. This residue should not have been affected by any of the factors discussed above and should yield relative, non-empirical data on sedimentary facies.

The carbonate was removed by solution of a sediment sample of about 250 g in cold 50% HCl over a period of several days. Fresh acid was added periodically as necessary. When digestion was complete the acid was decanted off and the sediment residue washed through a $^{+}4\phi$ sieve which removed clay and silt-sized sediment. The residue was dried in an oven and then sieved at 0.5ϕ intervals in the standard way.

b) Statistical grade parameters used in this study

Using the results obtained from the sieve analyses statistical grade parameters could be calculated. Jones (1970) discussed the relative merits of graphic and moment measures. He showed that graphic measures are less influenced by truncation of the tails of a distribution than are moment measures. However he also found that graphic parameters of sediments with high skewness and extreme kurtosis were not entirely independent of each other. Fortunately, no values of extreme skewness were found for the Coralline Crag sediments. This study uses graphic measures in preference to moment measures. These measures are defined and discussed in appendix 3.

c) Results

The results of granulometric analyses are listed below under the facies to which the sediment samples are assigned.

Facies A1

A complete discussion of the results of granulometric analysis on samples from facies A1 and their vertical trends can be found in Chapter 7 on the Tattingstone borehole.

Table 5 Grade parameters for facies A1

	Sample	ϕMd	ϕMz	$\phi\sigma_i$	Sk_i
1 Tattingstone Valley	214	2.09	2.09	1.12	$^-$0.03
2 Tattingstone Hall Fm.	097,102-112	1.96	2.09	0.87	0.21
	Average	2.02	2.09	1.00	0.09

Samples from facies A1 were found to have an average mean diameter of 2.09ϕ. The average value of the sorting coefficient

$\phi\sigma_i$, was 1.00 which is moderately to poorly sorted using the classification of Folk and Ward (1957). The value of 0.09 for Sk_i indicates a nearly symmetrical grain-size distribution but is close to the positive skewness category. Positive values of Sk_i indicate a tail of 'fines' in the grain-size distribution which is indicative of winnowing of fine-grained sediment to leave a dominantly coarse-grained mode.

Facies A2

Table 6 Grade parameters for facies A2

Locality	Sample	ϕMd	ϕMz	$\phi\sigma_i$	Sk_i
3 Ramsholt Cliff	090	2.51	2.34	0.97	-0.24
5 Rockhall Wood	058	2.24	2.26	0.82	0.03
7 Gedgrave Cliff	114	1.85	1.90	0.60	0.07
16 Sudbourne Park	127	1.90	1.99	0.92	0.04
	Average	2.12	2.12	0.83	¯0.02

Samples from facies A2 were found to have an average mean grain-size of 2.12ϕ. The average value of sorting (σ_i) was 0.83 which is moderately well sorted using the definitions of Folk and Ward (1957). The average value for skewness was ¯0.02 which indicates a nearly symmetrical distribution of grain-size frequencies.

Samples from facies A2 are thus similar in mean grain-size to samples from facies A1, but are slightly better sorted.

The grain-size ditribution is on average nearly symmetrical but the negative skewness value for sample 090 from Ramsholt Cliff indicates a 'tail' of coarse grain-sizes in the distribution due to deposition of fine-grained sediment in preference to coarser sediment.

Facies A3

Only 1 sample from Facies A3 was analysed

Table 7 Grade parameters for facies A3

Locality	Sample	ØMd	ØMz	Øσi	Sk_i
4 Rockhall Wood	134	1.60	1.70	0.62	0.26

This facies, which unconformably overlies facies A2 at Rockhall Wood, can be seen to differ significantly in the grade parameters from the samples from the underlying facies. The sample from facies A3 has a coarser mean grain size, a smaller value of $\phi\sigma_i$ indicative of better sorting and has a positively skewed grain-size distribution indicative of a 'tail' of fines due to winnowing.

Facies B

Thirteen samples from facies B were analysed and the results summarised in Table 8.

The average mean grain-size of 1.81Ø indicates a coarser sediment than from facies A1 or A2. The localities in Table 8 are arranged geographically with the southernmost localities at the top and the northernmost localities at the bottom (see figure 3). There is a slight tendency for samples with the smallest mean grain-size to be from localities in the southernmost portion of the extent of facies B, i.e. the geographically nearest localities to facies A. Values of $\phi\sigma_i$ average around 0.43 which falls into the category of well sorted distributions. Thus samples from facies B are better sorted than those from facies A. Values for Sk_i are variable ranging from 0.41 to $^-0.24$. The average value of Sk_i is 0.17 which is positively skewed, is indicative of winnowing of finer grain-sizes. It will be noticed that negatively skewed grain-size distributions arise from samples

Table 8 Grade parameters for facies B

Locality	Sample	ϕMd	ϕMz	$\phi\sigma_i$	Sk_i
9 Gedgrave Hall	072	1.78	1.80	0.42	0.14
11 Richmond Farm	073	1.86	1.90	0.32	0.29
12 Orford Castle	011	1.97	2.06	0.42	0.41
13 Daphne Road	019	1.84	1.87	0.44	0.13
14 Lodge Farm	066	1.96	2.05	0.40	0.40
18 White Lodge	053	1.56	1.58	0.40	0.14
19 Sudbourne Church	013	1.80	1.87	0.43	0.38
20 Crag Farm	079	1.81	1.82	0.43	0.09
23 Valley Farm	055	1.80	1.86	0.40	0.25
24 Tunstall Forest	082	1.76	1.82	0.45	0.29
25 Crag Pit Cottage	068	1.71	1.65	0.44	-0.24
27 Red House Farm	052	1.86	1.87	0.47	-0.03
30 Poplar Farm	084	1.39	1.35	0.58	-0.07
Average		1.78	1.81	0.43	0.17

from the northernmost localities within this facies.

Facies C

The average values of ϕMz and Sk_i for samples from facies C are similar to those found for facies B. Average mean grain-size is 1.84ϕ and average value of Sk_i is 0.20 (positively skewed). The average value of $\phi\sigma_1$ of 0.51 (moderate sorting) is slightly higher than for samples from facies B (See table 9).

d) Trend surface analyses

In order to study the trends of the grade parameters within the outcrop of the Coralline Crag a computer trend surface technique was used. The program used was KW1KR8 (Esler *et al*, 1968). Using this program 3rd Order trend surfaces were produced (Figures 9 - 12).

The trend surface program plots a general trend for the values given over a 2 dimensional surface. It takes no account of any discontinuities in the data such as facies breaks and will therefore attempt to plot a smooth trend where the trend may in reality be discontinuous. This fact should be remembered when studying figures 9 - 12. Although data from the outcrop at Tattingstone was considered in the analysis the resultant attenuated form of the printout was difficult to interpret in this area. Therefore contours have been left off from this area but the data has influenced the form of the contours elsewhere. Contours have only been plotted in the immediate vicinity of data points as excessive extrapolation from these points is unlikely to be justified.

i) Median ϕMd (Figure 9)

The 3rd order trend surface for ϕMd shows a fairly

Table 9 Grade parameters for facies C

Locality	Sample	ϕMd	ϕMz	$\phi\sigma_i$	Sk_i
26 'Firs' Reservoir	032	1.64	1.57	0.60	-0.13
28 Red House Farm Reservoir	133	1.84	1.90	0.30	0.28
31 Stanny Farm	087	1.87	2.05	0.76	0.30
32 Aldeburgh Hall	131	1.80	1.86	0.31	0.44
33 Aldeburgh Brick Pit	012	1.89	1.89	0.45	0.07
36 Round Hill	049	1.80	1.89	0.61	0.27
38 Crag Pit Nursery	005	1.69	1.71	0.56	0.08
Average		1.79	1.84	0.51	0.20

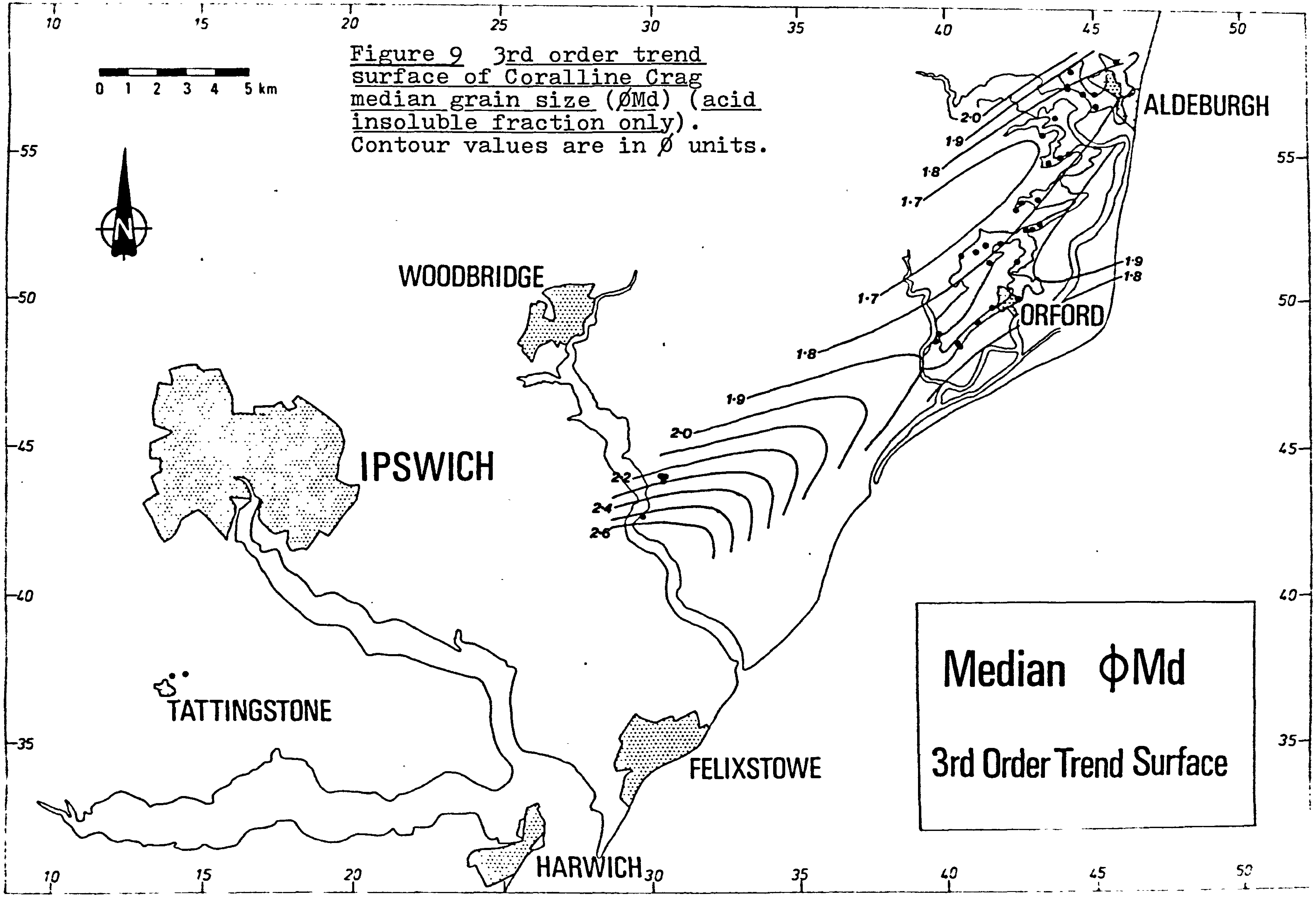


Figure 9 3rd order trend surface of Coralline Crag median grain size (ØMd) (acid insoluble fraction only). Contour values are in Ø units.

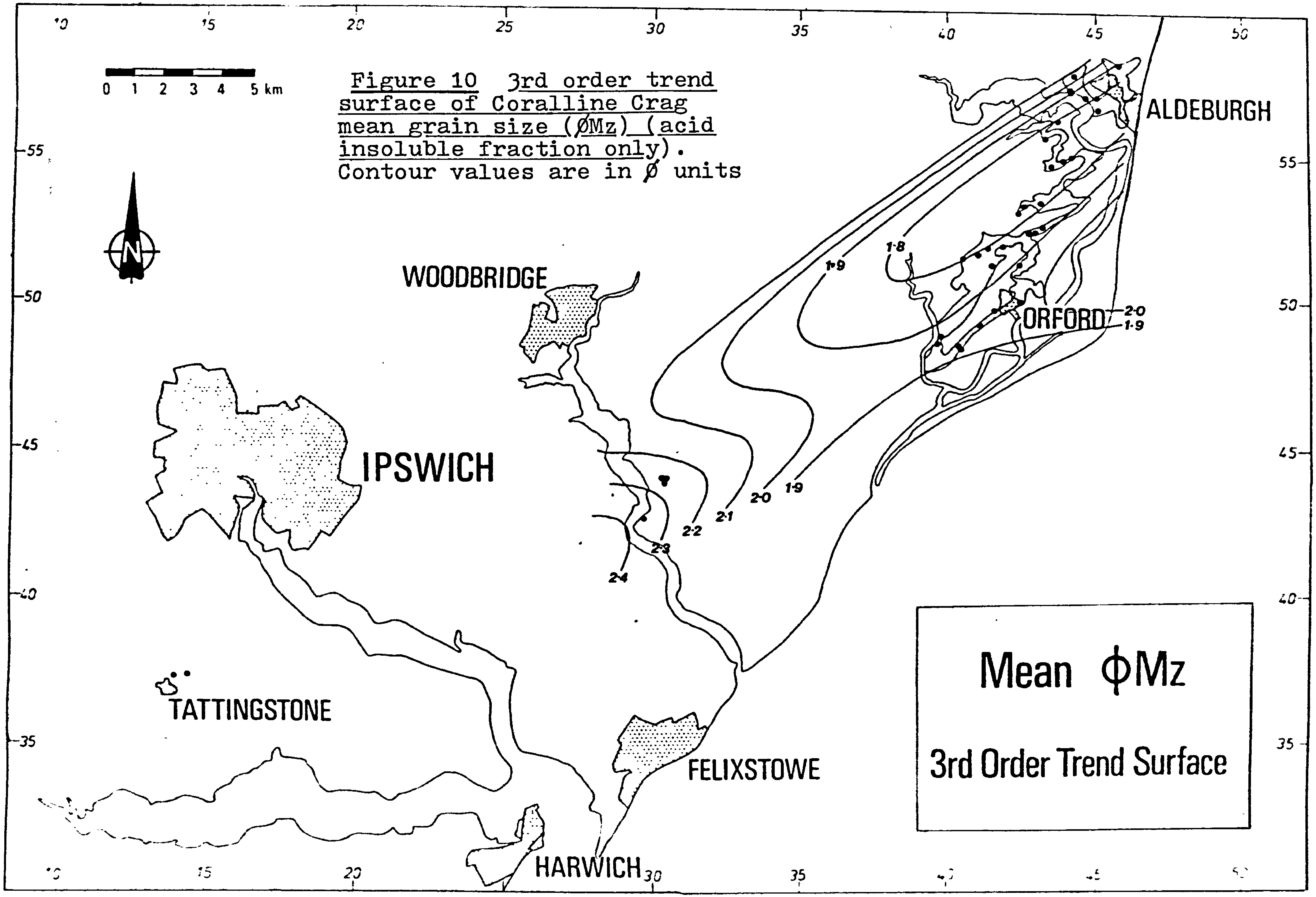


Figure 10 3rd order trend surface of Coralline Crag mean grain size (ØMz) (acid insoluble fraction only). Contour values are in Ø units

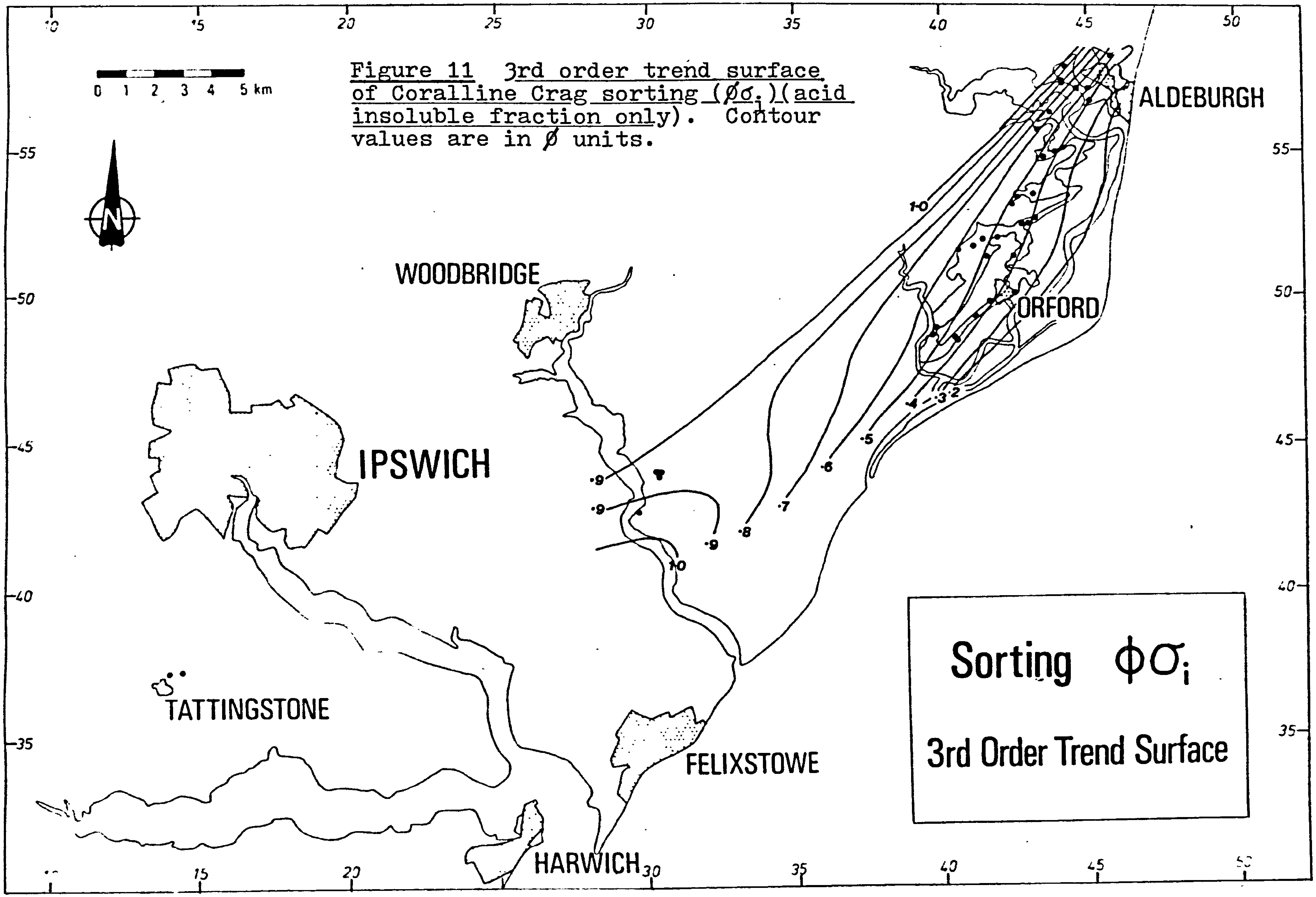


Figure 11 3rd order trend surface of Coralline Crag sorting ($\phi\sigma_i$)(acid insoluble fraction only). Contour values are in ϕ units.

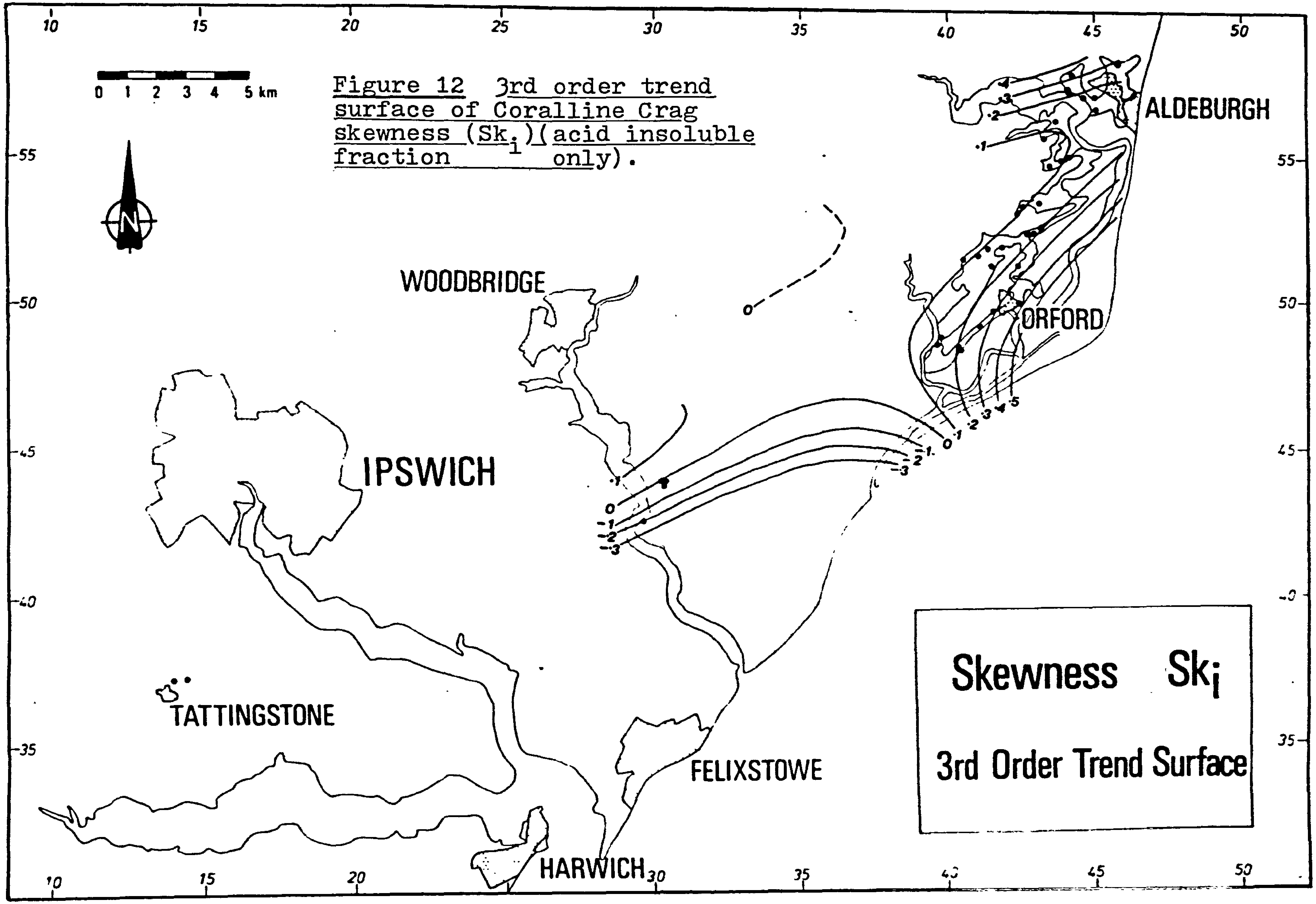


Figure 12 3rd order trend surface of Coralline Crag skewness (Sk$_i$)(acid insoluble fraction only).

simple trend to coarser median grain-sizes in a north-easterly direction.

ii) Mean ϕMz (Figure 10)

As expected the 3rd order trend surface for ϕMz is closely similar to that obtained for ϕMd with a trend towards coarser mean grain-sizes in a north-easterly direction.

iii) Sorting $\phi\sigma_i$ (Figure 11)

The 3rd order trend surface for values of $\phi\sigma_i$ shows a simple trend towards lower values (better sorting) in an easterly direction across the area of the Coralline Crag outcrop.

iv) Skewness Sk_i (Figure 12)

The 3rd order trend surface of values of Sk_i shows a combination of several local trends. In general more negative values occur in the south-westerly localities while positive values are characteristic of the main outcrop around Orford and Aldeburgh.

6.3 Carbonate content

The carbonate content of the Coralline Crag sediments varies considerably between different localities and facies. When interpreting a component percentage it should be remembered that if the abundance of another component increases for any reason then the percentage of the component being analysed is, by necessity, decreased. The effects of this "dilution" by terrigenous material, particularly quartz, are particularly marked in the Coralline Crag. This section examines the carbonate content of the sediments. More specific discussion of the nature of the larger carbonate grains, their mineralogy and preservation will be found in Chapter 9. Two methods were used to assay the carbonate content of sediment samples.

a) Method 1

A weighed sample of sediment (c 200 g) was placed in a large 'Xylon' beaker in a fume cupboard. Small amounts of cold 50% HCl were added to the sediment until there was no further effervescence on the addition of further quantities of acid. The acid was decanted away and the insoluble residue sieved through a 63μ ($^{+}4\phi$) sieve until all silt and clay had been removed. The acid insoluble residue was then air dried in an oven and reweighed when cold. The difference in the initial sample weight and the weight of the insoluble residue was taken as a measure of the carbonate content. This method takes no account of the carbonate contributed by sediment finer than $^{+}4\phi$. However, the error caused by this factor is probably quite small. Most sediment samples contained less than 10% of sediment finer than $^{+}4\phi$, When the carbonate content of the fine sediment was determined it was found to be in similar proportion to the carbonate content of the whole sample (see Chapter 8 , table 13). It was also assumed that all material removed by the analysis was either finer than $^{+}4\phi$ or was carbonate. Small quantities of apatite may also have been dissolved but probably do not significantly affect the results.

Results

The results of carbonate content averaged for individual facies are shown in Table 10. Facies A1 has the lowest

Table 10 Carbonate content of samples

Facies	Locality	Sample No.	% acid insolubles	% carbonate
A1	1 Tattingstone Valley	214	n.d	n.d
	2 Tattingstone Hall Farm	097,102-109,111	40.1	59.9
		Mean	40.1	59.9
A2	3 Ramsholt Cliff	090	39.8	60.2
	5 Rockhall Wood	058	21.4	78.6
	7 Gedgrave Cliff	114	21.2	78.8
	16 Sudbourne Park	127	14.9	85.1
		Mean	24.3	75.7
A3	4 Rockhall Wood	134	25.8	74.2
		Mean	25.8	74.2
B	9 Gedgrave Hall	072	35.7	64.3
	11 Richmond Farm	073	35.3	64.7
	12 Orford Castle	011	24.7	75.3
	13 Daphne Road	019	24.4	75.6
	14 Lodge Farm	066	16.3	83.7
	18 White Lodge	053	17.6	82.4
	19 Sudbourne Church	013	17.7	82.3
	20 Crag Farm	079	24.7	75.3
	23 Valley Farm	055	22.5	77.5
	24 Tunstall Forest	082	16.4	83.6
	25 Crag Pit Cottage	068	29.3	70.7
	27 Red House Farm	052	15.0	85.0
	30 Poplar Farm	084	16.5	83.5
		Mean	22.8	77.2
C	26 'Firs' reservoir	032	19.0	81.0
	28 Red House Farm reservoir	133	22.5	77.5
	31 Stanny Farm	087	6.1	93.9
	32 Aldeburgh Hall	131	11.9	88.1
	33 Aldeburgh Brick Pit	012	10.3	89.7
	36 Round Hill	049	7.5	92.5
	38 Crag Pit Nursery	005	12.5	77.5
		Mean	12.8	87.2

n.d. = not determined

carbonate content while facies C has the highest carbonate content. Facies A2,A3 and B have similar, intermediate values of carbonate percentage. The values of percentage acid insoluble residue were analysed using trend surface program KW1 KR8 as described in section 6.2. The contour map produced by the 3rd order trend surface is shown in figure 13. Figure 13 shows a trend of increasing percentage of insolubles and decreasing carbonate percentage towards the south-west. By way of comparison a similar trend surface was obtained from thin sections using point counted quartz percentages. The contoured trend surface for percentage quartz grains is shown in figure 14. This trend shows slightly greater complexity than that for acid insolubles but has the same general trend to increase in quartz percentage to the south-west.

Although the acid insoluble residues are dominantly of quartz,there are varying proportions of glauconite and other mineral grains present. Clearly, carbonate content decreases in a southwesterly direction with increasing 'dilution' of the sediment by terrigenous mineral grains.

b) Method 2

For a more accurate determination of total carbonate content a Schroetter alkalimeter was used (Grant, 1947, p.90; Furman, 1962, p.300). This method measures the quantity of carbon dioxide evolved when a powdered sample of carbonate sediment is treated with a known weight of acid.

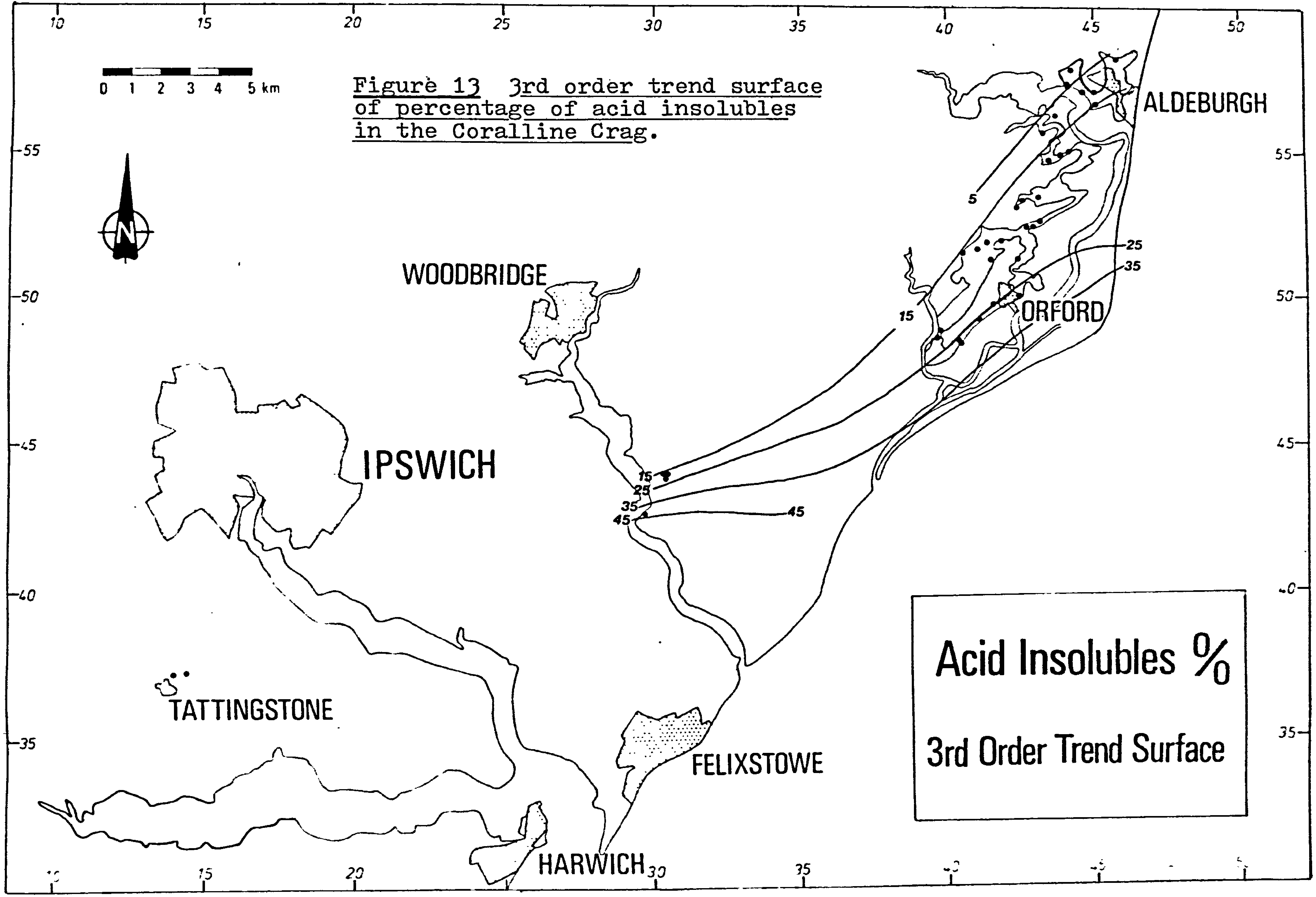
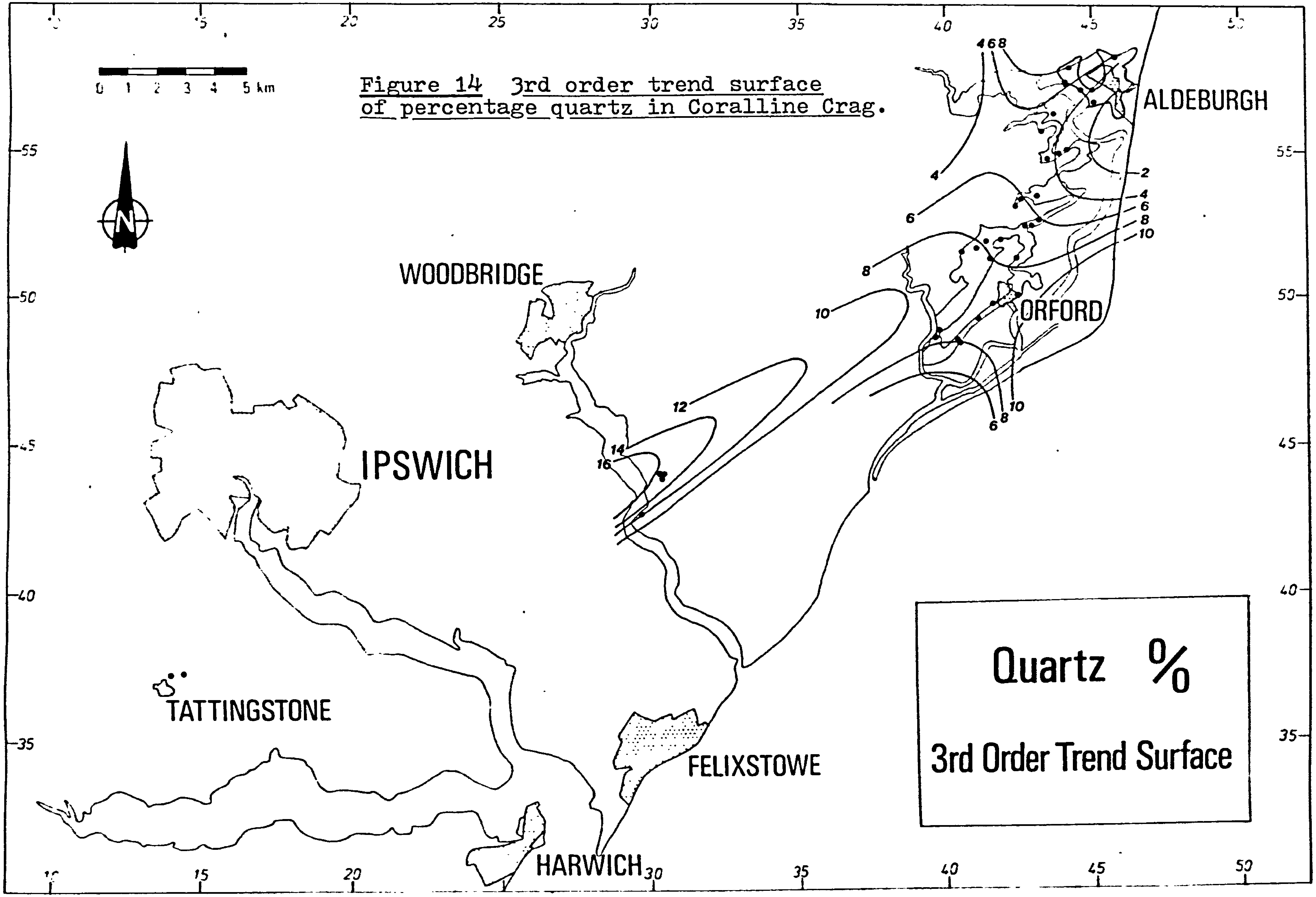


Figure 13 3rd order trend surface of percentage of acid insolubles in the Coralline Crag.

Figure 14 3rd order trend surface of percentage quartz in Coralline Crag.



A known weight of 50% phosphoric acid was placed in the apparatus with a known weight (roughly 2 g) of powdered sediment. The acid was allowed to run slowly into the reaction chamber. The CO_2 is passed through concentrated sulphuric acid to absorb any moisture. After the vigorous effervescence had ceased the apparatus was gently heated and aspirated with air to drive off all traces of CO_2 remaining in the flask. The loss of weight of the combined apparatus plus the acids and sediment sample is taken to be the loss of CO_2 from the carbonate. From this quantity the weight of carbonate in the powdered sediment sample can be determined.

This method was used in more detailed examination of the effects of diagenesis in Chapter 8.

6.4 Silt/Clay content

Method

The presence of 'fines' within a sediment, that is silt and clay sized sediment finer than 63 μm ($^{+}4\phi$), may be an important indicator of environmental conditions and may significantly affect bottom dwelling suspension feeders. Determinations of silt/clay content obtained by sieving may be rendered invalid if electrostatic interparticle attraction occurs or imperfect disaggregation of the sample is involved. For this reason the following method was used to determine the silt/clay content of the Coralline Crag sediment samples.

Approximately 50 - 100 g of unconsolidated or gently disaggregated sediment was placed into a previously weighed powder jar with a screw top. The jar and sediment were weighed together to obtain the exact weight of the sample. A quantity of distilled water and detergent were added until the sediment was completely immersed, the lid of the jar was replaced and the jar was shaken vigorously, and then left to stand for several hours. The sample was then transferred to a 63 μm mesh sieve and washed clean of any silt and clay.

The sample was returned to the jar, dried in an oven and then weighed at room temperature as before. The weight percentage of silt plus clay in the original sample was calculated from the weight loss after sieving.

Results

The results for the samples analysed for silt/clay content are tabulated by facies in Table 11. The content of silt/clay sized sediment can be seen to fluctuate slightly but generally comprises between 3 and 8% of the total sediment in facies A1, A3, B and C. Facies A2 has a conspicuously higher silt/clay content of between roughly 19 and 35%. Two factors may be important in creating this distribution of fine-grained sediment. The effect of diagenesis on the fine sediment content is discussed in Chapter 8 and the effects of sediment transport are discussed in Chapter 12.

Analysis of the fine sediment ($<63\mu m / <^{+}4\phi$) for carbonate content reveals that it may comprise 67·5% carbonate (sample from Facies A2, Gedgrave Cliff, locality 7). This carbonate is probably derived from the degradation of carbonate grains within the depositional basin of the Coralline Crag (see Chapter 9).

Table 11 Silt/clay content of sediment samples

Facies	Locality	Sample	% silt/clay
A1	1 Tattingstone Valley	214	n.d.
	2 Tattingstone Hall Farm	102- 111	3.62
		Mean	3.62
A2	3 Ramsholt Cliff	090	20.01
	5 Rockhall Wood	058	35.50
	7 Gedgrave Cliff	114	21.88
	16 Sudbourne Park	127	18.91
		Mean	24.07
A3	4 Rockhall Wood	134	3.69
		Mean	3.69
B	9 Gedgrave Hall	072	3.70
	11 Richmond Farm	073	2.98
	12 Orford Castle	011	6.02
	13 Daphne Road	019	4.82
	14 Lodge Farm	066	7,77
	18 White Lodge	053	3.62
	19 Sudbourne Church	013	7,36
	20 Crag Farm	079	3.02
	23 Valley Farm	055	5.13
	24 Tunstall Forest	082	4.52
	25 Crag Pit Cottage	068	5.27
	27 Red House Farm	052	4.88
	30 Poplar Farm	084	6.41
		Mean	5.04
C	26 'Firs' reservoir	032	6.57
	28 Red House Farm reservoir	133	3.61
	31 Stanny Farm	087	3.89
	32 Aldeburgh Hall	131	4.29
	33 Aldeburgh Brick Pit	012	3.91
	36 Round Hill	049	4.52
	38 Crag Pit Nursery	005	8.03
		Mean	4.97

n.d. = not determined

6.5 Glauconite

Glauconite is an ubiquitous component of the Coralline Crag sediments. In addition to its occurrence as grains within the sediment, glauconite grains are commonly found to occlude the zooecial apertures of bryozoans. The large, unrestricted apertures of the large cyclostone Meandropora are frequently occluded in this way. The glauconite grains may have been derived by:-

1) The physical lodging of glauconite grains from the sediment within the apertures.
2) Primary mineral growth within the zooecial chambers.

It is unlikely that the first mechanism has been important in this process. Glauconite is the commonest mineral grain seen to occupy these apertures, whereas it is far less common in the surrounding sediment than quartz. Secondly the grains usually totally occupy the chambers. In thin section this is clearly shown by glauconite found occluding intraparticle voids of barnacle plates (Plate 17,A) and possible decomposed glauconite within algal borings in shell material. This glauconite is considered to be authigenic.

The origin of glauconite is only poorly understood. Glauconite is believed to be polygenetic (Selley 1976, p.78). Triplehorn (1966) wrote "....at a given time, and in a given place, glauconite may form by more than one process and from several parent materials". It has been proposed that there is an illite or montmorillonite precursor to glauconite, thus glauconite could arise from the clay infillings of organisms. Triplehorn also suggested that glauconite morphology may be dependant on the site of formation. This might yield specific information on local environmental variations within an overall glauconite-producing environmnent. It is known that glauconite formation is characteristic of slightly reducing conditions in a marine environment. Fairbridge (1967) noted that "Reducing conditions can be established on the open shelf in a micro-environment such as the rotting interior of a molluscan shell, of certain Foraminifera, or associated with faecal pellets". Thus a microenvironment of decay within zooecial chambers of bryozoans would seem to be ideal for glauconite formation.

Opinions vary on the other conditions necessary for glauconite formation. Fairbridge (1967, p.45) wrote that glauconite is characteristic of warm water shelf and slope environments with an optimum depth of formation of between 15 m (wavebase) and 500 m (shelf margin). Selley (1976) records the formation at low temperatures and at optimum depths of between 50 and 1000 m. Certainly, glauconite has been forming on the Rockall and Hebrides shelf off the North of Scotland since the last glaciation. Glauconite formation does not appear to occur in areas of rapid burial implying that the process is fairly slow but it does occur on shelves that have been inundated during the last 10,000 years. A time span of 100 - 1000 years has been proposed for the formation of a 2 mm particle (Fairbridge, 1967). The glauconite reaction occurs in the activity field of heterotrophic anaerobic bacteria at pH 7-8, Eh 0- $^{-}$100 mV and a temperature between 5 and 25°C. It is very stable under alkaline conditions but rapidly breaks down under acid conditions liberating potash and iron oxides. This latter reaction will be discussed in the section on iron staining in the Coralline Crag (Section 8.3).

The correlation between glauconite formation and areas of relatively reduced deposition in the Coralline Crag is important. A carbonate skeleton with authigenic glauconite within voids need not necessarily imply reduced sedimentation at that particular point as the skeleton may have been derived locally from an area in which deposition rates are favourable to glauconite formation. Once formed, glauconite is stable in sea water and can thus survive transportation in a marine environment (Selley 1976, p.78). Abundant glauconite within a carbonate sediment would however imply that reduced rates of sedimentation existed within the depositional basin. Thus in the Coralline Crag although deposition within the sandwave facies was undoubtedly fairly rapid, elsewhere the rate of deposition was slow enough to allow formation of glauconite within chambers of carbonate skeletons.

6.6 Other minerals

The accessory mineral grain types of the Coralline Crag have been described in detail by Double (1924). He noted that the sands of the Coralline Crag were much coarser than those of the succeeding Crags, the heavier particles having an average diameter of around 0.2 mm. The most striking minerals in the assemblage, apart from glauconite and quartz, were found to be garnet, staurolite, andalusite, chiastolite and kyanite. Zircon, tourmaline, ilmenite and muscovite were also found to be common. Among the lighter minerals, other than quartz, orthoclase and microcline were noted but the commonest feldspar found was one having the optical properties of oligoclase - andesine.

In the present study grains of feldspar were found to be most numerous in localities towards the southwest of the outcrop where quartz and other terrigenous material was also most common. Occasional small grains of apatite were also noted from localities where the London Clay basal contact was near to the surface. Muscovite flakes were found to be particularly common at Rockhall Wood (localities 4,5 and 6) and Ramsholt (locality 3) in the sediments of facies A2.

The composition of the mineral suite should yield important information on the provenance of the terrigenous sediment in the Coralline Crag. Double (1924, p.352) writing on the source of the mineral assemblages of the Crag deposits wrote "It is hardly possible that the present area of the Lower London Tertiaries, or any greater extension of these in the past, could have yielded the mineral assemblage characteristic of the Pliocene deposits..." He also dismissed the possibility that the mineral assemblage could have been derived from either the Upper Chalk or the Lower Greensand of Cambridgeshire and Norfolk. The abundant occurrence of garnet, staurolite, dusky andalusite, kyanite, mica, epidote and hornblende suggest derivation from metamorphic rocks. Double (1924) and Boswell (1915, p.258) suggest that the Ardennes is the nearest area of rocks containing such an assemblage of minerals and that this was the probable provenance of the Crag minerals. Boswell's (1915) work on the mineral assemblages of the 'boxstones' may be important in the context of Crag mineral provenance. He wrote [p.258] that "The mineral suite of the box-stones conforms generally to that of the East Anglian Pliocene deposits, and is entirely different from the assemblage found in the Eocene beds".

The following explanation can be proposed: If it is conceded that the 'boxstones' represent lithified concretions within a generally unlithified sediment and that '*in situ*' erosion of the "Trimley Formation" led to the 'boxstones' being left as remanié material on the London Clay surface, then the source of the Coralline Crag mineral assemblage could easily arise from the winnowing of the unconsolidated sediment of that formation.

The mineral assemblage of the Red Crag bears a strong resemblance to that of the Coralline Crag but the grains are generally smaller (Double 1924, p.347). Subsequent break up of the Coralline Crag by the Red Crag transgression and derivation of terrigenous material into the Red Crag sediments could account for the observed similarity of mineral assemblage between those two deposits. It is certainly true that derived Coralline Crag fossils are common in the Red Crag (Wood, 1859).

It therefore seems most likely that the majority of the non-carbonate sediment of the Coralline Crag was derived from the winnowing of unconsolidated quartz-rich sediments of the 'Trimley Formation'. The observed distribution of non-carbonate sediment in the Coralline Crag shows much greater terrigenous content in samples from localities which are inferred to be nearshore with the proportion of terrigenous material gradually decreasing with the upbuilding of contemporary carbonate skeletal sediment.

6.7 Coralline Crag fabric

Attempts are frequently made to relate carbonate rock fabric to depositional environment e.g. Fairbridge et al (1967). Two methods which attempt to quantify this supposed relationship are the calculation of the Grain-micrite ratio (GMR) and the Energy Index (EI). GMR shows the relative amounts of coarse and fine textured carbonate material, theoretically related to wave or current action (Fairbridge et al, 1967, p.17). For rocks having 90% grains, GMR is 9/1; for 50% grains, 1/1, for 10% grains, 1/9, and so on. EI is a quantitative index for the appraisal of the rock and its environment. > 90% grains indicate strongly agitated waters; 75-90%, moderately agitated; 50-75%, slightly agitated; 25-50%, intermittently agitated; and 10-25%, gently agitated.

Values of GMR for the Coralline Crag range from 0.66 to 2.78 with a mean of 1.54. Values of EI range from 39.8% to 72.3% grains with a mean of 56.3%.

The usefulness of such measures however, for the Coralline Crag is very limited. Subaerial diagenesis of the sediment (see Chapter 8) is likely to significantly affect the grain to matrix ratio. Aragonite grains may be dissolved and the carbonate redistributed as cement. Selley (1976) discussed the polygenetic origin of micrite and wrote; "It is possible for a clean carbonate sand to be deposited in a high energy environment. Subsequently, however, micrite may develop by bioturbation, algal micritization and by infiltration due to high permeability". These mechanisms may all have occurred in the Coralline Crag sediments, thus any conclusions on the depositional environment drawn from the proportion of micritic mud within the sediment must be regarded as suspect.

Details of the fabric of Coralline Crag sediments related to aspects of diagenesis are discussed at length in Chapter 8.

6.8 Summary

1) Granulometric analysis of the acid insoluble fraction of the Coralline Crag is considered to yield more useful results due to the bioclastic nature of the sediment.

2) A number of trends of various grade parameters can be identified within the outcrop area of the Coralline Crag. Generally the acid insoluble sediment shows a trend towards smaller mean and median sizes, poorer sorting and more negatively skewed distributions in a south westerly direction.

3) Carbonate content of the sediment shows a trend towards a smaller proportion of carbonate in a south-westerly direction due to increased 'dilution' by terrigenous sediment.

4) Facies A2 has a much greater content of fine-grained sediment ($<{}^{+}4\phi$) than the other facies. Over two-thirds of this fine sediment is composed of carbonate presumably derived from the degradation of carbonate skeletal grains.

5) Deposition of the Coralline Crag sediments was, in places, slow enough to allow the formation of glauconite within localised micro-environments of reducing conditions within bryozoan chambers, foraminiferid chambers etc.,

6. The mineral suite of the Coralline Crag is very similar to that from the 'boxstones'. Breakup of the 'Trimley Formation', the sediments of which the 'boxstones' are

lithified concretions, was probably the source of the majority of the terrigenous content of the Coralline Crag.

Chapter 7 The Coralline Crag outcrop at Tattingstone

7.1 Introduction

7.2 Sedimentary structures

7.3 Sediment analysis

Method

Interpretation of results and data

i) ϕMd & ϕMz

ii) $\phi\sigma_i$

iii) Sk_i

iv) % acid insolubles

v) % sediment $<^{+}4\phi$ (silt/clay)

7.4 Faunal Analysis

7.5 Basal phosphorite deposit

7.6 The London Clay surface

7.7 Conclusions

Chapter 7 The Coralline Crag outcrop at Tattingstone

7.1 Introduction

The first record of the Coralline Crag outlier at Tattingstone seems to be the description by Charlesworth (1835a). He described the Coralline Crag as being exposed for a distance of 70 yards (60 m) beneath the overlying Red Crag with a vertical extent of less that 6 feet (2 m). In an attempt to dig through the Crag to the London Clay, work was stopped by the water table at a depth of a further 2 feet (0.6 m). Lyell (1839) said that he "caused a pit about 7 feet deep to be sunk in the yard at Tattingstone Hall Farm, piercing the lowest part there exposed of the Coralline Crag, through green marls, with intervening layers of flaggy limestone, two or three inches thick". At this depth work was again stopped by the water table flooding the pit. Whitaker (1877) described the locality and the outcrop itself as "little more than a quarter of a mile along the bottom of the valley from north to south, and only an eighth of a mile wide at most. It is bounded westward by the narrow alluvium, on the other side of which London Clay crops out, and elsewhere by Red Crag which comes on above, and the underground extent of the older Crag is probably small". Boswell (1913) thought the outcrop was rather smaller and produced a map which indicated an outcrop only 280 m long and 160 m wide.

The position of the outlier is rather anomalous in comparison with the other Coralline Crag outcrops, being 16½ km to the south-west and at an elevation 12 m greater than the nearest outlier at Ramsholt. . In recent years it has become apparent that the small body of Coralline Crag mapped by Boswell (1913) [TM 143 374] is not the only one in the Tattingstone Valley. Excavations during the construction of a road bridge at Lemon's Hill have revealed further patches of Coralline Crag on the west side of the valley. [TM 139 375] Markham (1971) described another small section [TM 140 368] exposed during a temporary excavation at Tattingstone Place. The known exposures are shown on a map of the Tattingstone Valley (Fig 15).

In 1972 the Anglian Water Authority announced plans to flood the Tattingstone Valley as part of the Alton Water Reservoir scheme (now completed). In order to obtain as much data as possible from this outlier before impounding of the reservoir made future study impossible it was decided to sink a borehole through the entire thickness of the Coralline Crag down to the underlying London Clay. The equipment used was a Pilcon Wayfarer six inch diameter percussion shell and auger. A bailer was used for obtaining samples from beneath the water table. In this way a continuous sequence of disturbed bulk samples was obtained for analysis. Information from the borehole samples has been supplemented by information derived from a number of excavations made during 1977-1978, the borehole itself being sunk on 17th July 1978.

7.2 Sedimentary structures

No clear sedimentary structures have been identified at Tattingstone although some vague horizontal bedding can occasionally be seen (Plate 12, A). The poor preservation

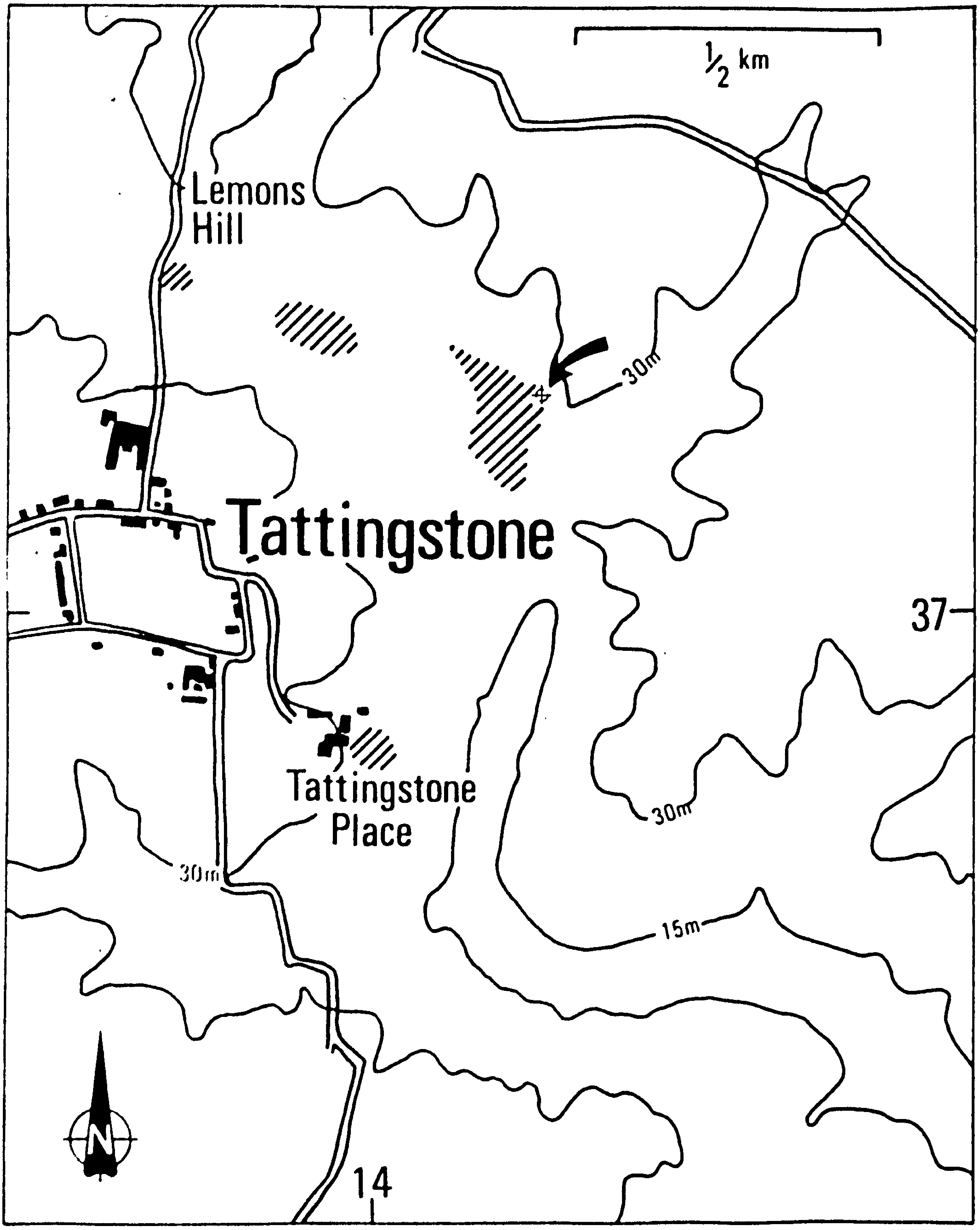


Figure 15 Map of the area around Tattingstone showing areas of Coralline Crag outcrop (oblique shading). Borehole site is arrowed.

of sedimentary structures may be due to extensive reworking of the sediments by organic or physical action. Localised irregular patches of cemented Crag are found and are discussed elsewhere (Chapter 8).

7.3 Sediment analysis

Method

Granulometric analysis was performed on the acid insoluble fraction of the sediment only. The reasons and technique for this procedure are discussed fully in Chapter 6. For each sample the ϕMd, ϕMz, $\phi\sigma_i$, Sk_i, %acid insolubles and $\% <^{+}4\phi$ were obtained and are tabulated in Table 12.

Interpretation of results and data

It can be seen from Table 12 that ϕMd, ϕMz $\phi\sigma_i$, and Sk_i show very little variation in samples from 1.65m - 5.10 m depth. Samples from 0.82 m - 1.65 m show much wider variations in these parameters. There is a gradual decrease in the percentage of acid insoluble material from the base of the Crag to 1.50 m depth above which there is an abrupt increase.

The grain-size distributions of samples from the top 1.65m of the borehole (Fig 16) are markedly different from those of the lower part of the borehole.

An additional sample (COR 097) was taken from the old quarry face a few metres away from the borehole site and analysed in the same way as the borehole samples. The sample was laterally equivalent to the borehole sample from 0.82 m - 1.20 m. The grain-size parameters and frequency distribution of this sample bear little resemblance to the corresponding borehole sample but are nearly identical to the values shown by the sample from 1.65 m - 1.95 m. It is unlikely that such

Table 12 Tattingstone borehole: Grade parameters, percentage acid insoluble and percentage silt/clay (Grade parameters for non-carbonate fraction only)

Sample N°	Depth below surface (m)	øMd	øMz	øσ_i	Sk$_i$	% acid insolubles	% $< +4$ø
COR 097	0.97-1.17*	2.15	2.25	0.94	+0.15	34.3	n.d.
COR 098	0.82-1.20	1.34	1.47	1.34	+0.05	n.d.	4.98
COR 099	1.20-1.35	1.29	1.49	0.91	+0.29	39.0	3.76
COR 100	1.35-1.50	1.29	1.36	0.76	+0.23	25.0	3.68
COR 101	1.50-1.65	1.32	1.76	1.10	+0.45	15.9	4.72
COR 102	1.65-1.95	2.60	2.45	0.98	-0.16	25.9	6.71
COR 103	1.95-2.30	2.30	2.33	0.91	+0.07	34.3	7.03
COR 104	2.30-2.70	1.93	2.12	0.90	+0.30	38.1	4.79
COR 105	2.70-3.25	1.71	1.96	0.92	+0.36	39.1	3.62
COR 106	3.25-3.55	1.75	1.98	0.88	+0.35	40.3	3.62
COR 107	3.55-3.90	1.75	1.97	0.89	+0.35	42.8	3.53
COR 108	3.90-4.40	1.76	1.97	0.86	+0.33	44.2	3.49
COR 109	4.40-4.50	1.83	2.00	0.82	+0.27	47.1	3.60
COR 110	4.50-4.75	1.93	2.03	0.79	+0.18	n.d.	3.21
COR 111	4.75-5.00	1.93	2.01	0.77	+0.20	55.3	3.30
COR 112	5.00-5.10	1.94	1.99	0.82	+0.08	n.d.	n.d.

*sample taken from excavation adjacent to borehole site.

n.d. = not determined

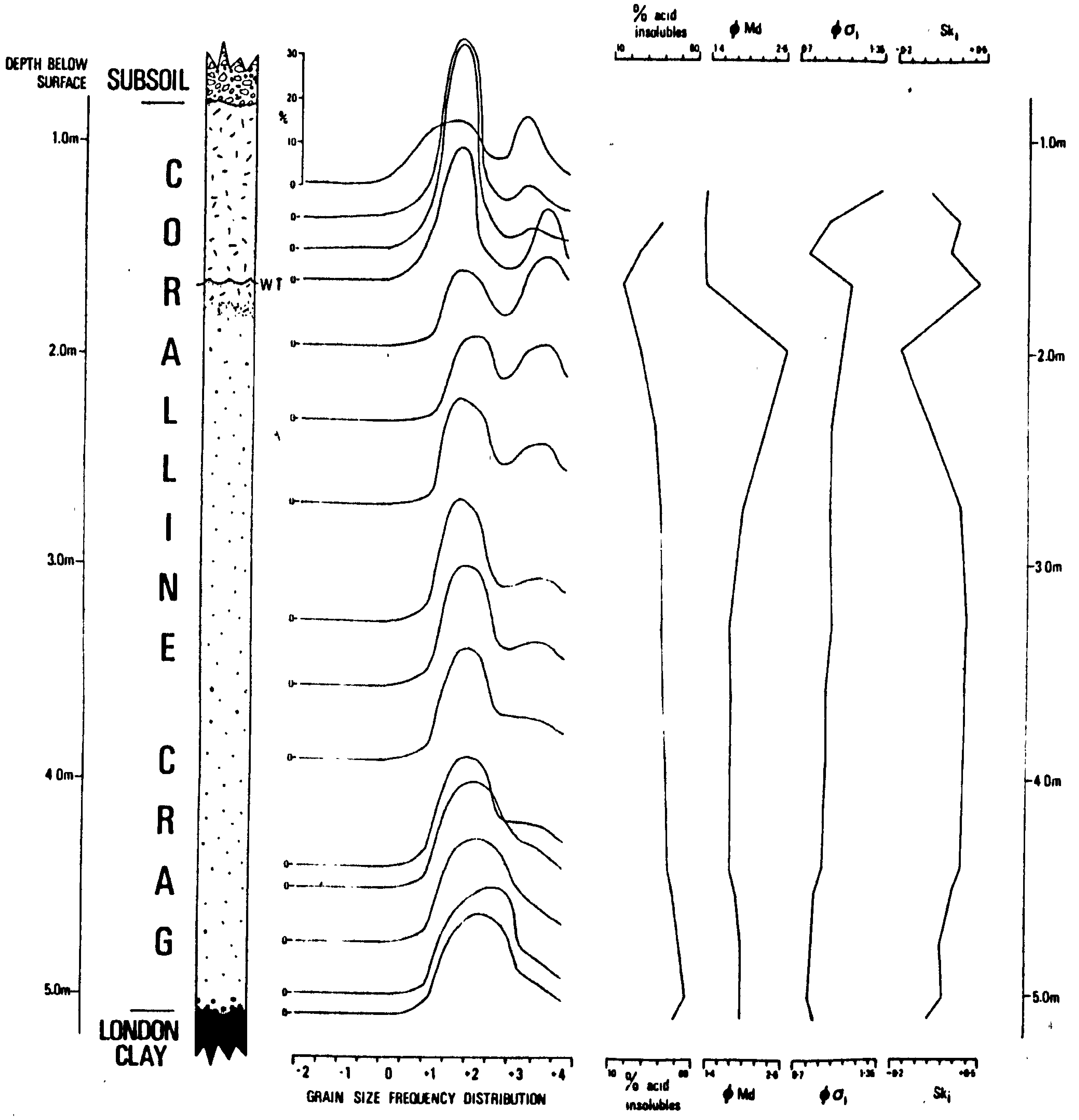


Figure 16 Diagram showing vertical changes in granulometric parameters in the borehole through the Coralline Crag at Tattingstone Hall Farm.

significant differences between adjacent samples could have arisen naturally. It is believed that the samples from 0.82 m - 1.65 m have been disturbed prior to drilling.

Perhaps significantly the lower limit of this disturbed zone is roughly equivalent to the level of the water table. The borehole site was on the floor of an old pit which was originally worked for Crag. Many geological excavations have also been made on this site, for example, Charlesworth (1835a) and Lyell (1839). It therefore seems quite probable that the initial stages of the borehole penetrated disturbed ground which resulted from previous excavations on the site.

In considering, therefore, only the results from samples from below the water table and thus below this zone of disturbance, the various grain-size parameters still show a variety of gradual trends. From a careful study of Table 12 and fig. 16 it can be seen that these lower samples (1.65 - 5.10 m) show the following trends.

i) $\underline{\phi Md\ \&\ \phi Mz}$

The median and mean grain-size show a gradual coarsening upwards from a depth of 5.10 m to 2.70 m. Coarsening upwards sequences have been noted elsewhere in the Crag as at Rockhall Wood (locality 4) and Gedgrave Cliff (locality 7). Between 2.70 m and 1.65 m there is a slight trend towards an upwards fining.

ii) $\underline{\phi\sigma_i}$

While all the samples are shown to be moderately well sorted ($0.5 < \sigma_i < 1.0$, Folk and Ward, 1957) there is a gradual trend upwards towards poorer sorting.

iii) Sk_i

Skewness increases from positive to very positive between 5.10 m and 2.70 m depth. Above this the trend is reversed with skewness becoming negative.

iv) % acid insolubles

The % of acid insoluble material in the sediment steadily decreases upwards from a value of 55.3% to 25.9%.

v) % sediment $< ^{+}4\phi$ (silt/clay)

The proportion of silt and clay size material is roughly similar in the lower part of the Crag. There is a slight but conspicuous increase in samples between 1.65 m and 2.70 m depth. It is possible that this parameter could be significantly affected by the sampling technique as samples from below the water table may have lost some fine sediment when the bailer was raised.

The individual grain-size distributions for each sample were plotted against a vertical log for the borehole (Fig 16). The grain-size distributions for the lowermost Crag(2.70 m - 5.10 m)are unimodal, while those from 1.65 - 2.70 m can be seen to be bimodal. This change from unimodal to bimodal distributions explains the changes in ϕMd, ϕMz, $\phi \sigma_i$ and Sk_i. The appearance of a second finer grain-size mode will result in the apparent reduction in mean (& median) grain-size, a decrease in sorting and the trend towards negative skewness observed in those samples from 1.65 - 2.70 m.

Three explanations can be advanced to explain the bimodal distributions at higher levels in the borehole.

a) A downward movement of fine sediment imprinting a second finer mode on a unimodal distribution.

b) Solution of coarse glauconite grains yielding fine grained iron oxides.

c) Primary sedimentary variations of sediment type.

The first two mechanisms would be expected to be widespread at other Coralline Crag localities but Tattingstone is the only site found to show distinct bimodal grain-size distributions. The observed variations can be best explained as follows:

Visher (1969) has shown that discrete populations within a sediment grain-size distribution can be attributed to suspension, saltation and traction transport. Additionally, of course, these populations will be affected by current velocities. Thus,when the current velocity increases,so larger grains can be included into the sediment load. If the two modes in the Crag sediments represented say, traction and saltation load, at a given current velocity, then bimodality might be expected at other Coralline Crag localities. It therefore seems most likely that the two modes represent transport by two discrete current regimes such as during flood and ebb cycles, the more powerful currents transporting dominantly coarser grains. Alternatively winnowing may be an important factor. Such winnowing could result from wave action in the littoral zone. The bimodality may thus result from a more littoral aspect of the facies at Tattingstone when compared with other Coralline Crag localities.

Sediment samples from other Coralline Crag exposures are found, in general, to contain smaller proportions of acid insoluble residue. The maximum percentage for acid insolubles at Tattingstone is 55.3%. The greatest value found at any other locality is 39.8% at Ramsholt which is also the closest Coralline Crag outcrop to Tattingstone. In general the proportion decreases in a north-easterly direction (see Chapter 6). The median grain-size is smaller at Tattingstone than at the other outcrops. Values of $\phi\sigma_1$, are greater, indicating poorer sorting at Tattingstone. These factors support the theory that the Tattingstone outcrop represents a nearshore facies within the Coralline Crag transgression. As the thickness of deposited sediment became greater so the proportion of insolubles became smaller as the terrigenous sediment source became blanketed by the bioclastic material of the Coralline Crag.

The grain-size distributions at Tattingstone show unimodal distributions passing upward into bimodal distributions. These bimodal distributions may indicate very shallow water with widely varying conditions, as for instance between flood and ebb tides, resulting in two distinct grain-size modes. From the fact that these bimodal distributions occur only at the top of the sequence it may be inferred that the Tattingstone sediments represent a regressive sequence. Other Coralline Crag exposures only show transgressive sequences.

7.4 Faunal analysis

The fauna of the Tattingstone outlier seems quite distinct from the rest of the Coralline Crag (see Chapter 9). This difference seems to have been noticed by Lyell (1839) who wrote; "Here the number of corals [= bryozoans] is so small, and the shells for the most part are so comminuted, that the distinctness of the inferior mass from the red Crag is far less striking than on the north of the river Deben". Boswell (1927) added: "The Coralline Crag is not seen here in its typical aspect, for it is much comminuted, and unbroken fossils are by no means common".

As with other localities it is important to distinguish between the _in situ_ fauna and the transported skeletal remains which make up the bulk of the sediment. In the case of Tattingstone the most striking element of the _in situ_ fauna are the small, occasionally articulated bivalves. This element of the fauna was noted by Charlesworth (1835a) who spoke of the Coralline Crag at Tattingstone as "containing several shells which were then new to me. Many of these had the corresponding valves in contact...." The fact that the valves are articulated are evidence not only of their _in situ_ nature but also of the lack of major sediment reworking. Nearly all the bivalves, whether articulated or not, are small. _Limopsis pygmaea_, _Digitaria digitaria_, _Pteromeris corbis_ and _Diplodonta rotundata_, all found at Tattingstone, are typically less than 1 cm in length. Very few large bivalves are found and those that are appear abraded and were probably derived from elsewhere.

Foraminifera are fairly abundant, particularly notable are the large tests of various polymorphinids. Fish otoliths are also fairly common. The plates of barnacles are very common, and are noticeably more abundant at Tattingstone than any other locality. The bryozoan remains were studied using the techniques described in Chapter 10. Although the results are discussed in that chapter, it is useful to consider here the specific interpretations which can be made from the bryozoan fauna. The skeletal remains of bryozoans only make up between 1.6 and 1.8% of the total sediment (see Table17). This is a smaller proportion than that found at most other localities.

The dominant bryozoan growth-form found in the Tattingstone sediments was 'eschariform' which comprised roughly 91% of all bryozoan fragments by weight. Cellariform,vinculariiform and lunulitiform growth-forms each comprised roughly 3% of the total. Reteporiform, celleporiform and membraniporiform Bryozoa, common elsewhere in the Coralline Crag, were not found in the Tattingstone sediment. The diversity of the bryozoan fauna is thus very low. The bryozoan fragments were, in general, very abraded.

It is considered, therefore, that the bryozoan assemblage at Tattingstone results from the effects of transportation and does not represent a life assemblage. Fragments of 'eschariform' bryozoans are robust and easily recognisable even when badly abraded. Other growth-forms are more fragile and more easily rendered unrecognisable by transportation and reworking. Thus, there was probably no appreciable production of large calcified bryozoan colonies in the Tattingstone are.

7.5 Basal Phosphorite Deposit

In the sample of sediment from just above the London Clay surface several small phosphorite pebbles were found. The largest of these pebbles had a long axis dimension of 47 mm. This is smaller than the majority of phosphorite pebbles at

Ramsholt where this horizon is also exposed but this may result from the small sample size represented by a 6" diameter borehole.

7.6 The London Clay Surface

The elevation of the London Clay surface in the borehole was 17.027 m OD. This is roughly equivalent to the interpolated height taken from data from Hollyer (1974, fig. 2) of 60 feet (= 18.29 m). There is therefore no evidence of any appreciable local depression in the London Clay surface at this point. The junction of the Coralline Crag with the overlying Red Crag was seen in the quarry face a few metres from the borehole at an elevation of 22.96 m OD. This gives a minimum thickness of 5.93 m for the Coralline Crag at this point.

7.7 Conclusions

1. The sediments of the Tattingstone outlier show no well preserved sedimentary structures. Structures may have been originally present but subsequently obliterated by post depositional organic or physical reworking.
2. The sediments show a number of vertical granulometric trends which are attributed to an upward gradation from unimodal to bimodal grain-size distributions. The bimodal distributions are believed to be due to variations in the depositional regime and not to post-depositional processes.
3. The proportion of terrigenous (acid insoluble) sediment decreases upwards. This is believed to result from the blanketing of the terrigenous source by an increasing depth of Coralline Crag bioclastic sediment.
4. The fauna of the Tattingstone outlier is of low diversity

and mostly abraded. The bryozoan fauna is also of low diversity and is dominated by robust and easily transported fragments of eschariform colonies. In situ fauna includes articulated specimens of small bivalve species. Barnacle plates are a dominant element of the skeletal debris.

5. The basal phosphorite deposit is present beneath the Coralline Crag at Tattingstone. Occasional phosphorite pebbles are also found at the base of the Red Crag where it overlies the Coralline Crag.

6. The Coralline Crag of Tattingstone probably represents a littoral or sub-littoral facies developed at the edge of the basin during the maximum extent of the transgression.

Chapter 8 Coralline Crag diagenesis

8.1 Introduction

8.2 Dissolution of aragonite

8.3 Iron staining

8.4 Cementation

- i) Unlithified skeletal calcarenites
- ii) Irregular lenses of lithified Crag
- iii) Loosely cemented, leached calcarenites

8.5 Diagenesis at Gedgrave Cliff (locality 7)

8.6 Diagenesis at Rockhall Wood (locality 4 and 6)

8.7 Silt/Clay drapes Aldeburgh Hall (locality 32)

8.8 Cementation related to original sediment petrography

8.9 Solution pipes

8.10 Solution fissures

8.11 Diagenetic sequence

8.12 Summary

Chapter 8 Coralline Crag diagenesis

8.1 Introduction

A conspicuous feature of many Coralline Crag exposures is the absence of aragonitic material due to post-depositional selective dissolution. The Crag at these localities has been cemented to form a porous ferruginous bioclastic limestone which, in some exposures, can be seen to overlie unconsolidated shelly sands in which aragonitic material is still present. This feature led Wood and Harmer (1872) (see figure 6) to divide the Coralline Crag into two portions. The lower portion consisted of a bed of calcareous sands while the upper portion consisted of a bed of lithified bioclastic material capped by a bed of eroded material from this upper portion. They termed the lithified upper portion the 'rock bed'. The term 'rock-bed' was later used by Harmer (1898) who subsequently qualified the term as 'ferruginous rock-bed' (Harmer 1910). In later years this division became generally known as the 'Bryozoan rock-bed' (Boswell and Double 1922., Boswell, 1928., Chatwin, 1937) and this term remaining in common usage up until the present time in one form or other ('Bryozoa rock' of Baden Powell and West 1960., 'Bryozoan Rock-bed' of Markham (1973) and Rose and Markham (1977)). It is felt in the present study, however, that the usage of this term, which is of no stratigraphical importance, should be discontinued for the following reasons.

a) Bryozoan skeletal fragments are found throughout the Coralline Crag and are no more characteristic of the leached sediments than of the unleached sediments.

Indeed in some localities, dependant on the facies, they are more common in sediments which, because of their local position, have remained unleached.

b) Leached sediments at some localities are only very poorly cemented and can be broken easily in the hands. This contrasts with the hard lithified irregular lenses which occur within the lower unleached sediments. Thus the term 'rock' is also misleading.

c) Leaching has affected the upper parts of the Coralline Crag outcrop to a varying extent. The extent has been dependant on original lithology and local variations of the height of the water table. The lower limit of the leached zone does not therefore follow, to any great extent, primary planes of deposition. Even the term'bed' is therefore, a misnomer.

In this chapter an attempt will be made to show how primary variations in the petrography of the Coralline Crag sediments have played an important part in limiting the extent of the zone of selective dissolution.

8.2 Dissolution of aragonite

The most obvious feature of the lithified upper portion of the Coralline Crag is the absence of aragonitic skeletal material. Aragonite has been removed by selective dissolution leaving only hollow moulds of aragonitic skeletal material such as is found in corals and the majority of molluscs. Where aragonitic material is absent the sediment is generally lithified, where it is present the sediment is generally unlithified. The dissolution of aragonite is therefore clearly connected with the cementation of the sediment.

Sanders and Friedman (1967) stated that in deep borings on Eniwetok and Bikini atolls at levels where the aragonite had been dissolved away, the calcium carbonate sediment had always been converted to calcite-cemented limestone, the calcite cement having been derived from the solution of the aragonite. Such levels coincided with indications of subaerial exposure and contact with meteoric ground water. Chave _et al_ (1962) demonstrated solubility relationships between aragonite, high magnesian calcite, and low magnesian calcite. They determined the following order of decreasing solubility.

high-Mg calcite $>$ aragonite $>$ low-Mg calcite

Aragonite thus has a lower solubility than high-Mg calcite but a higher solubility than low-Mg calcite. High magnesian calcite grains such as echinoderm test fragments are commonly found in the leached sediments of the Coralline Crag. These presumably have undergone an early diagenetic alteration to low-Mg calcite which may predate the dissolution of the aragonite.

8.3 Iron staining

The Coralline Crag sediment varies in colour at field exposures between a pale yellow and deep ochreous orange (see frontispiece). The colouration is due to the presence of iron oxides within the sediment and to staining of skeletal material by iron minerals.

In the Red Crag the deeper red-brown staining is similarly due to the presence of iron oxides. The colour results from the oxidation of ferric iron compounds as the Red Crag may be paler or be grey in colour when recovered from depth in well borings (Boswell, 1928;p28). Unfortunately little is known of the Coralline Crag at depth. Coloration of samples from the borehole at Tattingstone did not vary significantly throughout the depth but this may indeed be due to the shallowness of the borehole, Harmer (1898; p323) recorded "blue Crag" in the lowermost 12 inches (0.30m) of the Coralline Crag in some borings at Gedgrave and Sudbourne. The Crag was found to contain 3.80% of alumina and iron oxide, "the iron being mainly in the oxidized or ferrous state".

Ovey and Pitcher (1947) believed that the iron oxides in the Red Crag were derived from the decomposition of glauconite grains. They gave as evidence of this process the presence of innumerable glauconite casts of foraminifera. Presence of these casts would, however, seem to imply that decomposition had <u>not</u> occurred. They wrote: "That the iron is secondary is improbable, since the Coralline Crag ....is, in the main, untainted by the deposition of iron oxides, except locally where Red Crag had overlain it and seepage with consequent staining had taken place". Certainly, where Red Crag is seen to overlie Coralline Crag as at Aldeburgh Brick Works (locality 33), heavy staining of the upper few centimetres of Coralline Crag is evident. Additionally it is clear that the Coralline Crag is certainly not "untainted by the deposition of iron oxides". Harmer (1898) was the first to propose that the staining of the Coralline Crag was due to the breakdown of glauconite. He even used the name "Ferruginous Crag" (1898) and later "ferruginous rock-bed" (1910) to describe the leached Coralline Crag sediments. Harmer (1910;p93) believed that the lithification of the "ferruginous rock-bed" was ".... due to the infiltration of water charged with iron-oxide, arising from the decomposition of the glauconite of the unaltered Crag, the aragonite shells having been removed at the same time....".

In considering the origin of the iron staining in the Coralline Crag the following points would seem to be important.

1) Iron staining in the Red Crag is very heavy when compared to that seen in the Coralline Crag. In some places in the Red Crag iron pans can be seen.
2) Staining in the Coralline Crag is heaviest in the porous leached sediment and especially where it immediately underlies the Red Crag.
3) Glauconite is fairly evenly distributed in both leached and unleached Coralline Crag sediments although larger quantities of glauconite were seen in the sediment from Ramsholt Cliff (locality 3) near the base of the Coralline Crag.
4) Nearly all the glauconite seen in studied thin sections of leached and unleached sediment had a fresh appearance. Glauconite grains found in zooecial chambers of Meandropora in leached sediment from Aldeburgh Hall (locality 32) also appeared fresh and uncorroded. Decomposed grains were most commonly seen in thin sections of sediment from Ramsholt Cliff (locality 3).

Glauconite would be expected to be unstable under the acid conditions which resulted in the selective dissolution of aragonitic skeletal material.

Two mechanisms may be important in the production of iron oxides in the Coralline Crag.

1) Decomposition of iron-rich glauconite as proposed by Harmer (1898) for the Coralline Crag and Whitaker (1877) and Wood & Harmer(1877) for the Red Crag.
2) Oxidation of precipitated hydrous ferric oxide $Fe(OH)_3$. Krauskopf (1967) believed that most of the iron brought into the sea is first precipitated as $Fe(OH)_3$.

Conclusion Red Crag

It seems unlikely that the large quantities of iron oxides found in the Red Crag were derived solely from the decomposition of glauconite. Iron compounds may have been derived from bogs and marshes and brought into the Red Crag basin by sluggish rivers as suggested by Ovey and Pitcher (1947).

Coralline Crag Glauconite decomposition may have been important in production of iron oxides within the Coralline Crag, although the occurrence of glauconite grains of fresh appearance in heavily iron-stained sediment is unexplained. The staining is post-depositional and may be associated with the same subaerial diagenetic processes which resulted in the cementation of the Coralline Crag.

8.4 Cementation

Three types of cementation can be recognised in the Coralline Crag sediments.

i) Unlithified skeletal calcarenites

Unlithified shelly sediment is found at several localities towards the south-west of the Coralline Crag outcrop. The sediment contains a large proportion of aragonitic skeletal material including molluscan shells, corals and lunulitiform bryozoans. Thin sections of the unconsolidated Crag were made with difficulty from blocks of sediment, vacuum impregnated with araldite. Examination of thin sections shows that there is,in general,no cement present on the surfaces of carbonate grains. Intraparticle voids may be filled by equant crystals of drusy sparite. The sediment is characterised by a greater proportion of fine grained material ($< {}^{+}4\phi$) than at localities where there is extensive cementation.

Unlithified Coralline Crag is seen at Tattingstone (localities 1 and 2), Ramsholt Cliff (locality 3) Rockhall Wood (localities 4, 5 and 6) Gedgrave Cliff (locality 7), Gedgrave (locality 8) and Sudbourne Park (locality 16).

ii)Irregular lenses of lithified Crag

These irregular lenses are found within the unlithified sediments described above. The lithified patches range in size from a few to tens of centimetres across. In thin section a large proportion of the interparticle void space is seen to be occluded by drusy sparite (Plate 16, A, C). Drusy sparite is also found occluding intraparticle voids e.g. chambers of foraminiferids (Plate 16, B).

iii)Loosely cemented, leached calcarenites

Carbonate sediment cemented to varying degrees by the growth of sparite cement on the surfaces of carbonate grains. These sediments are equivalent to the "rock-bed" of Wood and Harmer (1872) and later authors. The cement generally takes the form of a palisade of fibrous sparite crystals orientated normal to the grain boundaries of molluscan shells and bryozoan skeletal fragments. In the case of echinoderm-derived grains a syntaxial calcite rim is found growing into available void space. (Plate 16, E,F). Growth of the syntaxial rim is truncated by contact with adjacent grains (Plate 16, E), evidence that primary porosity is required for the expansion of syntaxial rims. These sediments do not contain any aragonitic material. The majority of Coralline Crag exposures show sediments of this type. (Localities 9, 11-15, 17 - 38). At some localities sediment of this type is seen to overlie sediments of the type described in i) above (e.g Localities 4, 6, 7 and 36).

It seems clear that the dissolution of aragonitic shell material is an important aspect of the diagenesis of Coralline Crag sediments. However in the case of the irregular masses of cemented limestone there has been no visible loss of aragonite from the immediately adjacent sediment. The carbonate cement must therefore be allochthonous. The source of the carbonate was probably the overlying sediments within which aragonite dissolution has taken place. Cementation of these overlying sediments was brought about by redistribution of carbonate within the sediments. Thus,this cement is autochthonous.

To examine more closely the diagenetic sequence of events and any petrographical changes involved, two localities where lithified sediments containing no aragonite overlie unlithified sediments which have not suffered aragonite solution were studied in greater detail.

8.5 Diagenesis at Gedgrave Cliff (locality 7)

At Gedgrave Cliff, lithified cross-stratified sediments of the sandwave facies (facies B) in which aragonite material has been dissolved overlie unlithified sediments of facies A which contain abundant well preserved aragonitic fossils. A vertical sequence of samples was taken spanning the solution interface between these two sediment types. Each sample was analysed for carbonate content and insoluble content using the methods described in Chapter 6. The results are summarised in Table 13. From Table 13 it can be seen that the lower sediments have a smaller proportion of insoluble material with a slightly smaller mean grain-size. Such an increase in the proportion of insoluble material above the solution interface is expected if it is assumed that the sediment of the two divisions originally had the same proportions of carbonate and non-carbonate material.

It is important, however, to distinguish between diagenetic alterations and differences arising from purely sedimentary features. When using percentages relating to components which together comprise the total sediment, i.e. a sum of 100%, it should be remembered that an increase in the percentage of one component necessarily leads to the reduction in percentage contributed by one, or more, other components.

It is interesting therefore to note that while it can be seen from observation in the field that aragonitic mollusc shells have been dissolved from the upper sediments, Table 13 records virtually no difference in the content of coarse carbonate material. This fact was apparently first noted by Harmer (1898, p.322) who gave figures of 78.62, 70.9 and

Table 13 Diagenesis at Gedgrave Cliff (locality 7)

		Sediment below solution interface	Sediment above solution interface
% acid insolubles (1)		23.5	36.9
acid insolubles ØMz		1.98	1.83
% sediment <+4Ø (2)		21.9	7.6
% carbonate (3)		71.6	61.4
<+4Ø	% carbonate (4)	14.8	5.8
	% insolubles (5)	7.1	1.8
>+4Ø	% carbonate (6)	56.8	55.6
	% insolubles (7)	21.3	36.8

(1) Determined by solution in HCl.

(2) Determined by wet sieving.

(3) = (4) + (6)

(4) Determined by analysis in Schrötter apparatus.

(5) = (2) - (4)

(6) Determined by solution in HCl less value of (2)

(7) Determined by solution in HCl.

74.7% for the carbonate content of unleached sediment and 78.95 & 79.2% as the carbonate content of leached sediments. Primary differences in the carbonate/non carbonate ratio may be affecting the result. Another explanation for this result is that the solution of aragonite shells is providing autochthonous carbonate cement for calcitic bioclastic debris. Thus the cement is increasing the volume of large calcitic grains compensating for the loss of aragonitic grains.

The rise in the percentage of coarse insoluble material is due to the reduction of fine-grained material and an overall reduction of the carbonate content of 10%. It can also be seen that the proportion of carbonate:insolubles in the finer sized sediment ($< {}^{+}4\phi$) shows no great difference above and below the solution interface. This implies that:

a) The reduction of fine-grained sediment above the solution interface is not due to any diagenetic alteration. If fine-grained carbonate was being leached the proportion of fine-grained insolubles would correspondingly rise. However there is an indication that the reverse is true.

b) The greater proportion of fine-grained sediment below the interface is due to differences in the original sediment. It is possible that the increase in fine-grained sediment below the solution interface is due to physical downward movement of sediment. This seems to be extremely unlikely as fine-grained sediment drapes are common elsewhere interbedded with coarse, cemented bioclastic material with a high porosity. These drapes show no evidence of physical movement of fine-grained sediment into available void space.

Conclusion

The differences observed in sediment composition above and below the solution interface at Gedgrave Cliff are largely due to an original dissimilarity of sedimentary petrography at this locality. It appears that this difference of sediment type has been instrumental in affecting the type of diagenetic alterations which have occurred. The upper sediments at Gedgrave Cliff show large-scale cross-stratification. These sediments originally had a lower content of fine-grained sediment than the bioturbated sediments they overlie. These sediments also, therefore, had a higher original porosity allowing a greater movement of meteoric waters to dissolve metastable aragonitic material which was re-precipitated as autochthonous calcite cement. Downward percolation was inhibited by the much lower porosity of the underlying siltier sediments which therefore did not suffer aragonite dissolution and cementation.

Fine-grained sediment was thus probably originally absent from the overlying cross-bedded sediments of the sandwave facies and not removed by diagenetic solution. There may also have been original differences in the carbonate content of the two sediment types resulting in apparent variations due to diagenesis.

8.6 Diagenesis at Rockhall Wood (localities 4 and 6)

At Rockhall Wood fine, silty, bioclastic sediments of facies A2 are overlain with slight unconformity by coarser bioclastic sediment. The interface between unlithified sediments and the overlying lithified sediments, which are barren of aragonitic material, lies within the generally coarser A3 facies seen in the large pit at Rockhall Wood (locality 4). Samples were taken from the finer-grained sediment (COR 027), the coarser but unlithified sediment (COR 021), and the uppermost lithified division (COR 134). The samples were analysed for carbonate content and insoluble content using methods described in Chapter 6. The results are summarised in Table 14. An important point to note is the rapid increase of mean grain-size towards the upper part of the section. This appears to correspond to the transition from bioturbated sediment with no well-preserved sedimentary structures in the lower part of the face to the trough cross-stratified sediments in the upper part of the face (Plate 12 C). This increase in mean grain-size can thus be seen to be correlated to an increase in current energy as was the case at Gedgrave Cliff. Also following this trend is the marked decrease in the proportion of fine-grained material in the sediment. Thus it would seem that here also there is a primary lithological change within the sequence which probably directly affects the mode and extent of diagenetic alteration. The upper higher energy deposits had smaller amounts of fine-grained material due to current winnowing. This meant that porosity was greater allowing more extensive percolation of meteoric groundwaters which were thus able to dissolve metastable aragonite. This was redistributed as autochthonous cement. Some carbonate probably penetrated into the underlying silty sands where it precipitated as void filling sparite in irregular masses, thus acting as an allochthonous cement.

8.7 Silt/Clay drapes

Aldeburgh Hall (locality 32)

A sample was taken of one of the extensive silt/clay drapes

Table 14 Diagenesis at Rockhall Wood (locality 4,6)

		Sediment below solution interface		Sediment above solution interface
		COR 027	COR 021	COR 134
$<{}^{+}4$ø	% carbonate (1) % insolubles (1)	21.9	5.6	3.7
$>{}^{+}4$ø	% carbonate (2)	37.6	63.1	70.5
	% insolubles (3)	40.5	31.3	25.8
acid insolubles øMz		3.15	2.01	1.70

(1) Total determined by sieving.

(2) Determined by solution in HCl less (1).

(3) Determined by solution in HCl.

from this locality and analysed for carbonate content using methods from Chapter 6 . The results are summarised in Table 15.

Table 15 Composition of silt/clay drape at Aldeburgh Hall

% Total carbonate (1)	62.5
% insoluble $< +4\phi$ (2)	34.6
% insoluble $> +4\phi$ (3)	2.9

(1) determined by analysis in Schrötter apparatus
(2) = 100%- [(1)+(3)]
(3) determined by solution in HCl

This drape was interbedded with leached Coralline Crag sediments. 62.5% of the material in the drape is carbonate (presumably calcite) and nearly all of this is finer than $+4\phi$. Leaching, therefore has not significantly affected the fine-grained material. There is also no evidence of physical movement of the fine sediment into underlying skeletal sands. It is therefore implied that, unless the fine-grained material was dominantly aragonite which seems unlikely then large proportions would remain in the surrounding sediment if it was originally present at all. However, the surrounding sediment has a very low content of fine sediment (c.5%, see table 11). It is suggested that the silt drapes at Aldeburgh Hall and other localities in this area represent sporadic influxes of fine-grained sediment which was otherwise absent from the clean bioclastic sands.

8.8 Cementation related to original sediment petrography

It seems clear that the type of diagenetic change was, in part at least, due to the original petrography of the sediment which had a direct effect on sediment porosity.

An estimate of the porosity (% voids in thin section point counts), the proportion of sediment finer than $^{+}4\emptyset$ and the % carbonate content were obtained for samples throughout the Coralline Crag outcrop. The results were plotted on a triangular plot (figure 17). From this plot it can be seen that the majority of samples analysed form a group (delineated by a dashed line) with a silt/clay content less than 10%, a carbonate content between 50 and 90% and voids forming between 10 and 40% of thin section areal point counts. Five samples fall outside this group. All of these are samples of unleached sediment from the south western part of the Coralline Crag outcrop. However, the one other unleached sample (locality 10) has plotted within the same group as the leached samples. Samples from localities 3, 6, 5 and 16 have remained distinct from the main group by virture of their high content of silt and clay-sized material. The sample from locality 1 on the other hand has remained distinct by virture of its negligible content of fine sediment and its very low porosity.

Conclusion

The main group in figure 17 represent sediment samples where there is a low content of fine-grained sediment and where void space is appreciable (type iii) of section 8.4). Samples from localities 3,5,6 and 16 contain similar amounts of carbonate and

Figure 17 Triangular plot of Coralline Crag sediment composition. Numeric labels refer to locality. (See figures 2 and 3). Samples affected by aragonitic dissolution are enclosed by pecked line.

void space to the main group but have higher contents of fine-grained sediment. These samples correspond with cementation type i) of section 8.4. The sample from locality 1 has low porosity and negligible content of fine-grained sediment. The pore space had been occluded by drusy sparite in this well cemented sample which corresponds with cementation type ii) of section 8.4. This mode of cementation made analysis of the proportion of fine-grained sediment by sieving impossible. Thus it can be seen that both void space and carbonate content appear to be unaffected by subaerial autochthonous cementation if it is conceded that the various silt/clay contents of the sediment samples is primary and related to the environment of deposition. Removal of aragonitic material from the sediment is concomitant with precipitation of sparite cement and the primary porosity and carbonate content are thus maintained. Where cementation is by allochthonous carbonate (i.e. type ii of section 8.4) void space is occluded and the porosity drastically reduced. Apparent differences of carbonate content between localities can often be attributed to variations in the content of terrigenous material which directly affects the carbonate percentage.

8.9 Solution pipes

At many localities large pipes extend down into the Coralline Crag from the upper surface and were first described by Wood (1854). Locally the Coralline Crag may contain as much as 90% carbonate but the sediment within the pipes has no discernible carbonate content. These pipes have clearly originated by the dissolution of the Crag carbonate grains and cement. Once initiated the pipes probably controlled drainage of water in their immediate vicinity and slowly enlarged as described by West (1973) for pipes in raised beach deposits of Cornwall. The pipes of the Coralline Crag, however, do not appear to have any associated cement formation in sediments in the vicinity of the pipe. In those localities where pipes are formed in sediment from which aragonite had been previously leached this may be due to the lack of metastable carbonate. However pipes are also found at Sudbourne Park (locality 16) where they penetrate sediments which have retained their aragonite content,again with no noticeable cementation around the walls of the pipe. Unlike the pipes described by West then, their formation does not appear to have affected, or indeed to have been affected by, cementation of the host sediments. It is believed that the pipes, therefore, postdate the main phase of Coralline Crag cementation as first proposed by Harmer (1898, p.323).

Further evidence of the later formation of these pipes is their absence in the Coralline Crag where it is overlain by Red Crag as at Tattingstone Hall Farm (locality 2) and Aldeburgh Brick Works (locality 33).. This might imply that pipe formation postdated deposition of the Red Crag whose upper surface also is commonly penetrated by these solutional features. Erosion during the Red Crag transgression might be expected to have removed the uppermost Coralline Crag and thus destroy any pipes or at least significantly modify their form and infill them with Red Crag sediment if they had existed at that time. This does not appear to have happened which lends further strength to the argument that the

Coralline Crag pipes were formed after deposition of the overlying Red Crag. In common with the Coralline Crag, pipes in the Red Crag commonly form in sediments in which no selective dissolution of aragonite has taken place as at Vale Farm, Sutton.

It seems possible, then, that the solution pipes seen in the Coralline Crag formed during the same period as those of the Red Crag under subaerial conditions sometime during the Pleistocene. The only requirement for formation of the pipes was subaerial exposure of the upper surface of carbonate-rich sediment.

8.10 Solution fissures

Vertical solution fissures are seen at many localities where post-depositional processes have resulted in the dissolution of aragonite in the sediment. These are fissures in the loosely cemented Crag which may be vertical and straight (Plate 15, A,B) or subvertical and sinuous (Plate 15, C). They may be from less than a centimetre to many centimetres wide and some can be followed for several metres in length. They do not appear to follow bedding even when they penetrate cross bedded sediments. Some may be following pre-existing vertical joint planes which may explain the occurrence of the very straight vertical fissures. The fissures are usually filled with powdery white carbonate which X-ray diffraction analysis shows to consist only of low-Mg calcite. This carbonate may also be precipitated along bedding planes where no fissure is present. The carbonate has presumably been derived and reprecipitated from leaching of the adjacent sediments. The fissures in the Coralline Crag were found in leached sediments but in the Red Crag, as at Bawdsey, these fissures are generally found to penetrate sediments containing aragonitic material.

It may be possible to explain this apparent difference as follows. For precipitation of the carbonate a fissure or some form of vacant pore space is required. Unleached sediments of Coralline Crag are generally silty with very little available pore space. The unleached sediments being, in general, unlithified will also not readily form joints along which precipitation could take place. Another factor which might be of importance is the level of the water table. Precipitation probably only occurred under subaerial meteoric conditions above the level of the water table. It is believed that lithification and solution of the Coralline Crag is related to levels of the water table during subaerial exposure after a Pliocene regression. Thus in the case of the Coralline Crag large amounts of available pore space, joints, and quantities of mobile carbonate were associated with sediments above the water table and it is here that precipitation was able to occur. Below the water table precipitation occurred in the form of allochthonous sparite cement within intra-and inter-particle voids. It is not known in most cases why the fissures follow particular lines through the sediment except in cases where vertical joint planes may be involved. At Gedgrave Cliff (locality 7) many small 'stalactites' of reprecipitated carbonate resembling vertical burrows can be seen in cross-bedded leached sediments. They evidently formed along predetermined drainage paths.

The Red Crag has a higher content of coarse terrigenous material than the Coralline Crag. Available pore space for precipitation was greater. The Red Crag also does not appear to have been affected by selective dissolution of aragonite. Instead, it appears that where solution has occurred all the carbonate material has been dissolved. This carbonate was then precipitated in fissures in the underlying unleached sediment, again probably under subaerial meteoric conditions. The differences between the diagenesis of the two Crag deposits may in part be due to the difference in sedimentary petrography and partly to the difference in the time of lithification, the Coralline Crag being lithified before deposition of the Red Crag.

8.11 Diagenetic sequence

Land (1966) in a study of subaerial diagenesis of Bermudan limestones recognised 5 stages of petrographic changes with time which are summarised in Bathurst (1971) (See fig 18).

Stage I The initial sediment

Unconsolidated bioclastic sand containing an assortment of carbonate skeletal material.

This stage corresponds with Coralline Crag sediments of type i (section 8.4).

Stage II The first cement

Appearance of low-magnesian calcite on the surfaces of grains near their points of contact. The pores of echinodermal structures are filled with optically continuous calcite cement and these grains may be encrusted with a thin layer of optically continuous rim cement. Intragranular pores are partly or entirely filled with calcite cement. Primary grains

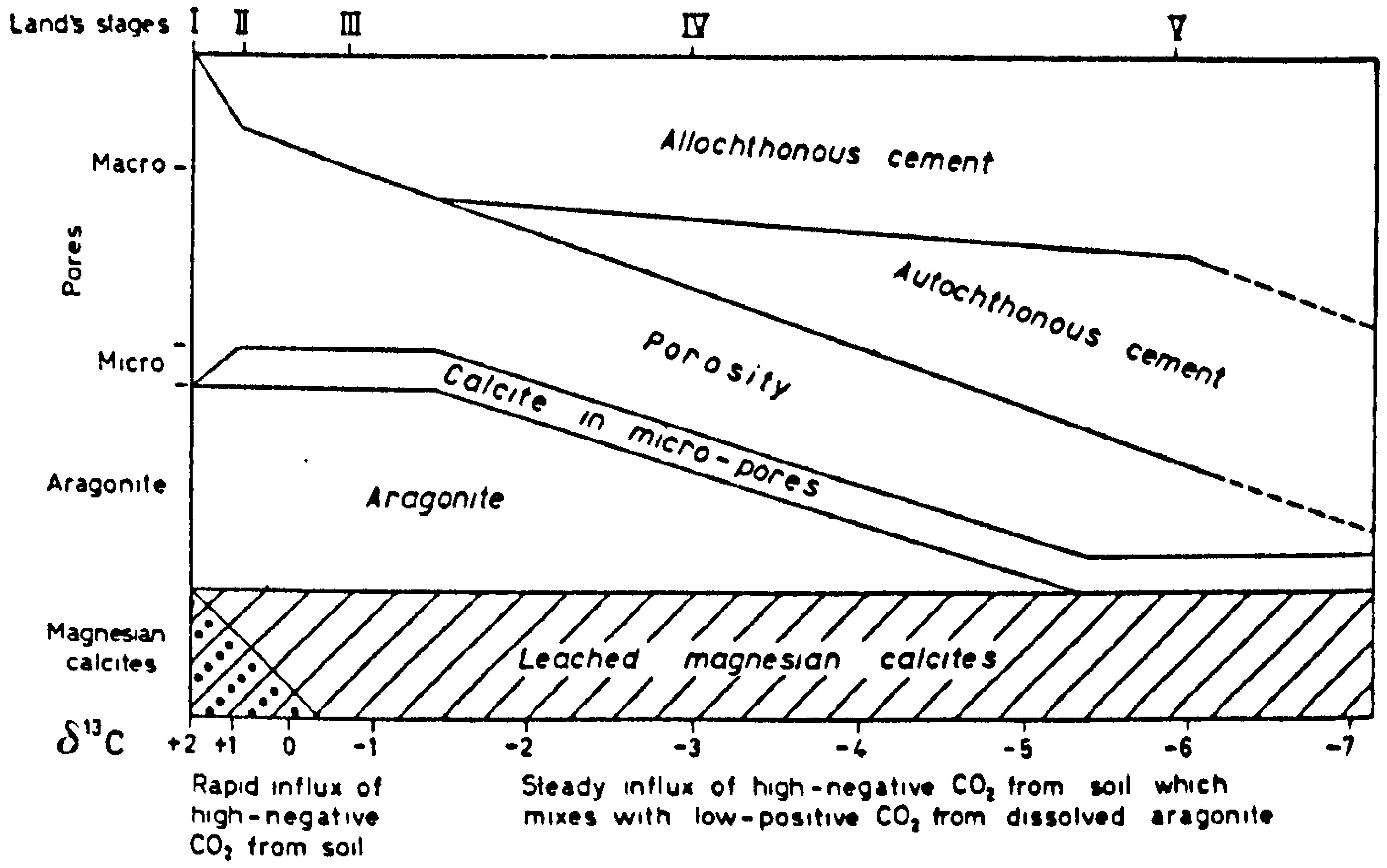


Figure 18 Idealised scheme of diagenetic change in Bermudan carbonates (after Land, 1966 and Bathurst, 1971)

of aragonite or high-magnesian calcite are unchanged and the rock is friable.

Stage III The loss of Mg^{2+}

Loss of Mg^{2+} from high-magnesian calcite grains. In stages II and III there is no visible sign of dissolution of $CaCO_3$ and thus the cement must be derived from outside the rock (allochthonous).

Stages II and III correspond with Coralline Crag sediments of type ii(section 8.4) although no determination of the Mg content of the Coralline Crag carbonate grains has been attempted.

Stage IV Dissolution-precipitation

Dissolution of aragonite. The porosity of the sediment remains reasonably constant as dissolution is balanced by precipitation of low-magnesian calcite cement. The calcite cement is thus autochthonous in origin.

Stage V Culmination in low magnesian calcite

This stage marks a limestone consisting wholly of calcite and the remaining porosity.

Stages IV and V correspond to Coralline Crag sediments of type iii(Section 8.4) with sparite rim cements on calcite grains and aragonite grains absent. There are no envelopes of calcite from growth on aragonite grains but where the original sediment contained quantities of fine-grained carbonate and clay minerals, hollow moulds of aragonitic shells remain.

8.12 Summary

Lithification of the Coralline Crag evidently occurred under subaerial conditions. It has long been known that blocks and boulders of lithified Coralline Crag are found in parts of the lowermost Red Crag (Prestwich, 1871.; p.341 at Rockhall Wood: Kendall, 1883.; p.499 at Boyton: and Harmer 1898.; p.323) but it was Lyell (1839;p.314) who, in noting that pholad borings at Sutton (= Rockhall Wood) penetrating 6 - 8 feet (1.8-2.4 m) into the Coralline Crag were filled with Red Crag sediment, first realised that cementation of the Coralline Crag must have occurred before deposition of the Red Crag.

During a period of regression after deposition of the Coralline Crag the upper part at least was subaerially exposed to the action of acidic meteoric waters. This resulted in selective dissolution of aragonitic skeletal material and a redistribution of the carbonate largely as sparite rim cements on calcitic grains. Some carbonate percolated downwards into the sediments below the water table where excess carbonate was precipitated as intra- and inter-particle drusy sparite cement in localised patches, the bulk of the sediment remaining uncemented. During this period mobile carbonate may also have been precipitated in the upper leached zone along fissures and drainage paths. Breakdown of iron minerals (possibly including glauconite) may have led to iron staining of the Coralline Crag sediments particularly in those zones exposed to meteoric groundwaters. After a renewed transgression and deposition of the Red Crag a regression meant further exposure to subaerial conditions which resulted in the formation of solution pipes in the exposed surfaces of the Red Crag and Coralline Crag.

Chapter 9 Coralline Crag Flora and Fauna

Chapter 9 Coralline Crag Flora and Fauna

9.1 Introduction

The total fauna of the Coralline Crag was put at 675 species by Bell and Bell (1871) and later at 707 species (Bell and Bell, 1872). The number of species largely reflects the amount of study that the Coralline Crag attracted during the 19th century.

Much of the evidence of the Coralline Crag biota is derived from study of carbonate skeletal material which comprises the majority of the Coralline Crag sediments. The study of variations in local abundance of the different skeletal grains is made difficult by variations in preservation which are largely dependant on the original grain mineralogy. As a result of subaerial selective dissolution aragonitic skeletal material is only preserved at a few localities. However, moulds of aragonitic grains may be preserved at other localities where the original sediment was relatively fine-grained. A limited amount of evidence of organisms without preservable hard parts can be derived from the presence of various trace fossils.

This chapter aims to summarise qualitative and quantitive observations of each major biological group combined with summaries of published observations and reference works. These individual observations are then placed in the context of the sedimentary facies already defined (see Chapter 5). The biofacies can be seen to strongly reflect the observed sedimentary facies. Quantitative observations are only quoted where the skeletal grains concerned were primarily of calcite and were therefore unaffected by selective dissolution. The results were obtained by picking and counting or weighing all identifiable carbonate grains from large (50 - 300 g) samples of the>1 mm sieved fraction. Thus the quantitative observations included in this chapter are weighted towards the macrofauna rather than the microfauna.

9.2 Plants

Evidence of the existence of plants in the Coralline Crag Sea is very scanty. One possible specimen of calcareous alga was found but was too poorly preserved for a certain identification to be made. The lack of evidence of calcareous algae from the Coralline Crag is, in itself, an interesting observation. The depth of deposition of the Coralline Crag was almost certainly less than the maximum depth of 75 m at which calcareous algae can deposit calcium carbonate (Milliman, 1977). Although this depth limitation is widely disputed it seems that terrigenous input and its resultant effect on decreasing light penetration is a more important influence on calcareous algal growth. It may be that this factor and possible competition from the bryozoans for substrates were more important than depth alone for the apparent absence of calcareous algae in the Coralline Crag.

The presence of endolithic algae within the Coralline Crag sediments is evidenced by the occurrence of algal borings seen in many carbonate skeletal grains in thin section (Plate 17 B,C). Harmer (1898, p.322) noted the occurrence of coccoliths within the finer sediment and commented that they were "somewhat larger than those in the Upper Chalk". Apart from the rather equivocal records above,other evidence of the occurrence of plants is lacking. The presence of certain adherent benthonic Foraminifera which are normally associated with plants e.g. Ammonia (see Section 9.3) is not definite evidence of the presence of plants as these Foraminifera may also have adhered to pebbles or shell fragments.

9.3 Foraminifera

The presence of the tests of Foraminifera in the Coralline Crag sediments appears to have been first noted by Wood (in Charlesworth, 1835a). The Foraminifera were later described in detail by Jones and Parker (1864), Jones et al (1866) and Jones (1895-1897). Reid (1890) recorded a total of 84 species of Foraminifera as occurring in the Coralline Crag. Burrows (1895a, 1895b) gave lists of abundant Foraminifera found at various localities and related their distributions to the 'zones' of Prestwich (1871a) which he considered as valid stratigraphic divisions (Burrows, 1895b, p.511). Very little other work has been done on Coralline Crag Foraminifera with the exception of a paper by Carter (1951) which attempted to distinguish between in situ and transported foraminiferid assemblages at Rockhall Wood (= ? locality 6). Carter showed that transported Foraminifera could be recognised by the similarity between the size distribution of tests and the sediment grain-size distribution. Thus, the size distribution of in situ foraminiferid species was independant of the sediment grain-size distribution. In this way he came to the conclusion that Planorbulina mediterranensis and cf Cibicides lobatulus were indigenous to the Rockhall Wood locality whilst other species were probably mostly transported from other areas. Both these species are extant and are described by Murray (1979) as marine inner shelf species which typically cling to firm substrates. Samples from Sudbourne Park (locality 16) yielded many Foraminifera including Nonion, Elphidium, Peneroplis and Ammonia beccarii which are all typically associated with marine plants (J. Whittaker pers. comm. 1980). Textularia is also common and is typically a sediment dweller.

The foraminiferid content of the Coralline Crag was assessed during analysis of the skeletal carbonate grains by counting from samples from which sediment finer than 1 mm (0ø) had been removed and also by thin section point counting and calculation of the % of the grain count only. The latter technique should give an indication of the total foraminiferid content, the former method is biased towards larger species. Both methods will be affected by a "dilution effect" where aragonitic material is present i.e. when aragonite has been selectively removed there will be an apparent increase in the proportion contributed by any calcite grain type. From table 16 it can be seen that while the number of Foraminifera per 100 g sediment >1 mm shows a very marked increase in facies A1 and A2, the % observed in thin sections is relatively constant in all samples. This probably reflects a real increase in abundance of large foraminiferids in the south-western localities while the smaller foraminiferids behaved as sedimentary particles and are fairly evenly distributed

9.4 Sponges

The only evidence of sponges within the Coralline Crag is in

Facies	Locality	Sample	No/100 g Sediment>1 mm	% thin section point count (grains only)
A1	2	110*	103.6	--
	2	111*	102.2	--
A2	3	089*	176.2	2.7
	5	057*	72.8	4.9
	7	129*	6.2	4.7
	16	126*	20.3	0.0
B	9	072	0.0	5.5
	14	066	7.8	0.9
	20	079	17.4	1.1
	30	084	1.4	0.0
C	26	032	34.9	2.0
	29	116	34.1	--
	32	131	16.3	3.6
	36	049	14.3	2.3
	38	005	29.8	2.1

* aragonite present

Table 16 Abundance data for Foraminifera in Coralline Crag samples.

the form of clionid borings which are found occasionally in larger bivalve shells. The borings are found in both calcitic and aragonitic shells. Where the aragonite has been selectively dissolved the borings are preserved as casts within the hollow moulds of the host shell. Larger shells would have been favoured because of their greater duration of exposure on the sediment surface before burial. Clionid borings are most numerous in facies C and may indicate a relatively slower rate of sedimentation in this facies. The role of boring sponges in the process of carbonate bioerosion is discussed later in this chapter.

9.5 Corals

As already mentioned the 'Coralline' Crag is far from rich in coral remains (Chapter 1). Only 3 species are known to occur and were described by Milne Edwards and Haime (1850).

Flabellum woodii Milne Edwards and Haime, was described as being very rare and that up until 1850 only 4 specimens had been found (Milne Edwards and Haime 1850;p.7). This species is probably identical with *Fungia semilunata* described by Wood (1844, p.12). The coral had a narrow peduncle for attachment as was presumed by Prestwich (1871a; p.131) to be indicative of deep water conditions.

Sphenotrochus intermedius Milne Edwards and Haime, is the most widespread and abundant of the Coralline Crag corals. This coral has no obvious basal attachment and was presumably free-living in the loose sediment.

Cryptangia woodii Milne Edwards and Haime, is a highly specialised form which lived commensally with large colonies of *Turbicellepora* (Bryozoa). Reid (1890; p.39) believed that

Mostly *Celleporaria palmata*

the coral was a branching type and that the bryozoan encrusted the coral colony. This is not the case, however, as there is no evidence of any internal connection between the calices. Milne Edwards and Haime (1850;p.8) wrote "It is....remarkable, that corals of this genus should never be found adhering to other extraneous bodies, and should always take up their abode on a cluster of Cellepora, which, increasing as they themselves grow up, imbeds them so completely, that the calices alone remain free on the surface of the common mass....." The mode of multiplication of Cryptangia is also worthy of notice. These corals always form clusters, and must be produced by gemminferous stolons..." Propagation by stolons within the bryozoan colony would explain the regularity of the spacing between the coral calices but as yet no evidence of stolons has been found. Cryptangia is also recorded from the Helvetien (Miocene) of Central France.

The aragonitic nature of coral skeletons means that fossil evidence will be restricted to those localities which have not been affected by aragonite dissolution. Cryptangia is abundant at Ramsholt (locality 3). It was also found at Rockhall Wood (locality 5).

Empty crypts which were probably occupied by Cryptangia were found in celleporiform colonies from leached sediments at several localities (localities 17, 28 and 32).

The coral may occasionally be seen to have been overgrown by the bryozoan which is evidence that both animals were alive contemporaneously. The calices are usually distributed on one side of an irregularly branching massive colony of Turbicellepora. This is evidence that one side of the bryozoan colony was inacessible to coral settlement and was probably slightly buried in the sediment. The bryozoan probably began growth vertically or attached to a vertical organic substrate before toppling over onto the sediment. Growth was then by horizontal or subvertical branching resulting in an irregular massive colony. Settlement by the coral in these cases occurred only on the uppermost surfaces of the bryozoan colony. The coral may in turn be the substrate for the settlement of the barnacle Pyrgomina anglica (see section 9.10).

Fragments of coral are rare constituents of the Coralline Crag sediments and due to their aragonitic composition are only found at those localities unaffected by selective aragonite dissolution.

9.6 Polychaetes

The calcareous tubes of tubiculous polychaetes are occasionally found in the Coralline Crag. Their localised distribution may render them useful palaeoenvironmental indicators. The polychaetes recorded are all carbonate tube dwelling forms and include species of Serpula, Spirorbis and Ditrupa. Wood (1842; p.458) lists 13 species while the subsequent lists of Bell and Bell (1872) and Reid (1890) contain only 12 species.

Tubes of Ditrupa were noted only in three samples (049, 087, 126) which came exclusively from localities in facies A2 and C. Ditrupa, like all other serpulids, is a suspension feeder. Modern Ditrupa arietina live with the tubes exposed and lying more or less horizontally on the sediment surface where the polychaete is capable of intermittent movement (Wilson, 1976). Gaemers (1978; p.190) noted that "Ditrupa always inhabits places where tide-induced currents are weak or absent". This statement is consistent with the record of Ditrupa on the Scottish shelf where the tubes may be a dominant component of the sea floor sediment comprising up to 50-70% of the total carbonate (Wilson, 1979). In the Coralline Crag the distrubtion of Ditrupa within facies A2 and C only, similarly indicates a preference for areas with relatively reduced currents. Facies A2 and C probably differed in rate of deposition with a relatively higher rate associated with facies A2. Ditrupa is, however, capable of digging itself out of coverings of 2-3 mm of fine sand (Wilson, 1976) so rate of deposition may not be a significant factor affecting its distribution. Some of the Coralline Crag Ditrupa tubes show the affects of marine ?algal borings possibly indicating a period of exposure on the sediment surface before burial.

Encrusting serpulids also were noted in only a few samples (005, 116 and 131) which belonged exclusively to facies C. In this case the relatively slower rate of deposition was important in allowing the shell substrates to remain exposed on the sediment surface for a sufficient time for colonisation by the serpulids.

9.7 Mollusca

Fragments of molluscan shell form a dominant component of the Coralline Crag sediment. The fragments are generally very abraded and indeterminate, complete molluscan shells being rather infrequent. The majority of molluscan shells are composed of aragonite with only genera like Chlamys, Pecten, Ostrea and Anomia being composed of calcite. It was therefore not possible to quantitatively analyse numbers of mollusc shells and fragments for the majority of Coralline Crag localities where selective dissolution of aragonite has occurred. Unaffected localities are exclusively in facies A so that no quantitative comparisons can be made between the different facies. Comments on the molluscan faunas derived from this study are therefore of a qualitative nature and are summarised in the section on biofacies. The large variety of molluscan forms have been the subject of two major monographs, Wood (1848-1882) and Harmer (1914-1925), the latter restricted to gastropod species. Jeffreys (in Prestwich, 1871a) gave a list of 316 species of Coralline Crag mollusc, a total which was later increased to 420 species by Wood (1882). Opinions varied on the total number of species, these opinions being largely dependent on individual distinctions between different fossil forms as species or variations. Many 19th century works attached great importance to the proportion of extant versus extinct species as a means of determining the relative age of the Coralline Crag. Lankester (1865b), for instance, compared the percentage of extinct mollusc species within the British Crags with figures for the Antwerp Crag of Belgium. These proportions, of course, also varied according to the opinion of the author regarding the species present. Woodward (in Prestwich, 1871a) was of the opinion that 168 of a total 327 species of 'Mollusca' from the Coralline Crag (this figure included 5 species of brachiopod) i.e. 51%, were extant species. Jeffreys (in Prestwich, 1871a) believed a much larger proportion, 264 out of 316 species (84%), to be still living. Irrespective of the differences of opinion the molluscan fauna of the Coralline Crag can be seen to be very rich with a large proportion, probably greater than 50%, of species which are extant.

Most early palaeoecological studies of the Coralline Crag were based largely on inferred ecological preferences of the Mollusca. One of the earliest studies of Coralline Crag palaeoecology was that of Wood (1842) who wrote (p.457) "....such genera as Glycimeris (sic), Trichotropis, Astarte, and Cyprina [= Arctica] , and the large development of these... forms, give reason to conclude the climate was at least as cold as what we experience at the present day". On the other hand he listed the genera Pholadomya, Chama, Cancellaria, Cassidaria, Columbella?, Terebra, Pleurotoma, Pyrula, and Mitra as indicative of waters warmer than those around present day Britain and compared the molluscan fauna as a whole with that from off the coast of Portugal. He later extended this list of characteristic warm water Coralline Crag molluscs to 15 genera (Wood, 1874; p.196).

Jeffreys (in Prestwich, 1871a) gave a breakdown of the modern distributions of the extant species found in the Coralline Crag. Of the 265 extant species 185 are still found in British waters. Of the remaining 80, 65 are now only found in seas south of the British Isles. He considered this to be evidence that the Coralline Crag molluscan fauna indicated warmer seas than those around Britain at the present time.

Harmer (1896a) believed it to be misleading to consider the total number of species in these comparisons as many Coralline Crag species are known only from unique or rare specimens. Omitting these species from those listed in the monograph of Wood (1848-1882) he considered 220 species to be representative of the Coralline Crag molluscan fauna. Of these, 138 i.e. 63%, are extant species, 119 of these species occur in the present day Mediterranean and only *Buccinum* (= *Leiomesus*) *dalei* was quoted as being absent from seas south of the British Isles at the present time. Harmer (1902; p.424) concluded that the large proportion of Mediterranean species indicated the Coralline Crag basin had a free communication with the Atlantic "....by means of a strait over some part of the south-east of England...." Furthermore he believed that the absence of "boreal Mollusca" implied that the Coralline Crag basin i.e. the southern North Sea, was closed to the north. Davies (1975), on the other hand, believed that the Coralline Crag contained a mixture of warm and cold water forms as Wood (1842) had done. He listed (p.385) the following genera as indicative of warm water; *Sinum* (= *Sigaretus*), *Galeodea* (= *Cassidaria*), *Ficus* (= *Pyrula*), *Demoulia* (= *Desmoulia*), "*Terebra*", and *Glans* (= ? *Cardita*). Associated with these he noted "a group of large flattish species of *Astarte* with tendency to gerontic loss of ornament..." which he presumed to be of boreal origin in addition to the genera *Buccinum*, *Leiomesus*, *Trophon*, *Yoldia*, *Macoma*, *Arctica* and *Mya*. Whether or not it is valid to deduce palaeotemperatures from present day distributions of species is open to debate. Certainly many of the genera and species mentioned above have wide geographical and climatic ranges. However, in the case of the Coralline Crag information derived from other fossil groups and from sedimentological considerations seem to indicate a sea temperature which was warmer than that around the British Isles today (see Chapter 12). Reid (1890; p.39) believed that the molluscan fauna indicated deposition of the Coralline Crag in water between 40 - 60 fathoms (73 - 110 m) deep. He based this conclusion on the premise that if the depth had been less there would be "a larger proportion of littoral and plant-eating species." Two species of non-marine mollusc, *Helix suttonensis* and *Clausilia pliocena*, have been recorded from the Coralline Crag (Reid 1890; p.228-229) and indicate proximity to land.

Attempts have also been made to use molluscan species in stratigraphic correlation of the Coralline Crag.

Harmer (1918) correlated the Coralline Crag with the Belgian zone à *Isocardia cor* [= *Glossus humanus*] (= Horizon de Kattendijk, Scaldisien: See Chapter 13). Although this bivalve is found in the Coralline Crag, it is rather uncommon. Baden-Powell (1955a) used the presence of abundant *Turritella tricarinata* in the Coralline Crag as evidence for correlation with the Astian deposits of the Mediterranean region. The wide geographical separation and climatic difference of the two areas may, however, render correlations using eurythermal molluscan species as meaningless. Cambridge (1977) correlated the Coralline Crag with the Sables du Luchtbal (zone à *Pecten gerardi*, Scaldisien) of Belgium and described *Pseudamusium gerardi* [= *Pecten gerardi*] as the "most typical fossil" of these two deposits. Although *P. gerardi* is fairly common locally in the Coralline Crag it is by no means the "most typical fossil" and may prove to be unsuitable as the basis for correlation (see Chapter 13).

9.8 Brachiopods

Six species of brachiopod are known to occur in the Coralline Crag but none are common enough to be significant sediment contributors. By far the most conspicuous of these species is *Terebratula maxima* Charlesworth which, at lengths of up to 15 cm, is the largest known species of *Terebratula* (Muir-Wood, 1938). Davidson (1852, 1874) and Wood (1874) referred to this species as *T. grandis* Blumenbach but Muir-Wood (1938) divided *T. grandis* into two distinct species; *T. maxima* and *T. orfordensis.* The Crag species of *Terebratula* were also described by Buckman (1908).

Both the Coralline Crag species of *Terebratula* are extinct but Recent species generally live attached to firm substrates by means of a pedicle. An interpretation of the Coralline Crag seafloor by Taylor (1978; fig.117) shows *T. maxima* attached to some large immobile substrates. Suitable large immobile substrates such as rocks are generally absent from the Coralline Crag with the exception of the rock fragments in the basal phosphorite deposit (see Chapter 2). The presence of such a large species in the absence of suitable substrates (with the possible exception of large shells) seems rather problematic unless *T. maxima* was adapted in some way to life on a particulate substrate. In this case the pedicle may have been adapted to rooting rather than adherence to rocks.

T. maxima is usually preserved only as fragments often consisting solely of the robust umbonal region of the pedicle valve. Occasionally, however, complete articulated specimens are found. Large fragments were found at localities 5, 7, 8, 16 and 28 which, with the exception of the latter locality (facies C) are all within facies A2, which is interpreted as being deposited as relatively soft, silty sediment.

Lingula dumortieri Nyst (L. dumontieri in Davidson (1852)) was noted from locality 7 (facies A2). Lingula is a burrowing inarticulate brachiopod and is thus favoured by relatively soft sediments such as those of facies A2. The other 3 species recorded from the Coralline Crag are relatively rare. Wood (1874) had found only 20 specimens of Argiope cistellula during his extensive research. This species is described by Davidson (1874) as living around Britain and in the Mediterranean at the present day. He also noted (p.16) that this species is "Always very rare in the Coralline Crag, Sutton" (= ?localities 4, 5 and 6). Terebratulina caput-serpentis is described by Prestwich (1871a; p.128) as inhabiting depths from the shore to 632 fathoms (1156 m). At the present day it is found around Britain at depths between 18 and 91 m (Davidson, 1852). Davidson (1874; p. 14) notes that it is found only at Sutton in the Coralline Crag, and quotes Wood as stating that even here it is very rare and that only very small and juvenile individuals had been found.

Discina fallens (= Orbicula lamellosa? in Davidson (1852); ? = Discina atlantica in Prestwich (1871a)) also appears to have been recorded only from the Coralline Crag at Sutton (= Rockhall Wood).

9.9 Bryozoans

The bryozoans are perhaps the most important sediment contributor in the Coralline Crag. It was the abundance of the skeletal remains of bryozoans ('corals') which led Charlesworth (1835a) to recognise the 'Coralline Crag' as a

Facies	Locality	Sample nº	Wt (g)/100g sediment 1 mm
A1	2	110*	1.75
	2	111*	1.64
A2	3	089*	8.41
	5	057*	41.38
	7	129*	10.12
	16	126*	3.31
B	9	072	0.01
	14	066	16.37
	20	079	3.90
	30	084	1.03
C	26	032	50.16
	29	116	79.80
	31	087	21.34
	32	131	46.33
	36	049	1.83
	38	005	15.43

* aragonite present

Table 17 Percentage contributions of bryozoan skeletal fragments (lunulitiform excepted) to Coralline Crag sediments coarser than 1 mm.

distinct Formation (see Chapter 1). In 1844 Wood gave a list of 53 species of bryozoan from the Coralline Crag while Busk (1859) later increased this total to at least 111 species. Reid (1890) lists 122 species of Coralline Crag bryozoan. Many species probably remain to be described, indeed one new species was discovered during this study (Balson and Taylor, in preparation). The bryozoans of the Coralline Crag are discussed in greater detail in Chapters 10 and 11.

The majority of bryozoan skeletons are composed of calcite. The lunulitiform bryozoans like Cupuladria are the only major group to have skeletons composed of aragonite (Rucker and Carver 1969; p.793) but this group is quantitatively insignificant in the Coralline Crag sediments. Comparisons can thus be readily made between bryozoan faunas from different localities whether or not they have been affected by aragonite dissolution. Comparisons of absolute abundance of bryozoans within the sediment will of course be affected by a "dilution effect" where aragonite material is present. Table 17 gives the total amount of bryozoan skeletal material (less contribution by Cupuladria) in 100 g of sediment coarser than 1 mm. From this table it can be seen that the contribution made to the sediment by bryozoans varies widely but can be up to almost 80% of the >1 mm fraction in samples where aragonite has been selectively dissolved.

9.10 Barnacles

The disaggregated plates of barnacles, mostly belonging to the genus Balanus, form an abundant component of the Coralline Crag sediments. Their robust and calcitic nature means that they are found at all localities irrespective of post-depositional diagenetic alteration.

For each sample analysed, the weight of barnacle fragments per 100 g sediment coarser than 0ϕ (= 1mm) was obtained. The results are tabulated in Table 18. From table 18 it can be seen that barnacle plates are much more abundant in facies A1 and A2, particularly localities 2 and 3. This abundance is relatively even greater when the effect of "dilution" by aragonite grains in these samples is taken into account. These localities are interpreted as the most nearshore remnants of the Coralline Crag (see Chapter 12). An abundance of barnacle plates is often thought to be related to the occurrence of sea floor rock exposures or pebbly sediments. The Coralline Crag seabed almost certainly had no exposures of rock and the only pebbly sediments are those of the basal phosphorite beds. The phosphorite pebbles in the Coralline Crag were not found with any adherent barnacles although occasional encrusted pebbles were noted from the Red Crag. In these cases the barnacles were normally adherent within small depressions left by the actions of marine boring organisms. Boillot (1965) noted that plates of Balanus crenatus were more common in homogeneous sands than elsewhere in the area of the English Channel off Roscoff. Although this implied that the barnacles were not associated with rock areas he wrote "It is impossible to accept that it [Balanus] develops on homogeneous sands accumulated in hydraulic dunes...." In the Coralline Crag, however, this does appear to be the case. Barnacles are fairly frequently found adherent to large bivalve shells or are found within bivalve moulds where the shell has been removed by dissolution. It seems probable that shells and

Facies	Locality	Sample nº	Wt (g)/100g sediment > 1 mm
A1	2	110*	8.18
	2	111*	7.24
A2	3	089*	6.37
	5	057*	0.52
	7	129*	2.05
	16	126*	1.27
B	9	072	<0.01
	14	066	0.03
	20	079	0.13
	30	084	0.35
C	26	032	0.40
	29	116	0.86
	31	087	0.31
	32	131	0.06
	36	049	0.56
	38	005	0.49

* aragonite present

Table 18 Percentage contributions of barnacle plates to Coralline Crag sediments coarser than 1 mm.

shell fragments formed the substrate for the majority of the Coralline Crag barnacles.

Pyrgomina anglica (Sowerby) is a creusioid barnacle which is noted for its choice of corals as substrates. Darwin (1855) recorded this species as Pyrgoma anglicum but was subsequently placed in the new genus Pyrgomina by Baluk and Radwanski (1967a). In the Coralline Crag P. anglica is found associated with the coral Cryptangia woodii (see section 9.5). The barnacle has a cup-like base. The shape of the base is the result of upward growth within an actively growing coral corallum. 'Creusiinae cannot develop on a substratum that does not gradually ascend and, therefore, cannot live on for instance, the coralla of dead anthozoans" (Baluk and Radwanski, 1967b). The barnacle is thus dependant on the coral as a substrate. Usually the coral in the association is able to continue living with the barnacle.

This is an example of commensalism with one partner (the barnacle) deriving benefit without detriment to the other partner (the coral). Where the corallite is either much larger than the barnacle or where the corallite is part of a larger colony, both partners are able to continue growth. If the individual corallite in a colony is smothered by the barnacle this is an example of exploitation with respect to the corallite but commensalism with respect to the whole coral colony. Where the corallites are small, discrete physiological entities, as in smaller solitary corals and probably in Cryptangia, the individual coral hosts are destroyed to the consequent detriment of the barnacle. Baluk and Radwanski (1967b) term this as an example of competition in which both partners suffer loss as the ultimate effect of their relationship.

Unfortunately P. anglica is the most eurybathic and eurythermic species of the Creusiinae (Baluk and Radwanski, 1967a, 1967b) and is therefore of limited use in palaeoecological interpretations. P. anglica was found only at Ramsholt in this study and it is interesting to note that this is the only locality mentioned by Darwin (1855) in his description of the species. The distribution of P. anglica is dictated by the distribution of Cryptangia woodii which is only common at this locality (see Section 9.5).

Darwin (1855) described a total of nine species of sessile barnacle as occurring in the Coralline Crag, of which 3 are extinct. 6 of the total were species of Balanus. Of these one of the most interesting is Balanus concavus. Single specimens and groups of specimens of this large barnacle (c 5 cm in height) occur at Ramsholt Cliff (locality 3) but appear to be extremely rare at other localities. Darwin (1854, 1855) believes the Crag species to be the same as Recent Balanus concavus from Panama, Peru and Baja California. He noted that the barnacles were generally "...attached to various shells and crabs, and to each other" (Darwin 1854; p.240).

9.11 Ostracods

Jones (1857) and Jones and Sherborn (1889) recorded a total of 19 species of ostracod from the Coralline Crag. Prestwich (1871a) described these species as mostly littoral but thought Bairdia subdeltoidea indicated deep water. In a more recent study Wilkinson (1980) recognised a total of 61 species which he divided into 3 distinct suites.

Suite I contained the most common species, *Aurila convexa* *Murrayina lacunosa* and *Quadracythere macropora*. Suite II contained 7 species which formed between 1 and 16% of the total population. Suite III contained the other 51 species represented only by unique or very rare specimens. Wilkinson believed that the species of suite I represented part of the original biocoenosis and were distributed throughout the deposit. In addition *Cytheretta harmeri* and *C. woodiana* were found to be common in more northern localities (= thesis localities 16 and 20) while *Haplocytheridea pinguis* and *Aurila trigonula* were found only in more southern localities (= thesis localities 3, ?6 and 7). The presence of *Aurila convexa* and *Loxoconcha rhomboidea* was thought to indicate deposition in water less than 20 m deep. In general the ostracod fauna was thought to indicate temperate to Mediterranean conditions although many of the Coralline Crag species are eurythermal. Reid (1890; p.231) recorded only one brackish water ostracod, *Potamocypris tuberculata*. Wilkinson (1980) records a total of 4 brackish or mesohaline species and noted a tendency for the abundance of these species to decrease towards the north. Unfortunately Wilkinson's study did not include samples further north than Crag Farm (= locality 20). On the basis of the ostracod fauna Wilkinson was able to propose correlation with the Sables de Kattendijk and Sables du Luchtbal (Scaldisien) of Belgium (see Chapter 13).

9.12 Decapod Crustacea

Prestwich (1871a; p.130) on the authority of Woodward lists 6 species of decapod crustacean as occurring in the Coralline Crag:

Gonoplax angulata, Cancer pagurus, Carcinus maenas, Maia squinado, Portunus puber and P. depurator.

Reid (1890; p.281) added a further 3 species to this list: Ebalia bryerii, Pagurus bernhardus, and Scalpellum magnum.

Apart from these two lists little study appears to have been made of the decapod crustacea of the Coralline Crag. Small claws are occasionally found in bulk sample analysis but otherwise remains are rare.

9.13 Echinoderms

Echinoderms are represented in the Coralline Crag almost exclusively by echinoids although 3 spp of comatulid are also recorded (Forbes 1852). Forbes (1852) in a monograph of the echinoderms of the Crag recorded 13 species of Coralline Crag echinoid which he described (p vi) as "distinctly southern and eastern" types. He particularly cited Brissus scillae as a Recent Mediterranean species. Prestwich (1871a; p.131) agreed with Forbes and wrote "...several of the Crag genera are such as are now found only in warm and tropical seas". Reid (1890; p.40) also commented that "The genera point to warm seas...." The list of echinoid species was revised by Gregory (1891) who was able to list 17 species and 1 indeterminate species of Cidaris. 11 of these species are extinct and 6 of these appear to be exclusive to the Coralline Crag. Gregory disagreed with Forbes and stated that "....the strictly Mediterranean species do not occur in the Crags". He also drew attention to the close similarity of the Crag echinoids to those of the Belgian Diestien.

Disaggregated echinoid plates are a fairly common and widespread constituent of the Coralline Crag sediments. Occasionally, complete or partially complete tests are found. Echinoid spines are also numerous. In thin sections of leached Crag, echinoid material often has conspicuous syntaxial calcite overgrowths (see Chapter 8). The robustness and relative lightness of echinoid plates probably made them easily transportable fragments and led to their widespread occurrence in the sediments.

9.14 Vertebrates

While a rich vertebrate fauna has been recorded from the Crag phosphorite deposits (e.g. Newton, 1891) this section will only examine those vertebrate fossils which are contemporary with the deposition of the Coralline Crag.

Fish The commonest contemporary vertebrate fossils are those of fish. Occasional disarticulated teleost vertebrae are found. Woodward (1890) described the vertebrae of a Tunny (Thynnus scaldisiensis) from the Coralline Crag of Aldeburgh. Teleost otoliths are fairly commonly found. Prestwich (1871a; p.132) noted that all the otoliths belonged to Gadoid fish and recorded at least 2 species as being represented; Gadus morrhua and G. merlangus. Newton (1891) records a total of at least 13 species of teleost. He believed that the presence of Gadoid fish was indicative of temperate and northern conditions similar to those around Britain today whilst genera like Chrysophrys, Thynnus and Platax indicated rather warmer conditions (p.122). Newton also recorded 5 species of Coralline Crag elasmobranch. Reid (1890; p.40) believed that the broken state of molluscan material in the Coralline Crag might be attributable to mollusc-eating fish.

Birds Newton (1891) records only Diomedea, an albatross, from the Coralline Crag.

Mammals Although Newton (1891) records 2 forms of terrestrial mammal from the Coralline Crag, Spencer (1964; p. 337) disputed the authenticity of these records and stated that the only contemporary mammalian fossils were those of cetaceans. Prestwich (1871a; p. 133) noted that vertebrae of whales had been found at various sites in the Coralline Crag and that on one occasion seven articulated whale vertebrae had been found. Newton (1891) listed at least 7 cetacean species and believed that they indicated a temperate climate.

9.15 Coralline Crag biofacies

Facies A1

The fauna of facies A1 is characterised by its generally poor preservation, most carbonate skeletal fragments having been heavily abraded. Barnacle plates form a large component of the skeletal material. They are robust and therefore have a high preservation potential. The bryozoan fauna of this facies is dominated by robust, platy fragments of 'eschariform' colonies belonging almost exclusively to Metrarabdotos monilifera. More fragile bryozoans are generally rare. Small bivalves, occasionally with both valves articulated, are common. With the exception of the rare articulated specimens, the shells are generally abraded. Foraminifera, particularly large polymorphinids, are fairly common and well preserved.

Facies A2

The fauna of facies A2 is rich and generally well preserved. Large well preserved bivalves are particularly notable in this facies. Some of the more typical mollusc species from this facies were listed by Baden-Powell (1960) when he described the sections at The Cliff, Gedgrave (Locality 7) and Sudbourne Park (locality 16). Even within this facies the fauna may vary in its composition between geographically adjacent localities. Thus while a species may be common at one location, it may be only rarely found at an adjacent location where otherwise the faunas present a similar aspect. These lateral variations were noted by Charlesworth (1836; p.532) who wrote "....we find that the beds of crag shells are not continuous but deposited in patches...." and drew a parallel with the distribution of mollusc shells on modern sea floors. The most typical bivalves are the shallow burrowers, *Venus casina*, *Arctica islandica*, *Glycymeris glycymeris*, *Lucinoma borealis*, *Ensis ensis*, *Cardita senilis*, *Astarte gracilis*; burrowing deposit feeder *Nucula* and the free-living *Chlamys* (*Aequipecten*) *opercularis* and *Pecten maximus*. All of these bivalves live in present day British waters (Tebble, 1966). The following extinct species were probably shallow burrowers; *Cyclocardia scalaris* and *Astarte omalii*. Some of these species were found with both valves articulated particularly specimens of *L. borealis* from The Cliff, Gedgrave (locality 7). Prestwich (1871a; p. 118) recorded specimens of *Mya truncata* in life position at Rockhall Wood in sediments assigned here to facies A2.

The bivalve fauna was thus dominated by shallow burrowing filter feeders. Gastropods are much less common than bivalves in the Coralline Crag. Gastropods found in facies A2 include *Turritella*, *Calliostoma* and the calcite-shelled *Epitonium*.

Borings resulting from predation by naticid gastropods are common, particularly at locality 7, in shells of Astarte, Cyclocardia, Lucinoma, Nucula and Turritella, while the shells of the predator are rare.

This facies is also notable for the occurrence of the large Terebratula maxima which was found at Rockhall Wood (locality 6), The Cliff, Gedgrave (locality 7) and Sudbourne Park (locality 16). On rare occasions both valves are articulated but more commonly only the robust umbonal region of the pedicle valve was found to be preserved.

The bryozoans of this facies are described in greater detail in Chapter 10 but the fauna is dominated by the eschariform colonies of Metrarabdotos monilifera. Colonies of the large cyclostome Meandropora are rather rare in this facies while Blumenbachium was not recorded during this study. The large cyclostome Multifascigera sp nov (Balson and Taylor in prep.) has, as yet, only been recorded from Ramsholt Cliff (locality 3).

Clumps of the large barnacle Balanus concavus are apparently restricted to this facies and are also found only at Ramsholt Cliff. The coral Cryptangia is also only found in this facies but as mentioned already (section 9.5) its non-occurrence in other areas may be due to diagenetic solution.

Facies A3

The fauna of facies A3 is notable for the abundance of Metrarabdotos monilifera which is also abundant in the underlying facies A2 at Rockhall Wood (localities 4,6). The fauna of the upper facies may indeed, have been wholly derived from the underlying facies at this locality. The sinuous,mobile dunes which characterised this facies were probably too unstable for colonisation by benthonic organisms. These organisms probably lived in areas not covered by dunes and their skeletons were reworked by the migration of these bedforms.

Facies B

The fauna of facies B consists of the transported and abraded fragments of various fossil groups and a rather sparse restricted fauna of organisms which probably represent the insitu biocoenosis of this facies. The latter fauna appears to have been dominated by species of 'eschariform' bryozoan whose rapid growth may have been a factor in enabling them to exist on the mobile sediment surface of submarine sandwaves which characterised this facies. These bryozoans are discussed in greater detail in Chapter 10. Other demonstrably in situ fauna is rather rare but valves of Chlamys are relatively common. The free living mode of life of this bivalve may have enabled it to dwell in this facies.

At some localities almost no in situ fauna can be recognised e.g. Gedgrave Hall (locality 9) and Richmond Farm (locality 11). At other localities e.g. Lodge Farm (locality 14) and Crag Farm (locality 20) there may be an abundance of colonies of the eschariform bryozoans 'Eschara' pertusa and Biflustra savartii which are both large and well preserved. Fragments of the large cyclostomes Blumenbachium and Meandropora are mostly very abraded but tend to become more common, larger and less abraded at the northern end of the outcrop of this facies. This distribution can be explained by derivation from facies C which outcrops in the northernmost parts of the

Coralline Crag outcrop. Fragments of the rich fauna derived from this facies become smaller and more abraded in the direction of transport until at the southernmost end of the facies B outcrop (e.g. Gedgrave Hall, locality 9) few skeletal fragments are identifiable.

Facies C

The fauna of facies C is dominated by the bryozoan fauna. The bryozoans in this facies are varied and generally well preserved. The most conspicuous forms are the large cyclostomes Blumenbachium globosum, Meandropora aurantium, Meandropora tubipora (see Chapter 11), large well preserved colonies of the eschariform Biflustra savartii and 'Eschara' pertusa and of celleporiform bryozoans.like Turbicellepora. At some localities Turbicellepora may be very numerous. Colonies often show small orifices on their surface leading to a narrow tube which represents the mould of an organic cylindrical substrate which may have been a hydroid. Fragments of Melicerita charlesworthii, Cellaria and many other bryozoans are also found. Several specimens of Cellaria were found with the calcareous internodes still in juxtaposition. Specimens representing the major portion of the original colony were found at Red House Farm Reservoir (locality 28), Aldeburgh Hall (locality 32) and Crag Pit Nursery (locality 38). The molluscs from this facies are mostly represented by moulds of aragonitic species which are often difficult to identify. The moulds include Arctica, Venus, Glycymeris, Cardita and and the gastropod Scaphella lamberti. Moulds of articulated Glycymeris are not uncommon particularly at Aldeburgh Hall (locality 32). Common calcitic bivalves are Chlamys

(Aequipecten) opercularis, Anomia, Pecten maximus and Ostrea. Facies C is notable for the presence of a well preserved encrusting epifauna. Where the substrate for the epifaunal organisms was an aragonitic shell, the former adherent surface of these encrusters can be seen on the surfaces of the mould. The encrusters include many species of bryozoan including Stomatopora and Berenicea, serpulids and barnacles. Clionid borings are most common in large shells in this facies. Where the host shell was aragonitic, the borings are preserved as casts in the hollow between the internal and external moulds of the bivalve.

9.16 Carbonate degradation

After the death of a carbonate secreting organism a number of factors come into play which will affect the preservation potential of the carbonate skeleton. These may be conveniently divided into biological and physical factors.

Biological erosion (bioerosion) of carbonate substrates can be the result of the activities of burrowers and borers, grazers, browsers or predators which all result in the ultimate breakdown of carbonate grains to smaller fragments. Physical erosion is the result of grain to grain abrasion during transportation and of chemical alteration processes. Both biological and physical factors were important in the formation of sediment from carbonate skeletons in the Coralline Crag.

The state of preservation of carbonate skeletons may yield evidence of the sedimentation rate. An organism which secretes a carbonate framework will not be preserved intact unless the rate of sedimentation exceeds the rate of bioerosion

(Scoffin et al, 1980). In this context the large frame-like clusters of Balanus concavus which are recorded from Ramsholt Cliff (locality 3) must have been buried fairly rapidly in order to have been preserved. Indeed, the general scarcity of evidence of boring and encrusting organisms almost everywhere in the Coralline Crag would suggest a generally more rapid rate of deposition than that, for instance, of the present day Scottish shelf west of the Hebrides and Rockall Bank where biogenic carbonate deposits are accumulating (Wilson, 1979; Scoffin et al, 1980). Carbonate grains from these Recent deposits often show extensive bioerosion.

In the Coralline Crag, facies C shows the greatest amount of evidence of in situ bioerosion. Borings by Cliona are fairly common in large shells (borings preserved as casts within hollow moulds of aragonitic shells in this facies). Elsewhere, borings are occasionally found in shells in facies A2. Endolithic algal borings are often seen in thin sections of large carbonate grains (Plate 17, B,C). Naticid borings in bivalve shells also contribute a small part to the process of bioerosion. Such borings were found to be fairly common in bivalve shells at Gedgrave Cliff (locality 7). Each of these types of borings will weaken the shell and make it more susceptible to breakage by physical factors. Shells may also be broken by physical action of predatory organisms such as fish or crabs as noted by Hoskin and Nelson (1969; p.584). Milliman (1974; p.253-269) provides a useful summary of the role played by various taxa in the processes of bioerosion.

Carbonate degradation by physical factors may also be important. Hoskin and Nelson (1969; p.585) described how abrasion and polishing of carbonate grains may result from wave action. This is an extreme case of high energy grain to grain impacts causing rounding. Obviously under lower energy conditions rounding can occur but will take longer. Hoskin and Nelson (1971) described how barnacle debris can be created by the action of crushing in "boulder mills" in the intertidal zone. In the Coralline Crag, however, this process would not be expected to be important due to the general absence of large boulders. Mechanical erosion is generally most active in depths shallower than 20 m (Milliman, 1974; p.262) where normal wave activity is sufficient to abrade sedimentary particles on the sea floor. Normal wind and tidally-generated currents could therefore have been an important factor in carbonate degradation in the shallow Coralline Crag Sea.

Chemical erosion of carbonate grains may also be an important process in certain environments. Hoskin and Nelson (1971) and Milliman (1974) have described chemical degradation in the intertidal zone. Solution under open marine conditions is less well documented. Solution will occur in deep waters which are undersaturated with respect to carbonate. In restricted environments decaying organic material may lower pH to a point where dissolution can begin (see Milliman 1974; pp.265-266).

Lefort (1970) gave some results of experiments on solution of carbonate grains in sea water over a period of six months at a constant temperature of 15°C. The percentage weight loss observed in various carbonate grains over this period varied between 5% in the case of barnacle plates, to 50% for ophiuroid fragments. These results suggest that ophiuroid carbonate is relatively unstable and may account for the absence of ophiuroid material in the Crag. Echinoid material, also high-magnesian carbonate, was found to be relatively stable. Lefort did not, however, record the pH during the experiment. In the Coralline Crag it is difficult to apply these results in any interpretation, as subsequent subaerial diagenesis is likely to have had a far greater effect on the carbonate grains than any contemporaneous sub-sea solution process.

The ultimate product of the processes of bioerosion and to some extent physical erosion will be a carbonate mud. As already mentioned (chapter 6) silt-sized carbonate is an important component of the sediments of facies A2 in the Coralline Crag. This silt was probably generated within the Coralline Crag basin by biological and physical erosion before being transported and concentrated within the skeletal sediments of facies A2.

Chapter 10 Bryozoan faunas of the Coralline Crag

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Chapter 10 Bryozoan faunas of the Coralline Crag

10.1 Introduction

Any faunal analysis applied to the Coralline Crag is hampered by the widespread dissolution of aragonite from the sediments. At only 10 of the 38 localities used in this study could the aragonitic skeletal fauna be studied, and these localities are not evenly distributed but are concentrated in the southern part of the outcrop (see Chapter 8). For this reason study of the calcitic skeletal fauna yields evidence on the widest range of habitat types in the Coralline Crag. Quantitatively the most important calcitic skeletal organisms in these sediments are the Bryozoa from which the Coralline Crag originally derived its name (see Chapter 1).

10.2 Importance of the Bryozoa in palaeoecological studies

The abundance of Bryozoa in many sublittoral marine facies, their sedentary existence, minute size and sensitivity to environmental conditions qualify them as a potentially important tool for palaeoecological interpretation. Information can be derived from studies of bryozoans in two different ways. The habits and habitats of living individual species may be useful in palaeoenvironmental reconstruction as demonstrated by Lagaaij (1963) for Cupuladria canariensis and Cheetham (1967) for Metrarabdotos. Alternatively assemblages of species may be used if they react as a unit to changing environmental factors (Rucker, 1967). Both approaches will be used here to interpret palaeoenvironmental features in the Coralline Crag. The usefulness of the Bryozoa however, is limited by the paucity of information on the relationships between modern Bryozoa and their environmental requirements and tolerances. Other limitations result from the fact that distributional patterns of benthonic organisms along continental shelves are due partly to ecological factors and partly to subsequent post-mortem transportation and mixing of the skeletal remains and sediments. For this reason a complementary study and interpretation of sedimentary facies and regimes is essential when examining thanatocoenose bryozoan associations.

10.3 Bryozoan growth-forms

Stach (1935, 1936, 1937) thought that the structural forms of Bryozoa could be considered as phenotypic responses to the environment. He applied this idea to collections of Tertiary Bryozoa from New Zealand. Lagaaij and Gautier (1965) were the first, however, to present a careful study which compared various Recent bryozoan growth-forms to observable environmental conditions in the Rhône delta. They particularly stressed the influence of sedimentation rate on structural variations. The degree of dependence between the environment and the growth-forms is still little understood. This uncertainty will obviously affect the reliability of conclusions if these are drawn only from an analysis of proportions of different growth-forms. Schopf (1969), comparing adeoniform and vinculariiform growth-forms, commented that "correspondence between growth habit and habitat may result from genetic or ecologic factors which are not directly related to the adaptability of flattened versus round branches. If a structural grouping is to be considered ecologically significant, then a definite environmental influence should be shown on the structure ...., this commonly has not been possible to do".

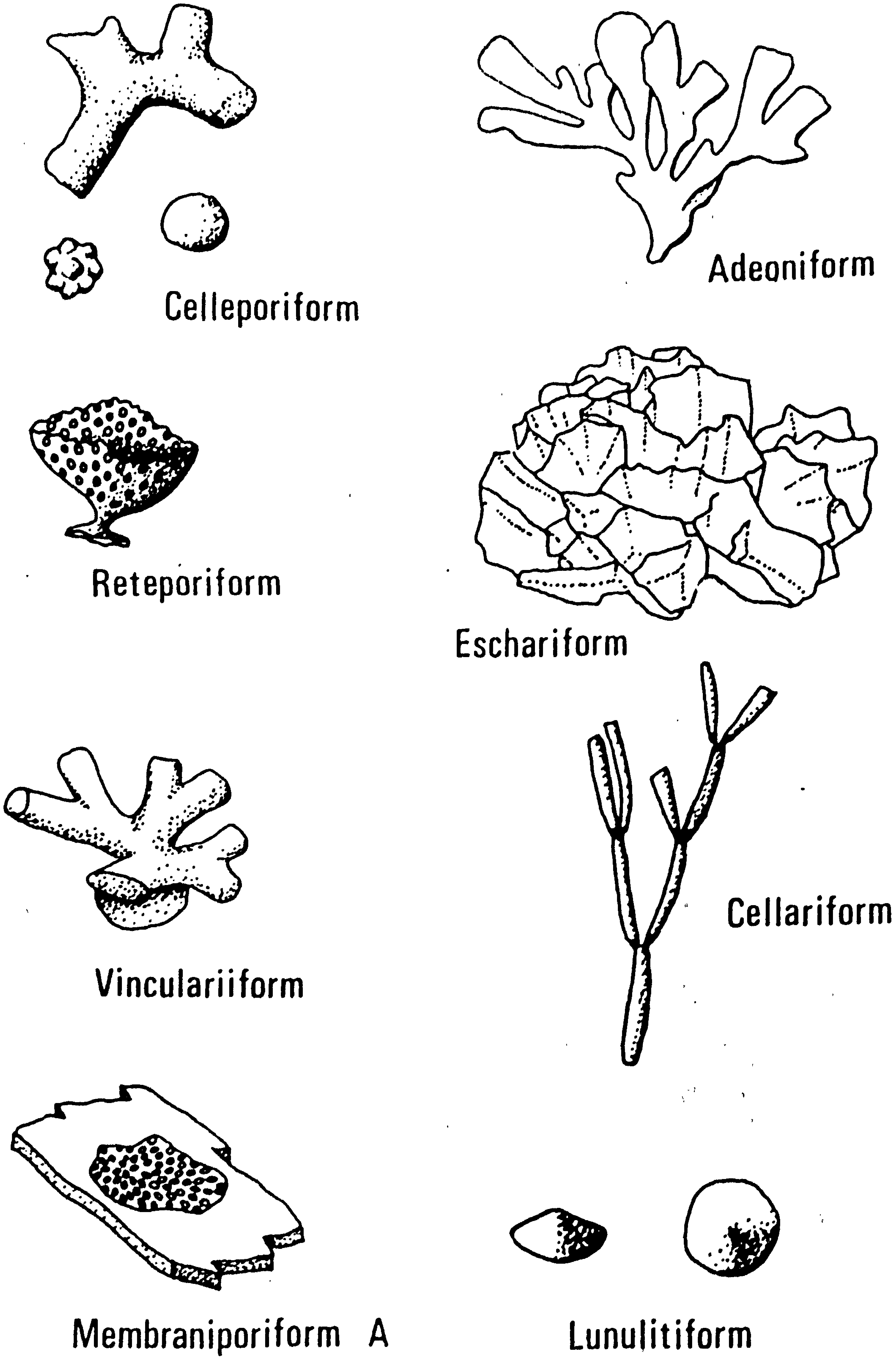
Due to these limitations involved in the analysis of bryozoan growth-forms, they will not be used here as an absolute criterion for environmental reconstruction. Rather, they will be used as a tool to be considered in conjunction with other palaeoenvironmental information derived by other means in an attempt to build up a complete picture of Coralline Crag habitats.

10.4 Growth-form categories

18 growth-forms are listed by Schopf (1969) for Recent Bryozoa. Some of these like flustriform, which are very poorly calcified, and membraniporiform B, which usually encrust marine plants, are unlikely to be preserved in fossil assemblages. Others which are very delicate, like catenicelliform, may not be preserved in coarse, mobile sediments. In the Coralline Crag only 8 growth-forms have been recognised (Fig. 19). The definitions below are from various authors but are all summarised in Schopf (1969).

a) Adeoniform [Brown (1952; p.32); Lagaaij & Gautier (1965; p.51)]
Colony erect, rigid, bilamellar, lobate, firmly attached to a solid substratum by a calcareous base. When examining only small fragments this growth-form cannot be distinguished from eschariform types. Lagaaij & Gautier (1965; p.52) wrote:
"It attains sizable percentages only on the sandy 'fonds coralligenes' between 40 and 50 meters in depth...., but is also found in minor percentages on the very calcareous sands in deeper water...."

b) Cellariform [Stach (1936; p.63; 1937; p.80), spelt Cellariiform by Brown (1952; p.32) and Lagaaij &



Celleporiform

Adeoniform

Reteporiform

Eschariform

Vinculariiform

Cellariform

Membraniporiform A

Lunulitiform

Figure 19 Common bryozoan growth-forms represented in the Coralline Crag. Nomenclature after Schopf (1969)

Gautier (1965; p.51)] Colony erect, flexible (jointed), calcareous, approximately cylindrical, attached to the substratum by rootlets. Internodes consisting of numerous individuals; orifices arranged on all aspects of the curved face of the cylinder. Lagaaij and Gautier (1965; p.56) wrote:
"Perhaps cellariiform (sic) growth as such is privileged [in occurring in moderate-deposition environments] .... since it combines erect growth with great flexibility and the inherent ability passively to 'shake off' settling clay particles". Gautier (1961; p.352) pointed out that most cellariiform (sic) species live in moderate depths on a variety of substrates.

c) Celleporiform [Brown (1952; p.33); Lagaaij and Gautier (1965; p.51)]
Colonies with individuals heaped irregularly in multilamellar masses of various shape, inherent with incrustation on or around a flexible substratum. In the Coralline Crag no restriction to flexible substrates is found, molluscan shells commonly acting as substrates. Lagaaij and Gautier (1965; p.52) wrote:
"[Chiefly distributed in the littoral and sublittoral where no active transport and resedimentation of sand takes place] ....but only in very minor percentages". Rider & Cowen (1977) made a distinction between celleporiform A and B growth forms. Celleporiform A is unlike celleporiform B (corresponding to description above) by growing in sheet like layers which gradually build up to form a massive colony (see Rider & Cowen, 1977). Celleporiform A colonies are very rare in the Coralline Crag but a specimen of Membranipora andegavensis Michelin was found exhibiting this growth-form (Sedgwick Museum specimen C51251). The irregular celleporiform B growth form is, however, very common, and will be simply referred to as "celleporiform" in this study.

d) Eschariform [Stach (1936; p.62; 1937; p.81); Brown (1952; p.33)]

Colony strongly calcified, foliaceous and bilamellar having the orifices of the two layers facing in opposite directions and with attachment to the substratum either by radicles or direct adherence. Stach (1936; p.62) wrote:

"This type is adapted for life in sublittoral zones at depths of at least 10 fathoms.... It may extend to deeper water but not to the littoral zone".

e) <u>Lunulitiform</u> [Stach (1936; p.63; 1937; p.81); Brown (1952; p.33)]

Colony free-living, shaped like discs or shallow thimbles and having zooids opening on outer face. Stach (1936; p.63) noted that:-

"Their free mode of life prohibits their existence in the littoral zone where wave action is strongly felt; and from their present-day occurrences, they are restricted to sandy bottoms where current action is strong, their upper limit being about 15 fathoms".

f) <u>Membraniporiform A</u> [Lagaaij & Gautier (1965; p.51) Membraniporiform A and B were included together by Stach (1936; p.61; 1937; p.81); Brown (1952; p.34)]

Colony usually unilamellar, dorsal wall of skeleton entirely calcified. Generally encrusting a solid substratum. (Membraniporiform B with uncalcified dorsal walls generally encrusts flat flexible substrates. Its preservation potential is thus very poor as once the substrate has decayed the calcitic skeleton will be very fragile). Lagaaij & Gautier (1965; p.50) observed:

"The highest percentages.... [occur] .:..in the.... areas where deposition is slow or does not take place...."

g) <u>Reteporiform</u> [Stach (1936; p.62; 1937; p.80); Brown (1952; p.34); Lagaaij and Gautier (1965; p.51)]

Colony erect, rigid, strongly calcified, fenestrate or reticulate, firmly attached to a solid substratum by a calcareous base. Stach (1936; p.62) wrote:

"This type is adapted for life in regions where wave action and currents are strong, these factors being overcome by the rigidity and fenestration of the colony".

Lagaaij & Gautier (1965; p.53) observed that the reteporiform growth-form was represented in areas where deposition is "slow or does not take place". Schopf (1969; p.243), however, suggested that a strongly calcified erect colony is not a phenotypic response to strong currents. He feels that "where water agitation is greatest, colonies tend to be either flat and encrusting or, if erect, they may be flexible in the manner of blades of grass in a strong breeze". Thus evidence from reteporiform colonies may not indicate that wave and current action were strong.

h) Vinculariiform [Stach (1936; p.62; 1937; p.81); Brown (1952; p.35); Lagaaij & Gautier (1965; p.51)] Colony erect, rigid, consisting of dichotomous subcylindrical branches (rodlike), firmly attached to a solid substratum by a calcareous base; the orifices open on all aspects of the curved surface. Stach (1936; p.62) observed that this growth-form is adapted to "life in deeper or sheltered waters where wave action is absent and currents scarcely active. This group typifies growth in quiet water...."

These growth-form categories are used in this study for both cheilostome and cyclostome Bryozoa which may or may not respond in similar ways to environmental factors. Many of the cyclostomes proved difficult to fit into these categories. This is particularly the case for the large cyclostomes Meandropora, Blumenbachium, ?Multifascigera and Heteropora. These cyclostomes will therefore be dealt with separately (Chapter 11).

10.5 Techniques and other considerations

In order to determine the proportion of the various bryozoan growth-forms present at each sample locality the following procedure was adopted.

Each sample was wet sieved at 1ø intervals for 20 minutes. Only the sieve fractions 0ø (1 mm) and larger were used for analysis. Below this size it was found to be impossible to assign the fragments to growth-form categories. A larger minimum size could not be used due to the small size of cellariform fragments which, being rod-shaped tended to drop through even small sieve meshes. The 0ø sieve retained most cellariform fragments. Unfortunately cellariform fragments are very distinctive so that some bias does enter due to the ease with which they can be identified compared to other growth-form types retained on the same size sieve mesh. All the bryozoan fragments were picked out of the samples and assigned to growth-form categories where possible. Where the sieve fraction was too large for all the bryozoan fragments to be removed the sample fraction was divided. The quantities of each growth-form in these subsamples were later multiplied by a factor representing the ratio of the subsample to the complete sample fraction. Thus if 5 g was taken from a 20 g sample fraction then the quantity of each growth-form was multiplied by $\frac{20}{5}$ to obtain the final result. After these quantities had been determined for each sample fraction they were added to obtain the quantities for the entire sample. When all the fragments had been removed and assigned to growth-form categories, each category was accurately weighed. In consideration of the method of analysis for the proportion of various growth-forms a number of points should be made.

1) In studies on Recent bryozoan material the bryozoan fragments are usually counted numerically (e.g. Rucker 1967; Lagaaij & Gautier 1965). This method is biased towards fragile growth forms or those which tend to readily break up into many individual pieces (e.g. cellariform colonies). Thus one fragile cellariform colony which rapidly breaks down into perhaps many dozen skeletal elements assumes a greater importance in such an analysis than a single robust celleporiform colony which may in real terms represent a far greater carbonate concentration and biomass. This problem is accentuated in fossil assemblages where compaction also serves to break up fragile colonies while leaving robust colonies intact. For these reasons the skeletal fragments were weighed in this study to give an estimate of carbonate production for each growth-form.
2) Another source of bias will arise from those bryozoans with a high rate of turnover which therefore contributed a larger amount of skeletal material to the sediment without necessarily being more numerous than more slowly growing bryozoans. Although this fact cannot easily be compensated for it should be borne in mind when interpreting the results.
3) In attempting to weigh the carbonate produced by each bryozoan growth-form type a number of further problems arise which result from diagenesis of the skeletal deposits. At some localities an appreciable amount of

calcite cement or glauconite was precipitated within the zoecial chambers of the colony. Adherent grains on the colony surface are often very difficult to remove a and are weighed with the skeletal fragments. Limonite staining may also serve to increase the apparent weight of fragments. These factors, however, probably have only a minor effect. Lunulitiform colonies are dominantly composed of aragonite (Rucker & Carver 1969; p.793), which has been lost by dissolution from many localities. Lunulitiform growth-forms are therefore not considered in this analysis.

4) The amount of bryozoans found in any sample will also be dependant on the sedimentation rate. Bryozoan material will be "diluted" by large amounts of other types of sediment.

5) There will be differences in absolute abundance caused by dissolution of aragonite. Where aragonite has been removed from the sediment, the proportion of bryozoans (calcitic) will be higher than in the unaltered sediment.

6) Other errors may result from sampling. Variations in bryozoan content, for example, are particularly noticeable in the sandwave facies where large skeletal material tends to be concentrated at the base of the foreset slopes. As large a sample as possible (usually 3 - 4 kg) was taken in the field in order to minimise these very local variations in fauna.

7) Membraniporiform A colonies encrust shell fragments and other hard substrates. In most cases the weight of the substrate far exceeded that of the bryozoan colony.

Therefore these colonies were not weighed but were simply recorded as present with an qualitative estimate of abundance.

10.6 Analysis of data

Before proceeding with cluster analysis of the bryozoan growth-form data each value was normalised to remove sample size effects. Each total weight was recalculated as the weight per 100 g of original sample. However, this could lead to bias in samples which are rich in fine sediment $<$ 1 mm diameter, which would "dilute" the bryozoan weights. For this reason the data was calculated as weights of the growth-form types in 100 g of the sample fraction greater than 1 mm diameter. Comparison between the cluster analyses for the two types of normalised samples described above (Cluster A and B respectively, Figs 21 and 22) shows only very minor differences in the dendrograms. Figure 25 gives a presentation of this data in the form of a histogram. This figure clearly shows the variation in abundance between the various samples which are arranged according to the sedimentary facies to which they are assigned.

a) Method of Cluster analysis

Cluster analysis was by means of weighted pair-group analyses of a similarity matrix using the program CLUSTR (Davis, 1973; p.467). Cluster analysis can be used in two different ways.

i) Grouping of growth-forms (variables) in terms of their occurrence in the sediments at the 17 analysed localities (cases). This form of procedure is known as R-mode cluster analysis.

ii) Grouping of localities (cases) in terms of the growth-forms (variables) found at each locality. This is known as Q-mode cluster analysis and groups localities into clusters which have a similar faunal aspect or biofacies.

Additionally the clustering can be performed using either correlation coefficients or distance coefficients. The difference between these two types of clustering can be illustrated quite simply by the following plot of variables measured on three objects:

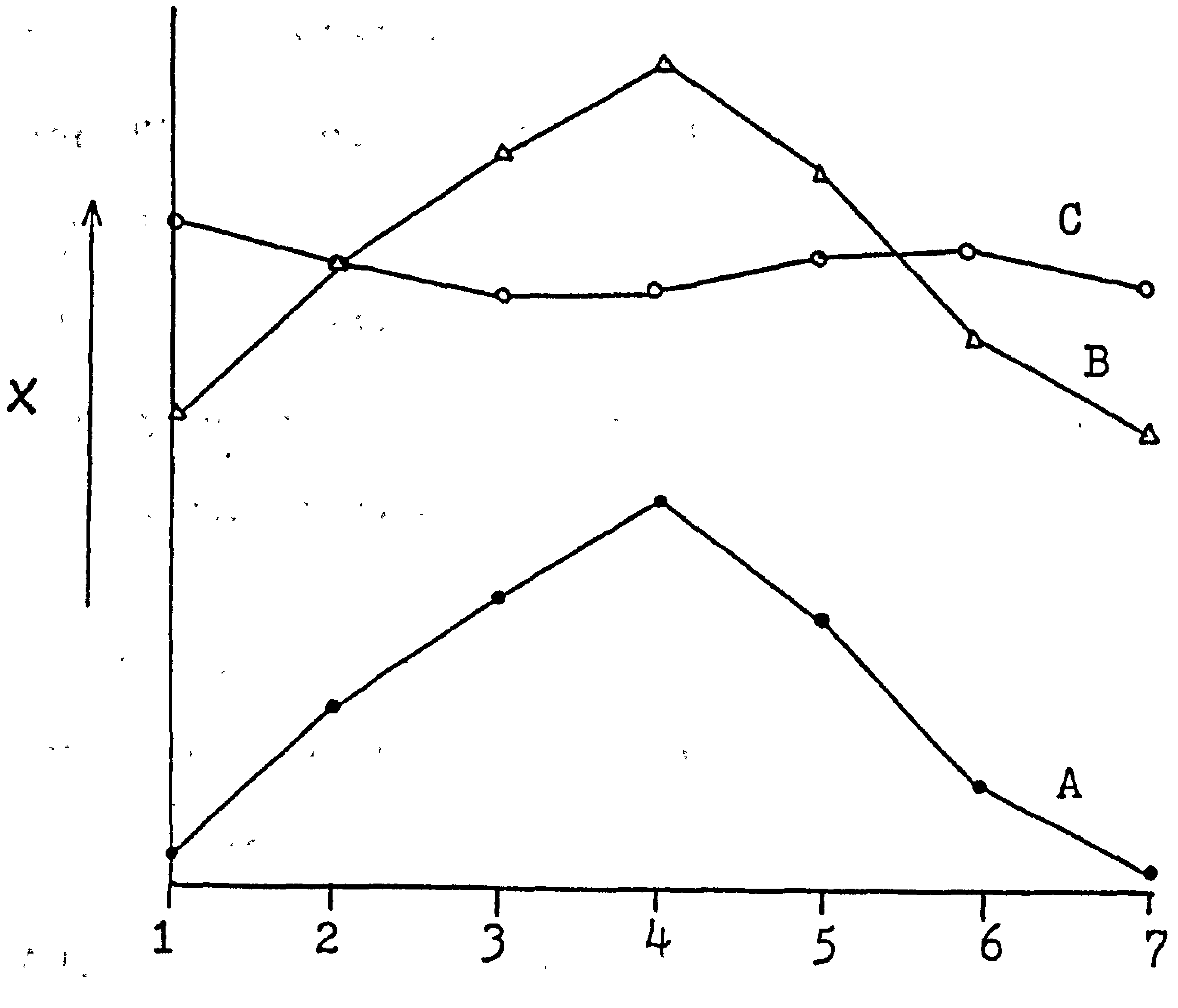


Figure 20 Correlation v Distance coefficients

Curves A and B are highly correlated but are separated by a large distance. Curves C and B are negatively correlated but are close in distance (After Davis, 1973).

Thus a correlation clustering will cluster assemblages with a similar composition but which may vary widely in their abundances in the sediments. Distance clustering will cluster assemblages with a similar abundance and take less account of the composition of the assemblage.

It was found, in general, that correlation clustering was more useful as it takes no account of any "dilution" effects resulting from either high sediment input or from relatively reduced bryozoan production.

b) Interpretation of results

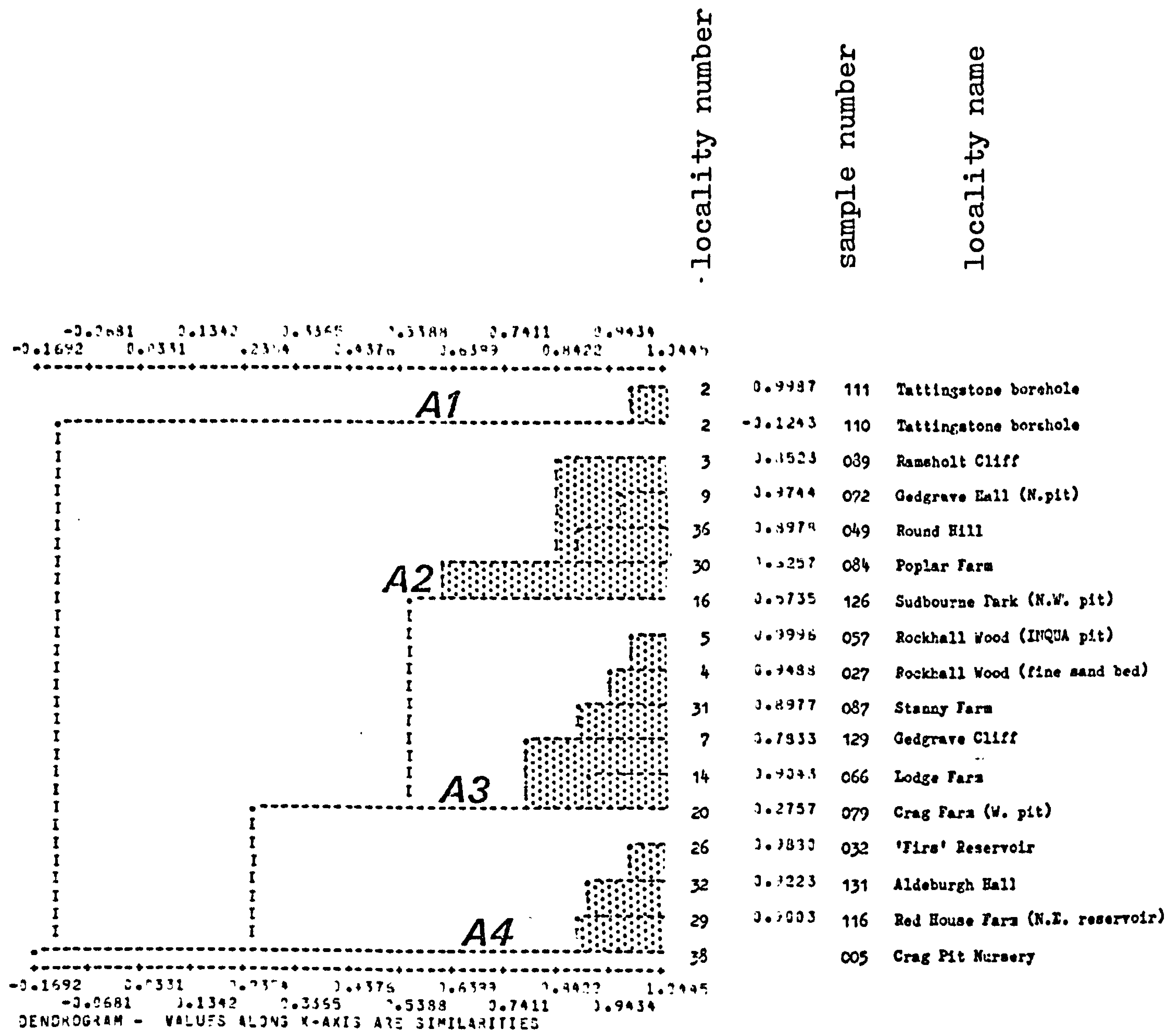
Cluster analysis A (figure 21) Weights expressed per 100 g of original sample. Clustering of correlation coefficients. Includes data on barnacle plates.

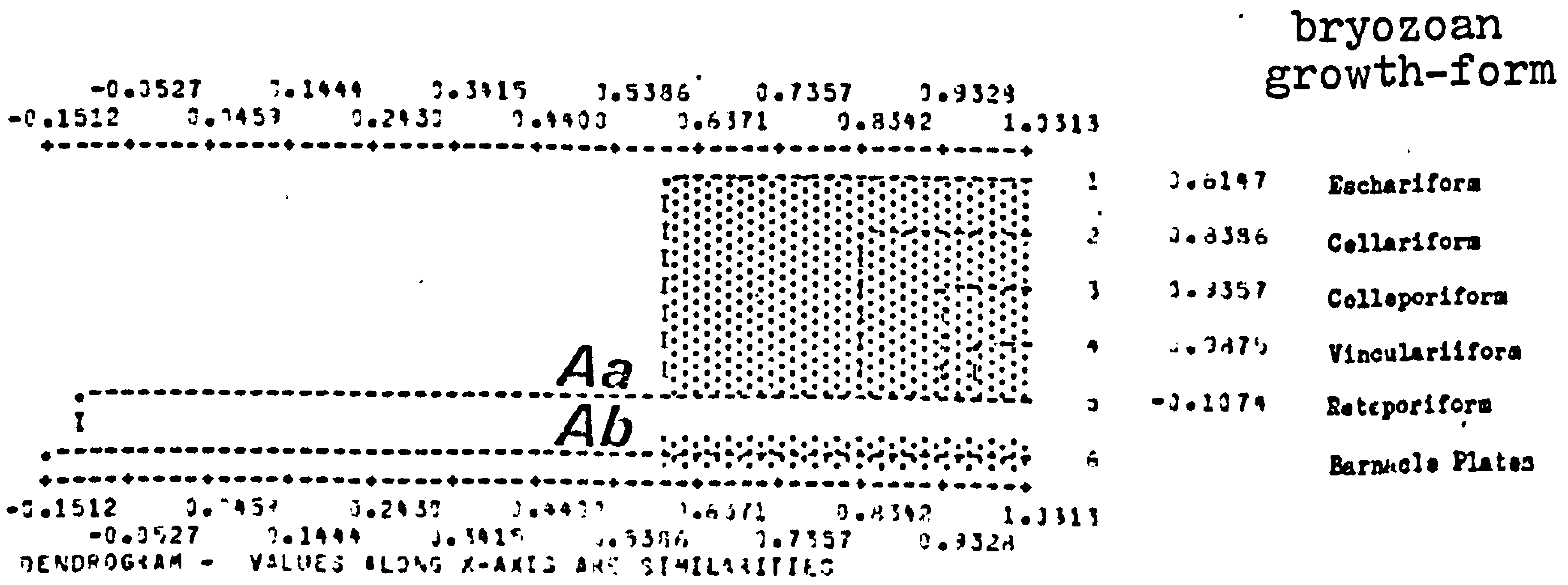
Q-mode

A1. Tattingstone (locality 2). This cluster's remoteness is probably due to a high percentage of barnacle plates in the analysed sample

A2 & A3. Most localities are included in A2 and A3 but the reason for the separation into two groups is not clear.

A4. The four localities in this group (localities 26, 29, 32, 38) all belong to facies C and are geographically close together. These samples are distinguished by the very high proportion of well preserved, unabraded bryozoan remains in the sediment.





<u>Figure 21</u> <u>Cluster analysis A</u> Dendrograms created by clustering of correlation coefficients using weight of each bryozoan growth-form expressed per 100 g of original sample. Includes data for barnacle plates.
Top: Q - mode cluster
Bottom: R - mode cluster

R - mode

Aa. All Bryozoan growth-forms

Ab. Barnacle plates

This grouping is due to a non-correlation between bryozoan faunas and barnacle occurrences.

Cluster Analysis B (Fig 22)

Weights expressed per 100 g of sample fraction greater than 1 mm diameter. Clustering of correlation coefficients. Includes data for barnacle plates.

Q - mode

The groupings are identical to that in Cluster A above. This shows there is only a slight difference between the 2 different normalising procedures.

R - mode

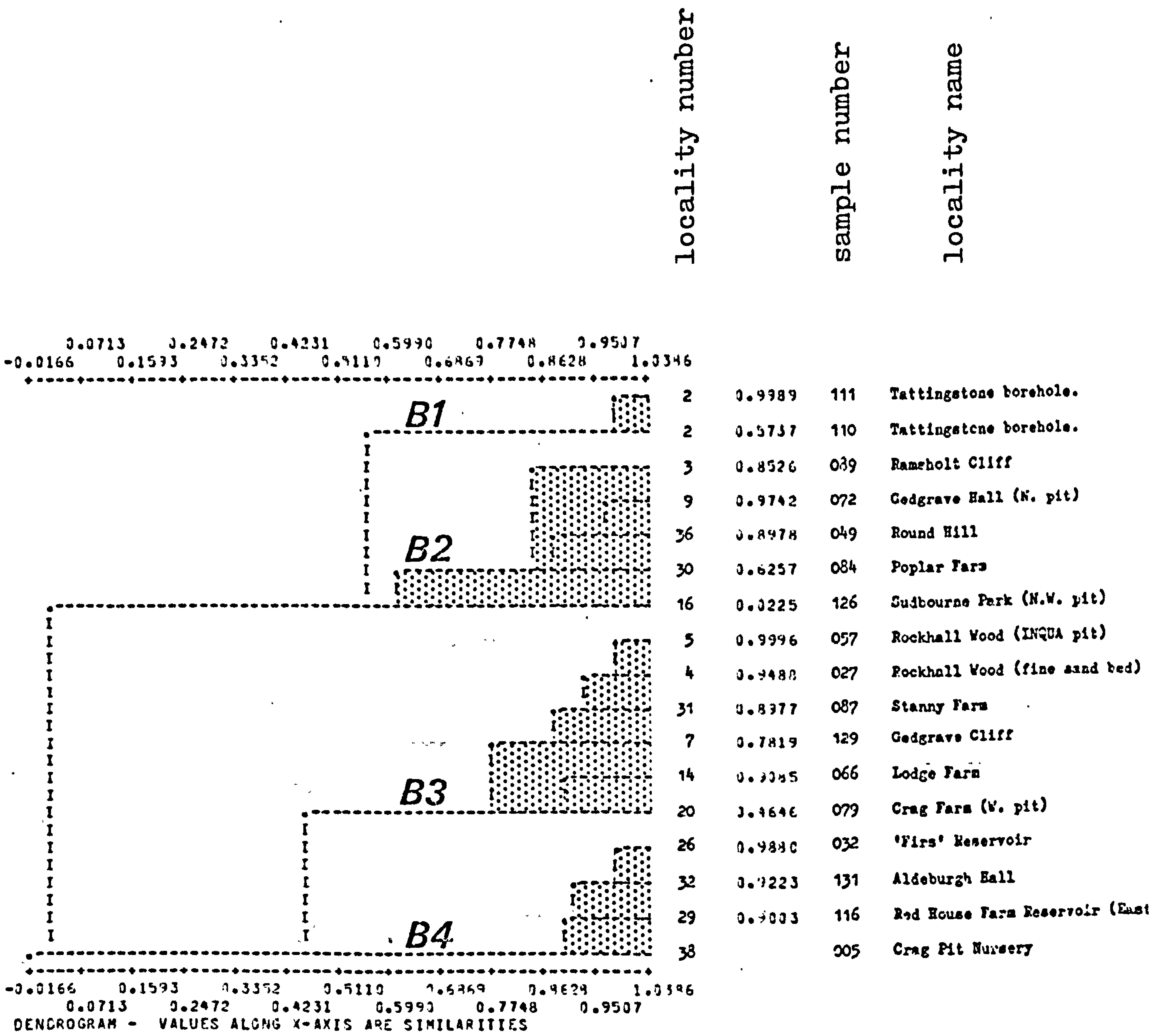
Groupings similar to Cluster A but eschariform is now a distinct cluster (Ba) from the other bryozoan growth-forms (Bb). This may be due to a difference of the "dilution" effects on eschariform colonies which are generally larger than the other growth-form fragments.

Cluster Analysis C (Fig 23)

Weights expressed per 100 g of sample fraction greater than 1 mm diameter. Clustering of correlation coefficients. Barnacle plate data not included.

Q - mode

With the barnacle plate data removed only 2 clusterings are formed. This data clearly had a strong effect on Clusters A and B. However the four localities of clusters



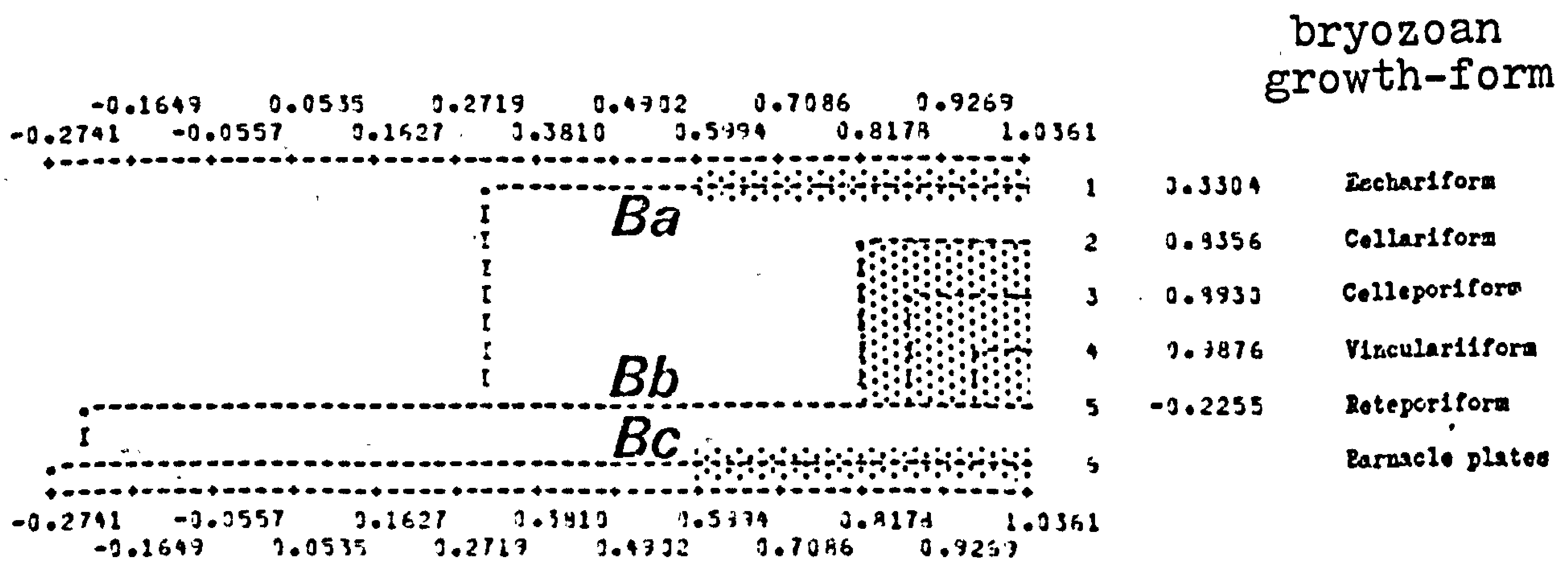
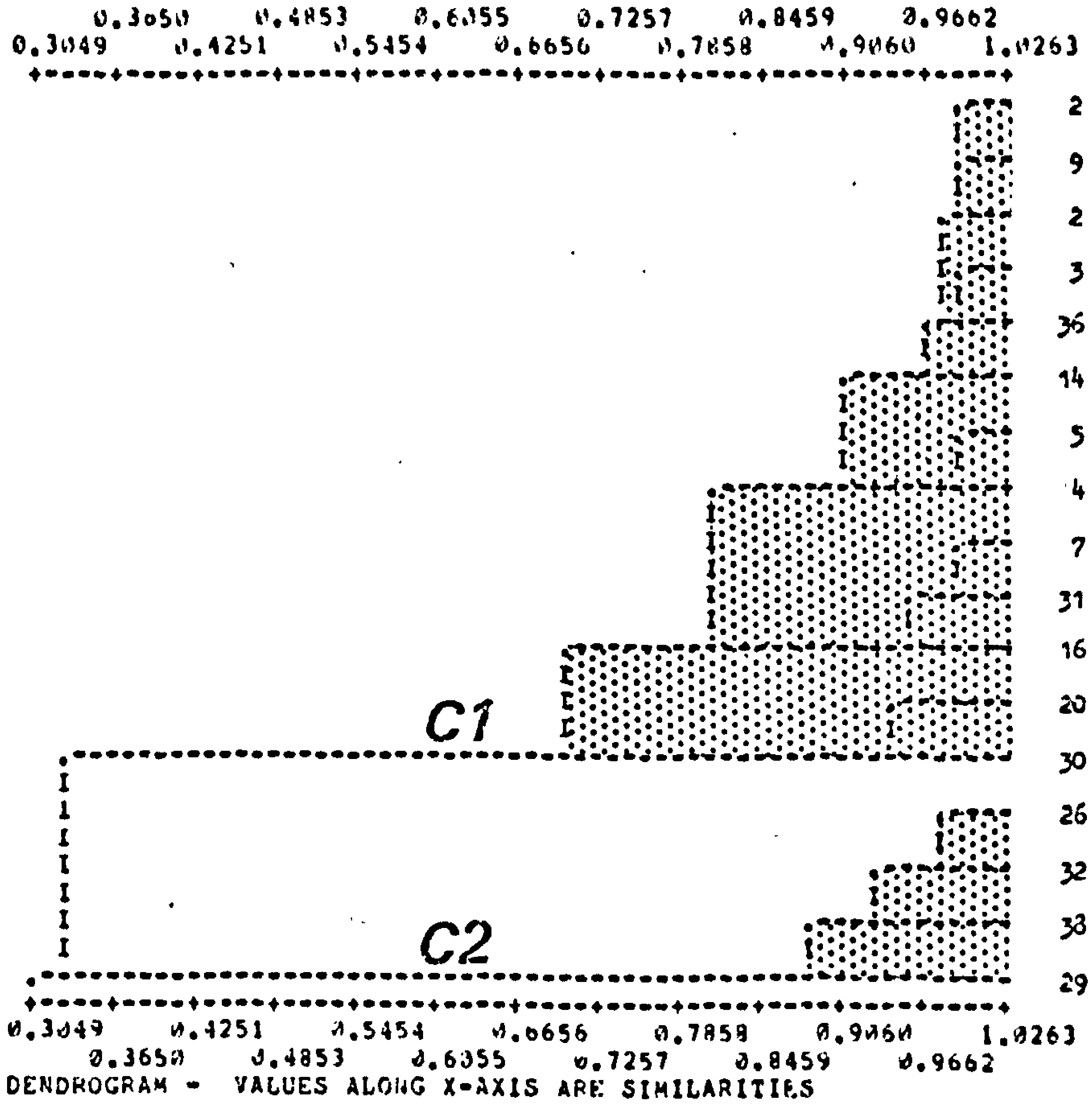
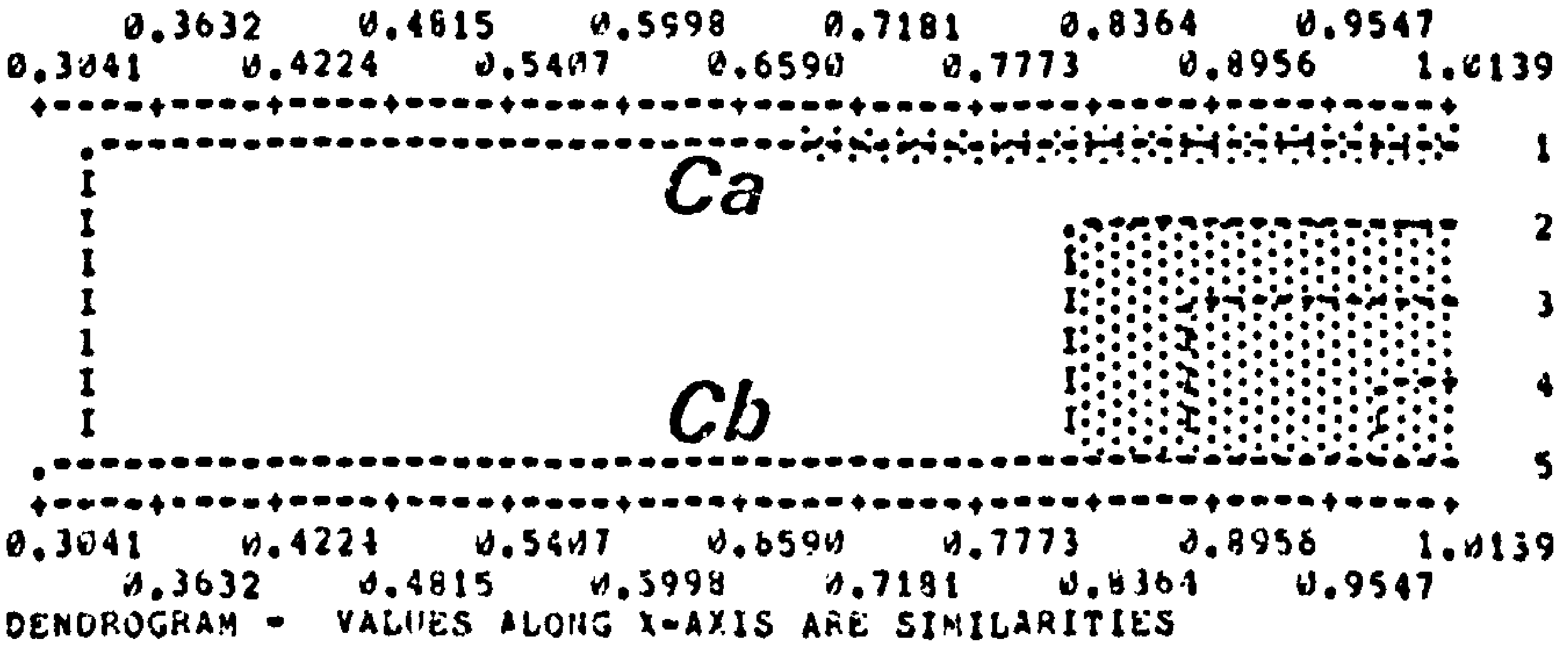


Figure 22 Cluster analysis B Dendrograms created by clustering of correlation coefficients using weight of each bryozoan growth-form expressed per 100 g of sample fraction greater than 1 mm diameter. Includes data for barnacle plates.
Top: Q - mode cluster
Bottom: R - mode cluster



locality number		sample number	locality name
2	0.9991	111	Tattingstone borehole
9	0.9981	072	Gedgrave Hall (N.pit)
2	0.9851	110	Tattingstone borehole
3	0.9961	089	Ramsholt Cliff
36	0.9675	049	Round Hill
14	0.9894	066	Lodge Farm
5	0.9995	057	Rockhall Wood (INQUA pit)
4	0.8110	027	Rockhall Wood (fine sand bed)
7	0.9927	129	Gedgrave Cliff
31	0.9626	087	Stanny Farm
16	0.7042	126	Sudbourne Park (N.W. pit)
20	0.9430	079	Crag Farm (W. pit)
30	0.3316	034	Poplar Farm
26	0.9864	032	'Fire' reservoir
32	0.9399	131	Aldeburgh Hall
38	0.8831	005	Crag Pit Nursery
29		116	Red House Farm (N.E. reservoir)



		bryozoan growth-form
1	0.3304	Eschariform
2	0.8356	Cellariform
3	0.8930	Celleporiform
4	0.9876	Vinculariiform
5		Reteporiform.

Figure 23 Cluster analysis C Dendrograms created by clustering of correlation coefficients using weight of each bryozoan growth-form expressed per 100 g of sample fraction greater than 1 mm diameter. Barnacle plate data not included.
Top: Q - mode cluster
Bottom: R - mode cluster

A4 and B4 remain distinct from all other localities.

R - mode

Ca. Eschariform

Cb. Other bryozoan growth-forms

Cluster Analysis D (Fig 24)

Weights expressed per 100 g of sample fraction greater than 1 mm diameter. Clustering of distance coefficients. Barnacle data not included.

Q - mode

The groups are different from the other analyses above. The groups can be related to the abundance of bryozoan material in the sediment and thus perhaps to bryozoan production.

D1. Localities with a small bryozoan content

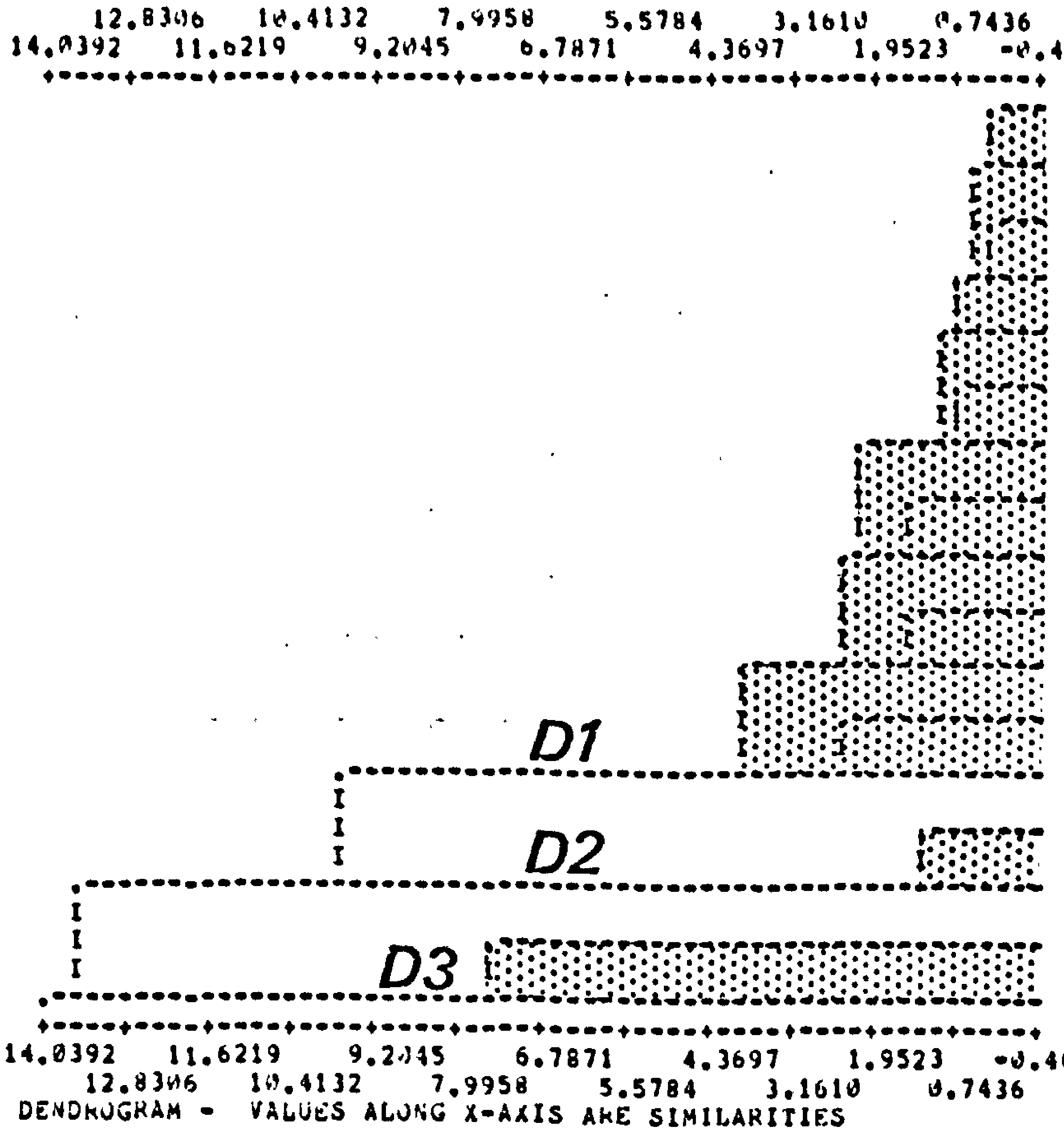
D2. Localities with a moderate bryozoan content

D3. Localities with a high bryozoan content

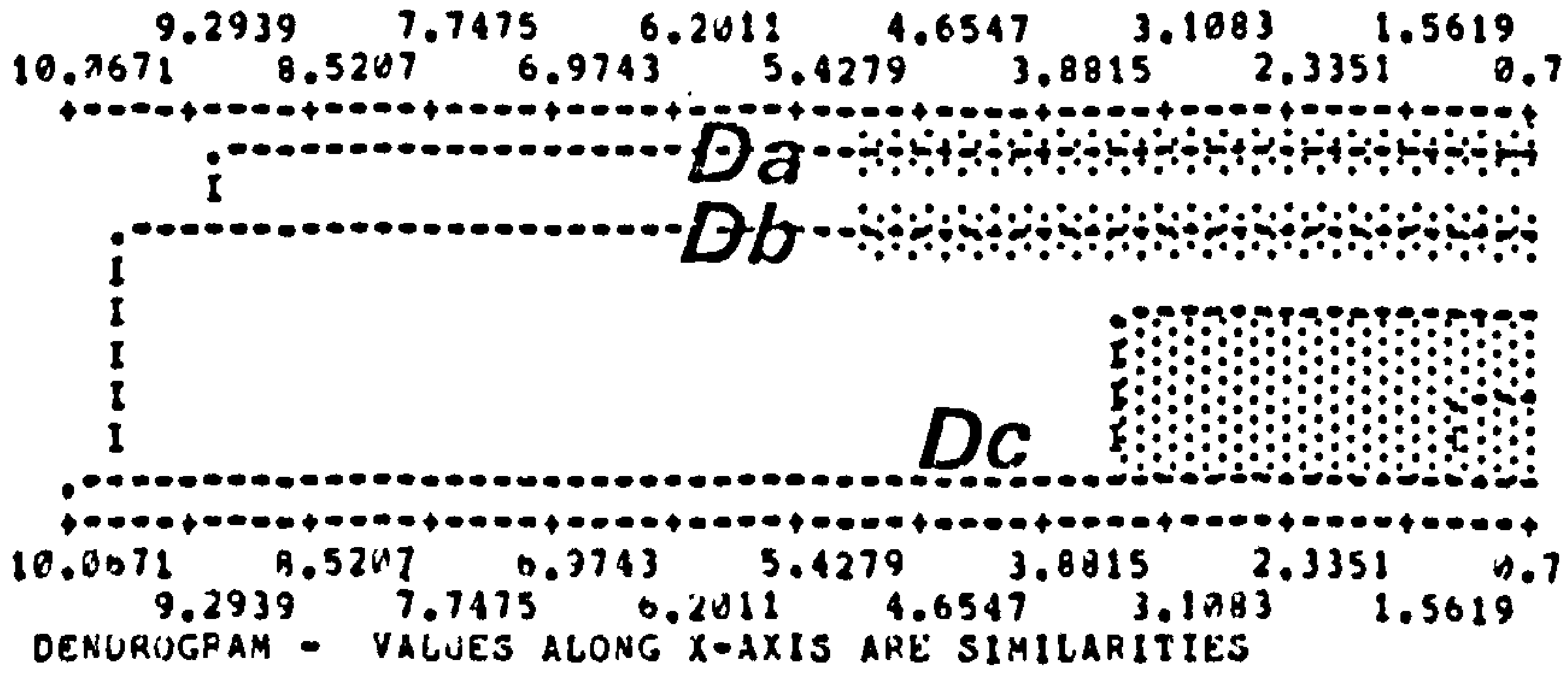
Locality 32 is known to have a high bryozoan content but is found in the group with a small content (D1). This is because much of bryozoan content in sample 131 is in the form of the large cyclostomes Meandropora and Blumenbachium which were not considered in the growth-form study.

R - mode

This clustering reflects the widely differing contributions to the sediment made by the growth-forms. Eschariform colonies (Ea) are common and ubiquitous. Celleporiforms (Eb) where present, may contribute a large percentage to the total weight of bryozoan fragments. The other types



locality number		sample number	locality name
2	0.0721	111	Tattingstone borehole
2	0.3366	110	Tattingstone borehole
30	0.2331	084	Poplar Farm
36	0.5583	049	Round Hill
9	0.7491	072	Gedgrave Hall (N. pit)
16	0.5343	126	Sudbourne Park (N.W. pit)
20	2.0633	079	Crag Farm W. pit
3	1.4045	089	Ramsholt Cliff
7	2.3575	129	Gedgrave Cliff
32	1.3433	131	Aldeburgh Hall
38	3.6829	005	Crag Pit Nursery
14	2.3781	066	Lodge Farm
31	9.6116	037	Stanny Farm
5	1.0229	057	Rockhall Wood (INQUA pit)
4	13.5020	027	Rockhall Wood (fine sand bed)
26	7.2929	032	'Fire' reservoir
29		116	Red House Farm (N.E. reservoir)



		bryozoan growth-form
1	9.0522	Eschariform
3	9.7234	Celleporiform
2	3.4058	Cellariform
4	1.1323	Vinculariiform
5		Reteporiform

Figure 24 Cluster analysis D Dendrograms created by clustering of distance coefficients using weight of each bryozoan growth-form expressed per 100 g of sample fraction greater than 1 mm diameter. Barnacle plate data not included.
Top: Q - mode cluster
Bottom: R - mode cluster

(Ec) are usually of minor importance as sediment contributors.

c) Conclusions from cluster analyses

Results from these cluster analyses must be considered in the light of sedimentary evidence of facies and sediment transport. However, it is clear that a group of localities from facies C (localities 26, 29, 32, 38) show very high, probably nearly in situ, bryozoan production. Selective transportation and destruction may have altered the composition of these faunas. Other in situ faunas with moderately high production are found at other localities from facies A2 (localities 3, 4, 5). Tattingstone (locality 2) shows a wholly transported fauna of bryozoans with a large contribution of barnacle plates to the sediment. This supports a more littoral interpretation for the sediments of the Tattingstone outlier (see Chapter 7).

10.7 Problems of thanatocoenoses

When examining the faunal composition of thanatocoenoses (death assemblages) it is important to recognise those members of the fauna which have suffered long transportation before being deposited from those members which are at or very near their place of life or death. Transported bryozoan fragments frequently are seen to exhibit abraded colony ornament, especially around the zooecial apertures. Abundance of unabraded fragile colonies should indicate in situ accumulations.

Other problems of faunal analysis of coarse, thanatocoenose deposits result from sampling difficulties.

Selective transportation or sorting can occur on the basis of grain size or shape. This results in a patchy distribution of skeletal fragments, which may significantly vary within a few centimetres laterally. This is particularly well seen in the sandwave faces (facies B) where large bryozoan fragments are often found to be concentrated at the foot of foreset slopes. It appears, however, that the sandwave facies may exhibit an extreme example of this sorting effect and that samples from other facies do not show this effect to the same degree.

Qualitative judgement was used on the cluster analysis samples to determine whether the fragments were unabraded and thus *in situ* or whether they were abraded and thus possibly transported. Figure 26 shows the general distribution of inferred *in situ* bryozoan colony growth-forms between the samples studied.

An alternative presentation of the growth-form analysis is shown in figure 27. This figure shows pie graphs for the proportions of growth-forms obtained from bryozoan fragments >2 mm ($> {}^{-}1\phi$) diameter for twelve geographically distinct localities within the area of the Coralline Crag outcrop. It is thought that by restricting the size range of the fragments considered to the larger size fractions the data obtained will more closely represent *in situ* material.

However, in a presentation of this nature it should be remembered that although the pie graph of bryozoan growth-form percentages for a sample from Tattingstone, for example, shows that eschariform fragments form 100% of the material

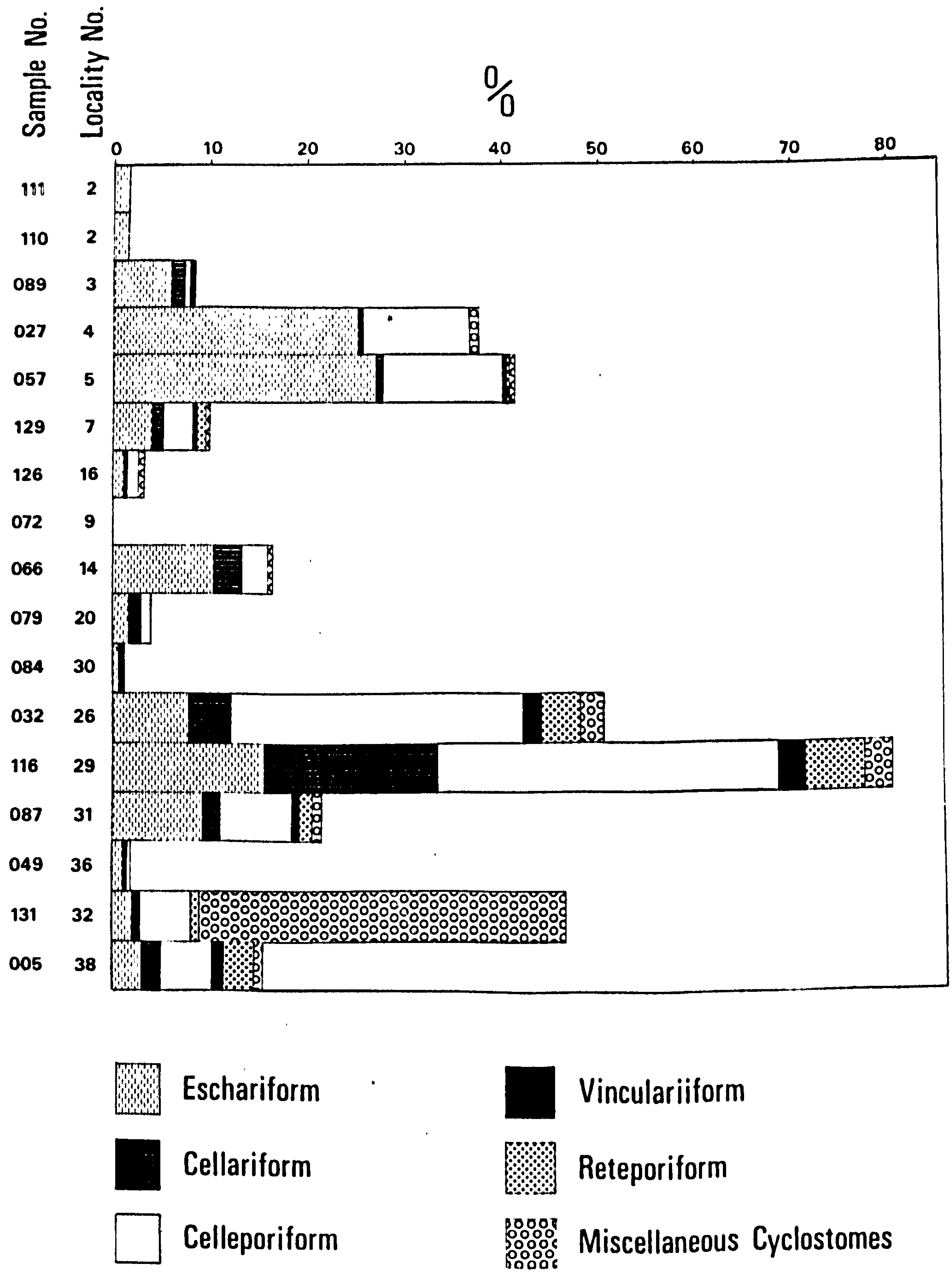


Figure 25 Histogram showing percentage contribution by bryozoans to the sediment fraction greater than 1 mm diameter. Southernmost localities are at the top.

Sample n$^{\underline{o}}$	locality n$^{\underline{o}}$	Esch	Cellar	Cellep	Vinc	Rete	Lun	Mem	Cyc*	Wt %	Cluster		Facies
111	2									1·75	C1	B1	A1
110	2									1·64	C1	B1	
089	3	Mt	▨	*	*				M Mu	8·41	C1	B2	A2
027	4	Mt	▨							37·55	C1	B3	
057	5	Mt	▨	▨						41·38	C1	B3	
129	7	Mt	▨	▨	▨	▨	▨	▨	M	10·12	C1	B3	
126	16	Mt	▨	▨			▨	▨	M	3·31	C1	B2	
072	9									0·01	C1	B2	B
066	14	B E								16·37	C1	B3	
079	20	E *								3·90	C1	B3	
084	30									1·03	C1	B2	
32	26	Mt Me	▨	▨	▨	▨		▨		50·16	C2	B4	C
116	29	MtMeB	▨	▨	▨	▨		▨	M Bg	79·80	C2	B4	
087	31	Mt Me	▨	▨	▨	▨		▨		21·34	C1	B3	
049	36							▨		1·83	C1	B2	
131	32	Me B	▨	▨	▨	▨		▨	M Bg	46·33	C2	B4	
005	38	Me	▨	▨	▨	▨		▨	M Bg	15·43	C2	B4	

Figure 26

P.T.O.

Figure 26

Inferred *in situ* distribution of bryozoan growth-forms. *In situ* occurrence deduced from bulk sample data shown by oblique shading. Asterisks indicate *in situ* occurrences deduced from other observations. Important *in situ* occurrences of certain species denoted by symbols within shaded areas. Mt = *Metrarabdotos monilifera*, B = *Biflustra savartii*, E = *'Eschara' pertusa*, Me = *Melicerita* charlesworthii, M = *Meandropora*, Mu = *Multifascigera* sp nov, Bg = *Blumenbachium globosum*.

Esch	eschariform
Cellar	cellariform
Cellep	celleporiform
Vinc	Vinculariiform
Rete	reteporiform
Lun	lunulitiform
Mem	membraniporiform
Cyc	large cyclostomes
Wt %	total weight of bryozoan skeletal material expressed per 100 g of sediment coarser than 1 mm (0ϕ).
Cluster	see section 10.6
Facies	see section 5.1

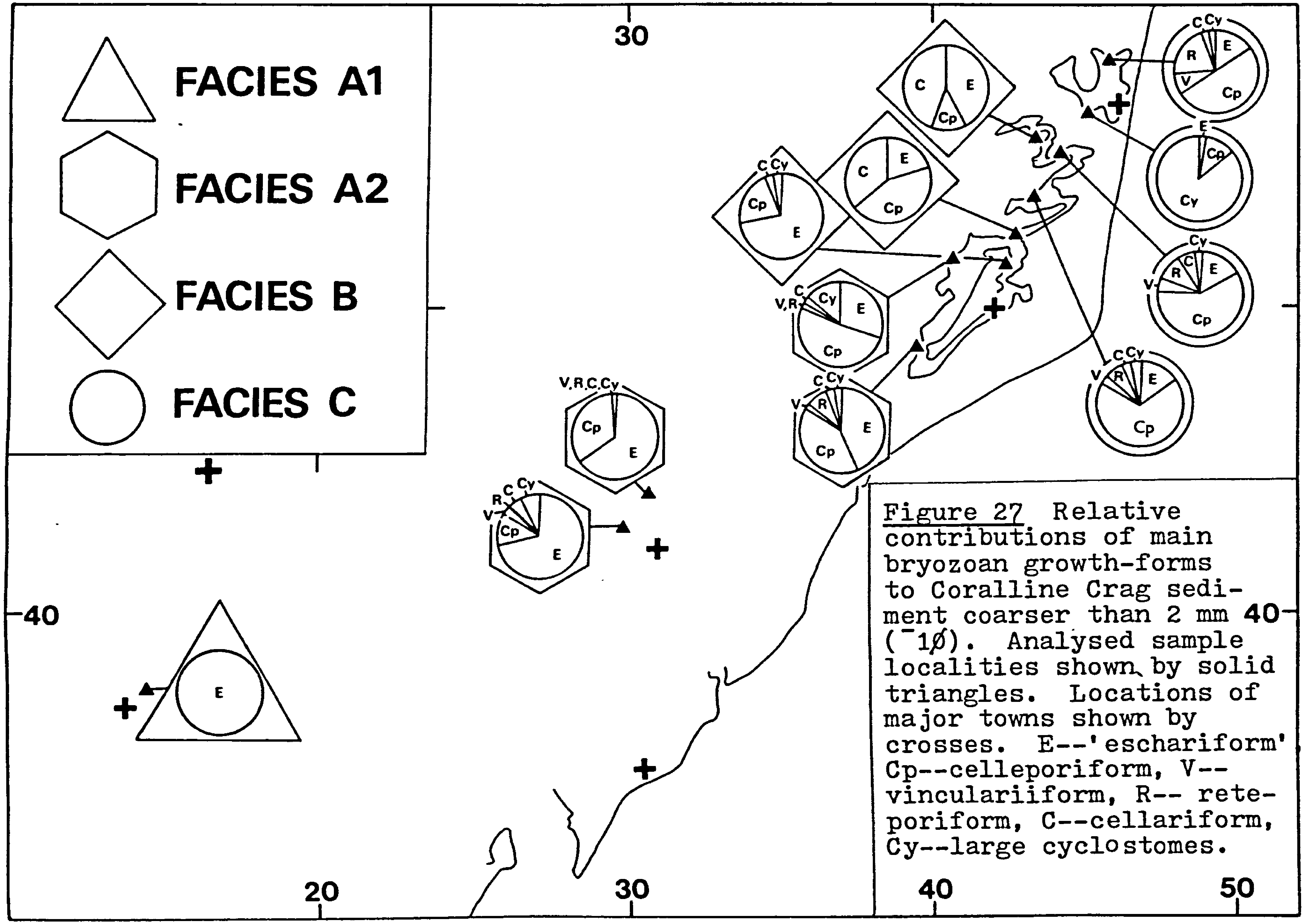


Figure 27 Relative contributions of main bryozoan growth-forms to Coralline Crag sediment coarser than 2 mm 40 (¯10). Analysed sample localities shown by solid triangles. Locations of major towns shown by crosses. E--'eschariform' Cp--celleporiform, V--vinculariiform, R-- reteporiform, C--cellariform, Cy--large cyclostomes.

analysed, this material is extremely abraded and is almost certainly transported. Another disadvantage with the display of percentage data is that a sample which, for instance, yields only one eschariform fragment may be compared with samples yielding many times more material and may therefore have an apparently greater diversity.

When studying fragmented colonies it is not possible to distinguish between fragments of eschariform and adeoniform bryozoans. For this reason the term 'eschariform' is used here to denote any flat,bilaminar colony fragments. *Melicerita charlesworthii* which has a flexible rooted,bilaminar colony is also included in this category.

'Eschariform' Bryozoa

From figures 25 and 27 it can be seen that the eschariform/ adeoniform growth-form is one of the most important contributors to the bryozoan assemblages of the Coralline Crag. Figure 26 shows that inferred *in situ* production of bryozoan colonies with this growth-form occurs mostly in facies A2 and C with a sporadic occurrence in facies B which will be discussed later. The absence of eschariform colonies and in fact of any other demonstrably *in situ* bryozoan, with the exception of some small well preserved membraniporiform types, at locality 36 which is otherwise assignable to facies C, remains unexplained at present. Closer examination of the species distributions within the general distribution of this growth-form has shown that some species are not ubiquitous and may indeed be shown to be facies related.

Nearly all the eschariform/adeoniform fragments were found to be assignable to five species; *Metrarabdotos monilifera*

(Milne Edwards), "Eschara" porosa Milne Edwards, Biflustra savartii (Audouin), "Eschara" pertusa Milne Edwards, and Melicerita charlesworthii Milne Edwards. The relative contributions made by these five species is illustrated by pie graphs on figure 28.

M. monilifera was the only representative of this growth-form type from facies A1. Facies A2 can also be seen to be dominated by this species. Facies B has a more variable content of eschariform bryozoans but in general M. monilifera comprises only around 25% of the total. The balance is made up by locally large proportions of 'E' pertusa,B. savartii or M. charlesworthii. In facies C M. monilifera is again a major component but is here associated with variable but substantial quantities of the other 4 species. These distributions seem well marked and perhaps result from differences in the growth mode or ecological tolerances between the 5 species. The effects of transportation must also be remembered when considering the ecological significance of these distributions. It seems clear that if derivation is due to south westerly directed currents (Chapter 5) then the source of debris at any locality should be expected to be to the north-east of that locality.

Facies A

Facies A1 (locality 2) shows a transported, abraded fauna in which 'eschariform' fragments are all assignable to the species M. monilifera. The localities to the north east of this locality have 'eschariform' bryozoan faunas almost completely composed of this species and may thus be reasonably supposed to represent the source area for the skeletal debris found in facies A1. This conclusion is supported by the

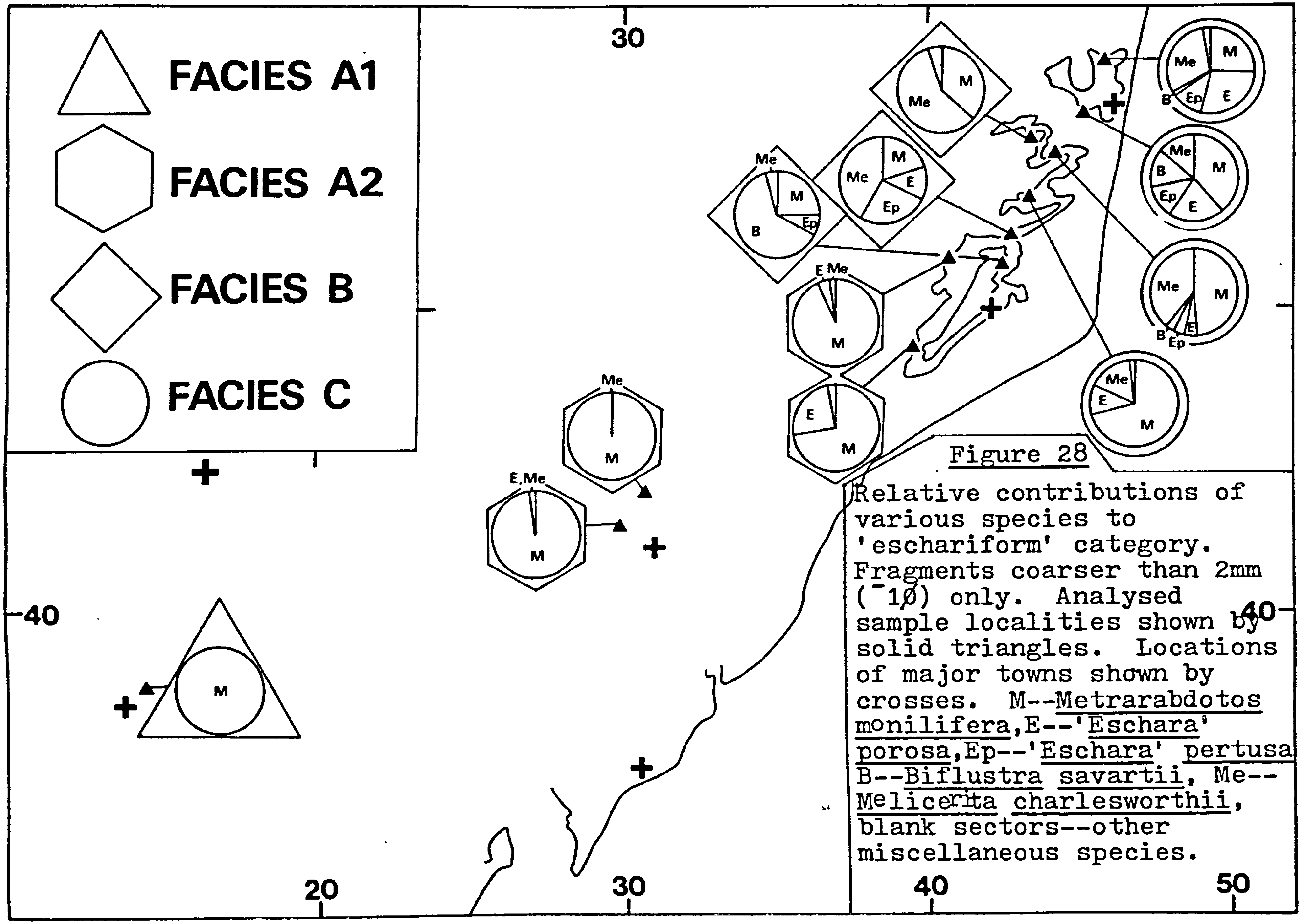


Figure 28

Relative contributions of various species to 'eschariform' category. Fragments coarser than 2mm (¯10) only. Analysed sample localities shown by solid triangles. Locations of major towns shown by crosses. M--Metrarabdotos monilifera, E--'Eschara' porosa, Ep--'Eschara' pertusa B--Biflustra savartii, Me--Melicerita charlesworthii, blank sectors--other miscellaneous species.

distributions observed in other bryozoan growth-forms. The only other species to form a significant proportion of the eschariform fauna in facies A2, is 'E'. porosa which forms just over 25% of the total at locality 7. Perhaps significantly 'E'. porosa has an adeoniform (s.s.) growth-form and thus probably had similar ecological habits to the dominantly adeoniform M. monilifera from this facies.

Facies B

In this facies M. monilifera forms only minor percentages of the 'eschariform' assemblages. Most of the fragments of this species from this facies are abraded and may indeed be derived. In situ eschariform colonies are dominated by the species B. savartii, 'E.'pertusa and M. charlesworthii the latter species becoming more abundant to the north. These species were clearly able to survive in the sandwaves which characterised this facies where strong tidal currents led to substrate instability and the dominance of bedload transport. Large colonies of B. savartii and 'E'. pertusa are often seen on foreset slopes where they have been thought to have acted as 'sediment traps'. Boswell (1928; p.18) observed that "Branching forms of bryozoa acted as a screen to the detritus borne by the currents, but were killed off by the material that accumulated about them". Funnell (1972; p.3) on the other hand believed that "...Bryozoans need a solid substrate on which to grown, and the presence of their remains in cross-bedded deposits.... implies post-mortal transport, and incorporation into hydraulic dunes or sand-waves on the sea floor away from their point of origin".

The statement that 'bryozoans need a hard substrate' is often interpreted as meaning a large immobile substrate but in fact small particulate substrates are often colonised. Most of the colonies of B. savartii and 'E'. pertusa examined showed evidence of breakage and reorientation although the colony surfaces were in general very well preserved.

It seems probable that they have accumulated as fragmented colonies derived from areas adjacent to the foreset slopes. Their derived nature is evidenced by the constancy of their location on the lower parts of the avalanche slopes, which is more likely to be a result of physical accumulation than of a preferred growth position. Nevertheless, they obviously grew within the sandwave field and were able to colonise a particulate substrate. Both of these colonies form eschariform (s.s.) colonies with a small basal attachment. B. savartii is an anascan cheilostome with uncalcified frontal walls; colonies are thus much less robust than ascophorans like M. monilifera or 'E'. porosa. Although growth rates for these bryozoans are not known it is possible that species like B. savartii and 'E'. pertusa, which do not undergo secondary calcification of the earlier-formed parts of the colony, were able to grow relatively rapidly. They were able to grow during periods of substrate stability, perhaps of the order of a few months, when sandwaves were not actively migrating and were subsequently fragmented and buried during renewed periods of strong current activity. Colony destruction and burial may also have resulted from increased bottom current activity during storms.

M. charlesworthii is also common in facies B particularly to the north where this facies is juxtaposed with facies C. Specimens from facies C are less abraded than those of facies B. It is possible that this species inhabited both facies, but transport from facies C south-westward into facies B may also have affected the observed distributions. Melicerita forms colonies of unarticulated bilamellar fronds which are loosely attached to the substrate by intertwining radicles (rootlets) (Powell, 1969). The colony is therefore suited to colonisation of particulate, mobile substrates and is thus similar in many respects to other members of the family cellariidae such as Cellaria. It is also interesting to note that at localities 20 and 30 where Melicerita forms a large percentage of the 'eschariform' content (see fig 28), cellariiform colonies are also very abundant (cf fig 27). Thus, although these bryozoans are anascans with characteristically poorly calcified frontal walls and thus with a less robust colony, the flexibility of the colony allows growth in higher energy regimes than would be otherwise possible without breakage.

Facies C

In facies C fragments of colonies of all 5 species are common in varying percentages (cf distribution of facies A). This facies is interpreted as an area where winnowing of fine-grained sediment maintained a coarse skeletal carbonate substrate with only a small proportion of terrigenous debris. The sediment surface was probably fairly stable with relatively low rates of sedimentation and transportation. This regime was evidently favourable to the growth of colonies of the 5 species discussed above.

Cellariform Bryozoa

In situ or nearly in situ Cellariform colonies have a similar distribution to 'eschariform' colonies. In facies C, cellariform bryozoans reach their greatest abundance. Here, colonies can occasionally be found more or less articulated (Plate 18; C,D). Cellariform colonies are made up of calcareous internodes linked by flexible organic nodes. These organic nodes would be expected to break up soon after death resulting in the disintegration of the colony. For colonies to be preserved with the internodes still juxtaposed must require fairly rapid burial and a lack of strong currents to disaggregate the colony. Articulated colonies have been found at Aldeburgh Hall (locality 32) and Crag Pit Nursery (locality 38) where they are associated with diverse bryozoan faunas including abundant epifaunal membraniporiform colonies indicating relatively reduced rates of sedimentation.

The presence of abundant cellariform colonies has been interpreted as indicating high rates of deposition. (Lagaaij & Gautier 1965). This apparent contradiction can be explained in an environment where deposition may be rapid but sporadic. Thus each type of growth-form may grow during favourable conditions, the membraniporiform types growing during times of reduced deposition and being overwhelmed by periodic rapid influxes of sediment which are less unfavourable to the growth of cellariform colonies. This mixing of growth-form types in a single deposit in an environment subject to periodic changes of conditions, such as a seasonal increases in bedload transport during winter storms, does not seem to have been considered by previous authors.

Celleporiform Bryozoan

Celleporiform colonies are also a major component of the bryozoan fauna of the Coralline Crag (see figures 25 and 27). The colonies are formed by irregular 'heaping' of zooecia to form a generally globular-shaped colony. Unabraded colonies are generally restricted to facies A2 and C in the Coralline Crag. In facies A1 only very rare abraded fragments were found. In facies A2 the large colonies of Turbicellepora coronopus found at Ramsholt Cliff (locality 3) are most notable. These large, irregular branched colonies often acted as a substrate for the coral Cryptangia whose calices are frequently seen embedded in the bryozoan colony (see Chapter 9.5). The coral individuals are usually found embedded on only 1 side of the bryozoan colony and may therefore be an indicator of the life orientation of the colony. It is believed that the bryozoan was orginally firmly attached by an encrusting base to some suitable substrate, probably a shell fragment and grew in an erect branching form. When the colony grew larger it may have toppled by the action of currents or benthic animals and become horizontal, lying on the sediment surface. Here it was able to continue growth growing upwards by means of large branching colony protuberances and in this way may have been able to maintain the colony above the surface of the sediment. Sedimentation rates in this facies are believed to have been relatively high allowing the preservation of large bryozoan colonies and clusters of the barnacle Balanus concavus by burial before being broken down by bioerosion on the sediment surface.

It is, however, in facies C that celleporiform colonies reach their greatest abundance. The colonies in this facies are mostly represented by globular colonies of Turbicellepora cespitosa (? = T. avicularis (Hincks)). Many of these colonies are penetrated by narrow cylindrical moulds presumably of an original organic substrate. Similar cylindrical moulds are frequently seen in colonies of T. avicularis from the present day Scottish shelf. Colonies of Cellepora pumicosa are known to be frequent encrusters of the hydroid Nemertesia antennina (Hughes, 1975; p.292). It is believed that colonies of Turbicellepora and Blumenbachium (see Chapter 11) were frequent encrusters of similar hydroids in the Coralline Crag fauna. Colonies of this type were presumably supported above the sediment surface during growth and were thus able to develop a spherical colony shape.

Many of the celleporid colonies have developed with numerous protuberances. Bryozoan monticules (modified groups of zooids forming local elevations or depressions on the colony surface) have been shown to indicate the presence of extra-zooidal feeding currents in the colony (Banta et al, 1974; Taylor, 1979). These regions represent avenues for excurrent water thus providing an efficient water circulation over the colony surface. Such a mechanism would be most effective in waters of low turbulence and current energy. While it is not suggested that facies C of the Coralline Crag was deposited under sluggish conditions, there is evidence that the current activity was not as great as that which deposited sediments of facies B and A3. Celleporiform colonies are thought to be particularly well suited to conditions of moderate current energy (Schopf, 1969) (See table 19) and therefore it is possible that the 'monticules' observed on these celleporid colonies do not in fact represent points of excurrent water currents and are therefore not comparable to those described by Banta et al (1974) and Taylor (1979).

Celleporiform colonies are also commonly found as encrusting epifauna, particularly in facies C.

Reteporiform Bryozoa

In the Coralline Crag this growth-form is represented by colonies of the cheilostome *Sertella beaniana* and by various species of the cyclostome *Hornera*. Fragments of this growth-form never formed a large proportion of the bryozoan skeletal material, presumed *in situ* colonies were found only from sediments of facies A2 and C with the greatest proportions found in the latter facies (figs 25 and 27). Reteporiform colonies require hard substrates such as large shell fragments. The fenestrate colony form in Palaeozoic fenestellids has been thought to indicate the presence of extrazooidal feeding currents which complemented passive water currents flowing through the colony (Cowen & Rider, 1972). The Crag reteporiform colonies are basically inverted cone-shaped, with the zooid apertures on the interior surface so that by analogy with Cowen and Rider's model inhalant currents would

Growth Type	Substrate			Current (cm/sec)			Rate of Sedimentation ($cm/10^3$ years)			
				20		100	10	100	1000	
	Hard	Flexible	Particulate	Low	Moderate	High	Low	Moderate	High	Very High
Erect, rigid										
Adeoniform	xx			x	xx		xx			
Eschariform	xx		x		xx		xx			
Reteporiform	xx			x	xx		xx			
Vinculariiform	xx			xx			xx			
Erect, flexible										
Cellariform	xx	x	x	x	xx	x	x	x	xx	
Encrusting										
Celleporiform	x	xx			xx	x	xx			
Membraniporiform	xx	x			xx	x	xx			
Free-living										
Lunulitiform			xx		xx	x	x	xx	xx	

x = occasional association

xx = frequent association

Table 19 Estimate of the association of aspects of bryozoan growth with environmental factors.
(after Schopf, 1969)

be inferred to have entered the cone from above and exhalant flow would have been discharged radially outwards. In common with celleporiform colonies described above this mechanism would be of most benefit in environments of reduced current activity. In the case of the Crag reteporiform bryozoans it may be possible that the extrazooidal currents supplemented passive water flow during stages in the tidal cycle when currents were low, becoming unnecessary during periods of increased passive current flow. It is interesting to note that the distribution of abundant reteporiform colonies is closely similar to that of celleporid colonies with monticules described above.

When the composition of the reteporiform assemblages was examined in greater detail an interesting relationship was discovered. Samples from facies A2 contained both cheilostome (Sertella) and cyclostome (Hornera) reteporiform colonies whilst facies C contained almost exclusively cheilostome colonies. It is possible that the distribution of the cyclostome colonies was limited by the siltier substrate presented by facies A2 but the exact causes of the differences in the distribution of these two bryozoan types remains unclear at present.

Vinculariiform Bryozoa

This growth-form similarly forms only small proportions of the bryozoan assemblages of the Coralline Crag. Colonies of this type were found to be most common in facies C forming up to 7.6% by weight of the bryozoan skeletal material >2 mm ($^{-}1\phi$). Colony fragments of various species of the cyclostomes Hornera and Idmonea made up the bulk of the fragments.

Vinculariiform colonies are thought to be typical of environments of low current energy and low rates of sedimentation (Schopf, 1969) (See Table 19).

Lunulitiform Bryozoa

Lunulitiform bryozoans in the Coralline Crag are represented by Lunulites conica Defrance and Cupuladria spp, the latter being by far the more common. The skeleton of Cupuladria and other lunulitiform bryozoans is aragonitic (Rucker and Carver, 1969; p.793) and so information on the occurrence of this genus is limited to those sediments which have not undergone aragonite dissolution. For this reason fragments of this growth-form were not included in the quantitative analyses. The ecology of Cupuladria has been intensively studied in recent years (e.g. Cook, 1963; Lagaaij, 1963). Lagaaij (1963, pp 174-175) lists 5 ecological characteristics of Cupuladria canariensis:

i) The ability to tolerate a certain amount of clay sedimentation owing to the possession of vibracular setae.
ii) The ability to exist on almost any kind of bottom as long as it consists of small particles.
iii) The ability to withstand a wide range of temperatures (eurythermal).
iv) The ability to withstand moderate salinity variations (euryhaline).
v) An insensitivity to hydrostatic pressure, light penetration, and other factors directly connected with depth.

The ideal biotope for lunulitiform Bryozoa is thought to be a small - particle (quartz and/or carbonate sand) bottom (Lagaaij, 1963; p.181) such as would have been present during Coralline Crag deposition. However Lagaaij also made the comment (p.187) that "A type of small - particle bottom from which it [C. canariensis] is excluded.... is one where the sand grains have a tendency to shift under the influence of water movements.... the lunulitiform Bryozoa thus seem to be confined to the stable small particle bottoms below wavebase". Stach (1936; p.63) also noted this limitation, stating "... their free mode of life prohibits their existence in the littoral zone where wave action is strongly felt". Cadée (1975) in a study of lunulitiform Bryozoa from the Guyana shelf found them to be best suited to life in currents of between 20 and 100 cm/sec and areas of low to absent sedimentation rates but this latter conclusion may be due to the lack of suitable substrates in areas where sedimentation is high. Lunulitiform colonies are in fact quite resistant to high sedimentation and can even regain the surface of the substratum after being covered with sand (Cook, 1963). Lagaaij (1963) found the present day distribution of C. canariensis to be restricted to areas (p.189) where temperatures were between 12 and 32°C and where the salinity was between 28 and 37% (p.190).

These ecological conclusions are of particular interest in the case of the Coralline Crag. All the lunulitiform fragments obtained during this study came from localities assigned to facies A2 and all belonged to the genus Cupuladria. Thus if the ecological requirements of the Pliocene Cupuladria were the same as those of the present day then it can be inferred that facies A2 was deposited in depths which were below the effective wave base for at least some of the time and that the minimum water temperatures was 12°C or greater.

There is, however, some controversy over the synonymy of the species within the genus Cupuladria. Cook (1965, personal communication, 1980) is of the opinion that almost all of the Crag Cupuladria assigned to the species canariensis belong in fact to C. biporosa. This need not affect the ecological implications as both species inhabit the same environments at the present time. Cadée (1979), on the other hand, divided C. canariensis into a number of subspecies, the Coralline Crag specimens being assigned to C. canariensis cavernosa.

10.14 Membraniporiform Bryozoa

The abundance of membraniporiform bryozoan colonies was not measured because of the difficulties of quantifying closely adherent colonies which have a very low mass and a variable areal extent over large fragments of shell or pebble. Their distribution within the Coralline Crag is restricted.

At Ramsholt Cliff (locality 3: facies A2) encrusting cheilostomes have been found on the surfaces of phosphorite nodules from the basal phosphorite deposit. However, only a very small minority of nodules showed any encrusting epifauna. Shells at this locality are also generally devoid of encrusting epifauna. The abundance of fine sediment at this locality may have been too great for the development of encrusting epifaunal filter feeders. During the early stages of the transgression, however, when there was no input of silty carbonate sands, the phosphorite nodules represented the only available hard substrate on the sea floor and were therefore colonised. Colonisation of these nodules may have been inhibited however, by their very smooth polished surfaces.

The greatest development of encrusting membraniporiform bryozoans is in facies C. In this facies almost all large shells were found to have been colonised by epifaunal encrusting bryozoans together with occasional other epifauna such as serpulids. The membraniporiform bryozoans include both cheilostome and cyclostome species. The membraniporiform colonies from facies A2 were almost entirely of cheilostome species perhaps indicating a greater tolerance to fine sediment by cheilostomes.

10.15 Summary

1) 8 bryozoan growth-forms are abundant in the Coralline Crag. Assemblages of these growth-forms correlate well with the observed sedimentary facies.

2) Facies C is characterised by a higher ? _in situ_ bryozoan production and more diverse fauna than the other facies. The apparent abundance of bryozoan material in this facies may be due in part to a 'concentration' effect caused by the removal of aragonitic skeletal material from the sediment.

3) The 'eschariform' growth-form forms a large proportion of the bryozoan skeletal material. _In situ_ production is believed to have occurred in facies A2, B and C. The 'eschariform' fauna in facies A2 is composed almost solely of _Metrarabdotos monilifera_. In facies B the 'eschariform' fragments are mostly of '_Eschara_' _pertusa_ or _Biflustra savartii_ while in facies C the total is composed of a greater variety of species. The relatively poor calcification of '_E_'. _pertusa_ and _B_. _savartii_ may

have been an adaptation towards rapid growth to exploit periods of reduced current activity in facies B.

4) Cellariform fragments are most abundant in facies C where occasional articulated colonies have been found.

5) Celleporiform colonies form a major proportion of the Coralline Crag bryozoan skeletal material and may in some cases form the bulk of the preserved sediment. Colonies are most numerous in facies C where they are often globular and penetrated by narrow cylindrical moulds indicating encrustation on some thin organic substrate, possibly hydroids. The presence of monticules on the surface of some colonies may indicate growth under conditions of relatively low turbulence.

6) The reteporiform growth-form is relatively insignificant in the bryozoan faunas. It is represented by the cheilostome <u>Sertella</u> and the cyclostome <u>Hornera</u> which appear to have different distributions in the Coralline Crag.

7) Vinculariiform fragments also form a relatively insignificant proportion of the bryozoan skeletal material. They are most numerous in facies C where they are believed to indicate low current energy and low rates of sedimentation.

8) Lunulitiform colonies of <u>Cupuladria</u> may be a useful palaeoenvironmental indicator in the Coralline Crag indicating sublittoral depths and a minimum temperature of 12°C. Unfortunately due to the aragonitic nature of

the colonies they have been found only in facies A2.

9) Membraniporiform encrusting bryozoans are most abundant in facies C where they are thought to indicate relatively low rates of sedimentation and an absence of large quantities of fine sediment.

Chapter 11 Bryozoan faunas: Large Cyclostome Bryozoa

11.1 Introduction

11.2 Development of colony shape

a) Colonies which had an external basal substrate

b) Colonies which had a thin cylindrical organic substrate

c) Colonies which enveloped an originally external basal substrate

11.3 Substrates

11.4 Distribution of large Cyclostome colonies

11.5 Reorientation in circumrotatory colonies

1) Reorientation by current action

2) Reorientation by mobile benthic animals

11.6 Reorientation of large Coralline Crag Cyclostomes

11.7 Biotic Associates

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Advantages of circumrotatory growth

Chapter 11 Bryozoan faunas: Large Cyclostome Bryozoa

11.1 Introduction

Among the most conspicuous of the bryozoan fossils of the Coralline Crag are the large colonies of four broadly similar cyclostome species; Meandropora aurantium (Milne-Edwards), M. tubipora (Busk), Blumenbachium globosum Koenig [Syn. Alveolaria semiovata Busk], and Multifascigera sp nov. (Balson and Taylor, in prep.). Each of these species has a broadly similar overall colony shape. Colonies are usually spheroidal to oblate spheroidal, less commonly hemispherical to tabular (see fig. 29). The majority have a long axis of between 4 and 8 cm, although colonies of M. aurantium are known to reach 16 cm across (e.g. BMNH 40034). In most colonies, growth evidently radiated from an origin situated close to the centre of an encrusting base. A minority of colonies have their origin situated within the core of the colony where an original substrate of attachment may be partly or totally enveloped (see section 11.2 on development of colony shape). The four species are not evenly distributed within the area of the Coralline Crag outcrop but can be shown to have restricted distributions within particular sedimentary facies (see section 11.4).

11.2 Development of colony shape

Three distinct colony types can be recognised in the large Crag cyclostomes on the basis of their gross morphology and inferred developmental history.

a) Colonies which had an external basal substrate (figure 30,a)

These colonies evidently developed in the conventional

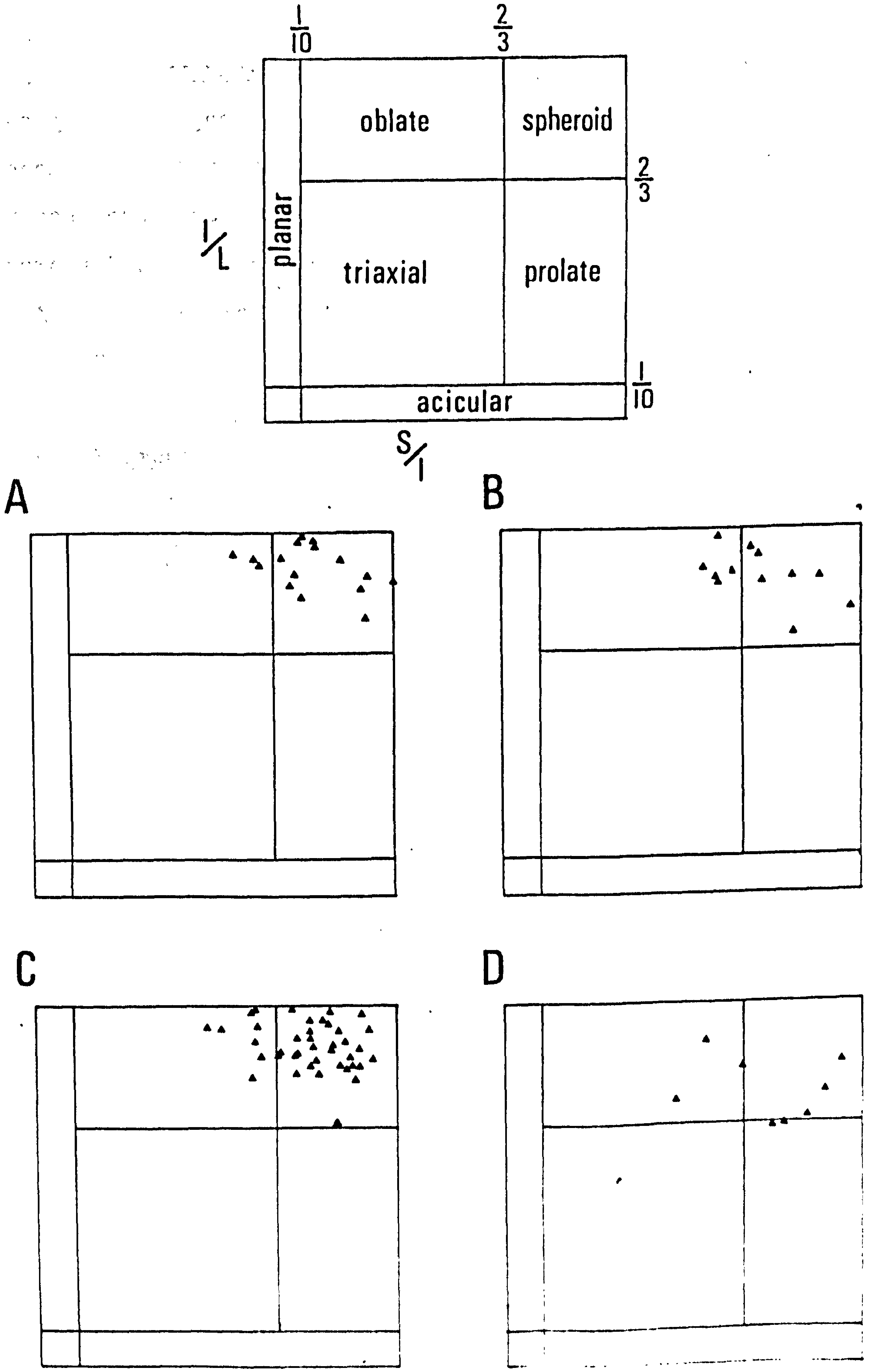

Figure 29

PTO

Figure 29 Zingg plots illustrating shape variation among large cyclostome colonies. The upper diagram shows shape nomenclature determined by plotting axial dimension ratio of three orthogonal axes. (s = short axis, I' = intermediate axis, L = long axis)

- A: *Meandropora aurantium*; 16 colonies from locality 32
- B: *M. tubipora*; 12 colonies from locality 32
- C: *Blumenbachium globosum*; 40 colonies from localities 28 and 32
- D: *Multifascigera* sp.nov. 8 colonies from locality 3

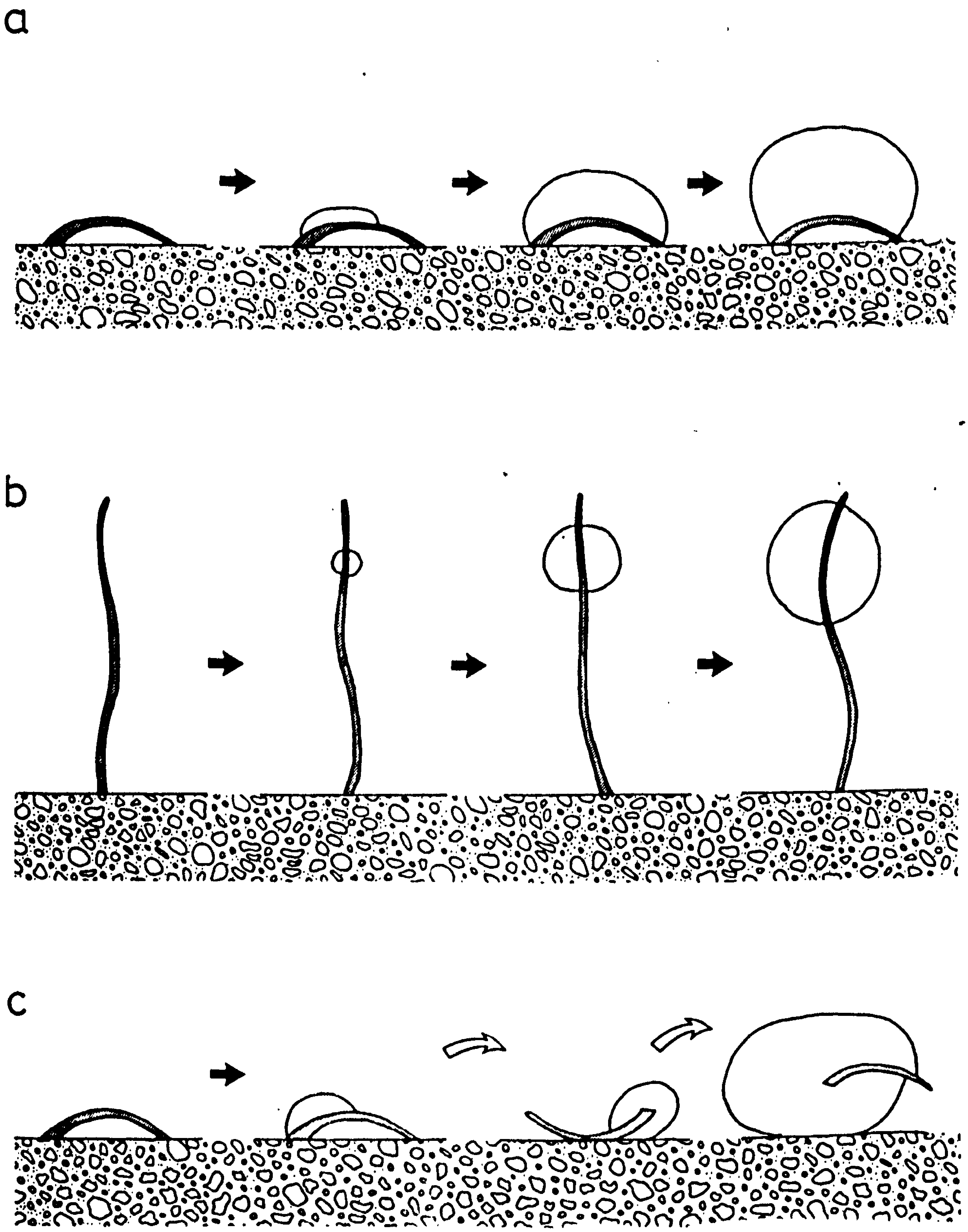

Figure 30 Diagram showing stages in development of colony shape in Coralline Crag large cyclostomes. Developing colony shown in outline, substrate stippled.
a: Colony with an external basal substrate
b: Colony with a thin cylindrical organic substrate
c: Colony enveloping and originally external basal substrate.

manner for a sessile bryozoan. The substrate they encrusted remained comparatively stable on the sediment surface and consequently had a permanent undersurface which was inaccessible to the bryozoan. Colonies did not spread sheet-like over the substrate, as in many other bryozoans, but instead grew in a semi-erect manner to produce a mound-like colony with a moderately high sphericity.

b) <u>Colonies which had a thin cylindrical organic substrate</u> (figure 30,b)

In these colonies the substrate is preserved as a narrow cylindrical mould of some organic, probably flexible, substrate such as a hydroid or an algal thallus. The colony was held above the sediment surface by the substrate allowing bryozoan growth to proceed equally in all directions and resulting in a colony with a very high sphericity. Celleporiform cheilostomes are also commonly found to have grown in this manner in the Coralline Crag.

c) <u>Colonies which enveloped an originally external basal substrate</u> (figure 30,c)

Such colonies partly or totally envelop their original substrate of attachment which was a potentially mobile skeletal fragment lying on the sediment surface. Changes in the orientation of this substrate would have brought different portions of the bryozoan colony into contact with the sediment surface and while these parts undoubtedly ceased to grow, other parts of the colony could have continued growth.

An originally external basal substrate could only become totally enveloped by being overturned allowing bryozoan growth to continue on the upturned surface. Comparable colony forms have been previously described in fossil and living bryozoans (Flor, 1972; Rider and Enrico, 1979). Morphological and developmental comparisons can also be made with algal rhodoliths (Bosellini and Ginsburg, 1971) and certain colonial corals (Kissling, 1973; Glynn, 1974). Kissling (1973) used the term 'circumrotatory' to describe mobile coral colonies which were frequently overturned during development and showed spheroidal growth. The term 'circumrotatory' in the present study is applied only to bryozoan colonies which were physically reorientated during growth and is thus used in a developmental rather than a morphological sense. Conversely, colonies which remained in a constant orientation during growth are here termed 'non-circumrotatory'. This distinction avoids confusion between circumrotatory colonies and those spheroidal colonies whose radial growth is the result of being supported above the sediment surface throughout their development (colony type b above). It seems probable that both types of non-circumrotatory colony may have been dislodged at some time during development and subsequently become circumrotatory. Those growing on erect flexible substrates may simply have become too large to be supported and have fallen onto the sediment surface. Their spheroidal shape would make them very mobile enabling continued holo-peripheral growth.

11.3 Substrates

The nature of the substrate was the major influence on colony type and shape of the large cyclostomes. The size and type of substrate dictated whether or not a colony was mobile and could be reorientated during growth and if so, how frequently.

Where it is possible to determine the original substrate of attachment it is very often found to have been a bivalve shell (Plate 24, A,B,E). These colonies are generally of low sphericity with a point of origin on the convex side of the bivalve shell. Shells orientated with the convex surface uppermost are very stable with respect to currents (Johnson, 1957), thus colonies which encrusted these large, relatively flat substrates are less likely to have developed a circum-rotatory growth-form than those which encrusted small, globose, relatively mobile substrates. Overturning of large shell substrates in the cases of the cheilostome genera Membranipora and Conopeum described by Rider and Enrico (1979) results in a colony form which strongly reflects the original substrate shape, at least in the earlier stages of growth. On the contrary the Crag cyclostomes appear to have retained a globose form at all stages of colony growth. Substrate shape was not found to be reflected in the shape of the colony. Bivalve shells were probably the largest common and comparatively stable substrates available to the large cyclostomes on the surface of the mobile Coralline Crag sediments.

Smaller, more mobile substrates appear less favourable to colony growth. Small substrates include shell fragments, shells of turritellid gastropods (Plate 24, D,F) and various bryozoan fragments (Plate 24, G). Fragments of erect bryozoan colonies are also occasionally found to have acted as substrates (Plate 24, G). These colonies were possibly still erect and in life position at the time of cyclostome settlement but may subsequently have broken off when the cyclostome colony became larger. Perhaps significantly, in the examples studied, the erect bryozoan substrate was seen to protrude from the surface of the cyclostome colony. The cyclostome had, therefore, not entirely enveloped the substrate implying that the substrate may still have been anchored to the sediment surface during the life of the cyclostome. The radial growth shown by these colonies therefore may not be a result of reorientation during life and are thus 'non-circumrotary' by the definition given above (Section11.2) Radial growth in this 'non-circumrotatory' manner also occurs where organic substrates such as hydroids supported the colony above the sediment surface.

11.4 Distribution of large Cyclostome colonies

The large cyclostomes show a distinct distributional pattern which is thought to reflect the distribution of differing sedimentary facies.

Facies A1

No colonies or colony fragments of large cyclostome Bryozoa have been found in this dominantly reworked nearshore facies.

Facies A2

Multifascigera sp. nov. is found only in this facies and is currently known to occur only at Ramsholt Cliff (locality 3) where it is found in association with occasional colonies of Meandropora aurantium and poorly preserved ? M. tubipora. Blumenbachium globosum has not been found in this facies in the present study. This facies is characterised by the absence of well preserved sedimentary structures and the high proportion of terrigenous and fine grained ($< 63 \mu m$) sediment which may be unfavourable to B. globosum. Large cylindrical branching colonies of Heteropora are most common in this facies.

Facies A3

This facies is seen only at Rockhall Wood (localities 4 and 6) where only occasional abraded specimens of M. aurantium have been found.

Facies B

Colony fragments of M. aurantium, M. tubipora and B. globosum have all been found in this facies. The colonies mostly show evidence of breakage and extensive abrasion and it is believed that they were derived, probably from facies C, which is inferred to be in an up-transport direction from facies B. The sandwaves which characterised this facies reflect the dominance of bedload transportation and avalanche slope deposition on foresets which were probably unsuitable areas for colonisation by the large cyclostomes.

Facies C

The large cyclostomes reach their greatest abundance in this facies. B. globosum is particularly numerous and unabraded unbroken colonies (? in situ) appear to be restricted to this facies. The apparent absence of large quantities of fine-grained sediment in this facies may be a significant factor in that bryozoans distribution. In facies A where fine-grained sediment was more abundant the large cyclostomes possibly cleared this sediment from the colony surface by powerful extrazooidal feeding currents (Taylor, 1979) that they may have created during life.

11.5 Reorientation in circumrotatory colonies

Circumrotatory growth clearly necessitated reorientation of the colony and its substrate. Several factors are known to be responsible for mobility in fossil and Recent corals (Gill and Coates, 1977) but only passive rotation by current action or mobile benthic animals are thought to have been factors in the reorientation of the large cyclostomes of the Coralline Crag.

1) Reorientation by current action

Kissling (1973) in a study of the coral Siderastrea radians believed that current action was responsible for the production of circumrotatory colonies. The coral was found to have a rigidly cemented hemispheroidal to flattened colony form where firm substrates were available. Where colonies lived on particulate substrates they were found to be circumrotatory almost without exception. The colonies ranged from near perfect spheres to prolate ellipsoids with a diameter of between 2 and 12 cm (cf Crag Cyclostomes; figure 29). These circumrotatory colonies were found to be most abundant at depths of about 0.8 m where surf action was greatest and therefore Kissling believed that current action was responsible for overturning the colonies. Overturning in such colonies was thought to be effected as often as weekly in the winter and once or twice monthly in summer, comparable to some algal rhodoliths (Bosellini and Ginsburg, 1971: cited in Gill and Coates, 1977). Rider and Enrico (1979) have described circumrotatory growth in colonies of Conopeum and Membranipora flabellata. These bryozoans form sheet-like laminae over substrates like molluscan shells which develop to form multilaminar 'ectoproctaliths' where the original substrate is enveloped by the bryozoan colony. They believed that current action was primarily responsible for reorientation of the bryozoan substrate. They also described [p.315] a mechanism whereby growth of the colony may begin to envelop parts of the shell substrate without overturning the colony. Back and forth water movements at wave base were thought to have produced sediment excavations on alternate sides of the colony allowing it to tilt towards the side of greater sediment excavation. This mechanism may have played a part in the formation of some of the large Cyclostome colonies.

2) Reorientation by mobile benthic animals

Glynn (1974) applied the term 'corallith' to circumrotatory coral colonies living on coarse bioclastic sand substrates from the Gulf of Panama. He came to the conclusion that circumrotatory colonies of Pavona gigantea, P. clivosa P. varians, Agariciella planulata and Porites panamensis were overturned during life by the actions of sympatric benthic organisms. The evidence which supported his conclusion was:-

a) The absence of wave or current formed sedimentary structures where circumrotatory colonies were most numerous.

b) The relatively deep occurrence of the communities studied.

c) The apparent random distribution of circumrotatory colonies in some populations.

d) The presence of fish tooth scars on circumrotatory colonies.

e) The frequent disturbance of surrounding sediments by infaunal, epibenthic and especially transient browsing fish populations.

Predation damage has not been observed on the colonies of the Coralline Crag cyclostomes but points a., c and e are in common with the observations of the present study.

11.6 Reorientation.of large Coralline Crag Cyclostomes

A number of observed facts seem important in consideration of the nature of the mechanism by which the circumrotatory colonies of the Coralline Crag large cyclostomes were overturned.

1) The occurrence of a circumrotatory growth form in the large cyclostomes is rare. The proportion of colonies which totally enclose their substrate is very small although up to 30% of colonies may show some degree of substrate envelopment. Some of these evidently

formed around an erect substrate which held the colony above the sediment surface and are therefore not circumrotatory. Others may have been able to envelop part of their substrate due to the effects of scouring and tilting as postulated by Rider and Enrico (1979, p.315).

2) If currents are held to be responsible for overturning colonies the occurrence of circumrotatory growth should be related to colony and substrate size and thus to hydrodynamic stability. In the Coralline Crag large colonies with large substrates may show circumrotatory growth whereas small colonies with small substrates may show non-circumrotatory growth. No examples have been found where the colony was initially circumrotatory but then became a non-circumrotatory form as it became larger and more stable. This is contrary to the situation found by Glynn (1974) in Pavona. Glynn (1974, p.192) also found that Psammocora colonies, which lived sympatrically with mobile coral colonies, were not moved during periods in which much larger mobile corals were reorientated despite the fact that they were much more readily moved by current action.

3) The Coralline Crag cyclostomes lack the symmetry of internal structure and sphericity of external form which characterises probable current overturned circumrotatory cheilostome bryozoans (H.M. Pedley pers. comm. 1980). This may be in part due to differences in the type of colony growth between cyclostomes and laminar cheilostomes.

4) The large cyclostomes seem to be absent from the higher energy sandwave facies indicating a preference for the less turbulent conditions and greater substrate stability in facies A and C.

5) The large cyclostomes are most abundant in sediments which were clearly disturbed by infaunal and epibenthic burrowing animals.

6) Some colonies have a large basal cavity (Section 11.7) which may have been excavated by benthic organisms.

The features listed above imply that overturning by currents may not have been an important factor in the development of circumrotatory growth in the Crag cyclostomes. It seems likely that the activities of benthic organisms were more important in reorientating the bryozoan colonies.

11.7 Biotic associates

A conspicuous feature of several of the colonies found was the presence of a large cavity where the earliest-formed parts of the colony and its substrate have been removed (cf Glynn, 1974). These cavities truncate skeletal walls and may have a narrow entrance which broadens into a large chamber (Plate 24, H,I). Comparable cavities in living celleporid bryozoans from the North Sea are the domiciles of crabs (P.J. Hayward pers. comm. 1978). Kissling (1973, p. 55) attributed similar cavities in colonial corals to the actions of mantis shrimps or clinid fishes. Glynn (1974, p. 185) mentioned coral colonies which had "undergone extensive internal erosion, producing large, centrally located cavities ".

It seems possible that microborers (eg algae) and macroborers (eg polychaetes) may have formed an initial cavity or weakening which was then enlarged by a crab, quite possibly while the bryozoan was still alive. It may be significant that other objects large enough to provide shelters for crabs etc are rare in the Coralline Crag.

The Crag large cyclostomes sometimes acted as substrates for a variety of encrusting animals including membraniporiform cheilostomes and serpulid worms. Examples of subsequent overgrowth of these encrusters by the host cyclostome, prove their life association. Serpulids, for example, are often found partly or wholly immersed within colonies of Blumenbachium globosum. The serpulid colonised the surface of the bryozoan but was covered when a new generation of overarching subcolonies formed. The encrusting epifauna may have settled and become established during periods (?seasonal) of colony dormancy.

11.8 Summary

Evidence from the pattern of occurrence of large cyclostome colonies within distinct sedimentary facies, the frequency of a circumrotatory relative to non-circumrotatory growth-forms, the inferred hydrodynamic stability of colonies and the association with fossils and traces of mobile infaunal and epibenthic animals are thought to imply that the reorientation of colonies was due to the activities of sympatric benthic animals rather than to the action of currents. It may be significant that objects large enough to provide shelters for crabs etc were probably rare on the Coralline Crag sea floor. Thus colonies may have been overturned or even just tilted by mobile animals such as crabs or fish which were searching for food or shelter, irrespective of whether the cyclostome colony was hydrodynamically stable or not.

Advantages of circumrotatory growth

Although circumrotatory growth in the Coralline Crag large Cyclostomes is a rare occurrence certain analogies can be drawn with similar growth in other bryozoan and coral species. Most colonies of this type are found in facies where the substrate was a coarse bioclastic sediment as in the case of the Coralline Crag cyclostomes. Glynn (1974) pointed out that coarse bioclastic sediments provide support, ie the colony does not sink into the sediment, and at the same time allows circulation around the undersurface of the colony which is in contact with the sediment surface. On such particulate sediment surfaces colonies may be initiated on small substrates such as mollusc shell fragments or some other piece of skeletal debris. The circumrotatory growth-form may simply be a response to the chance overturning of these small substrates. Gill and Coates (1977) believed that mobility allows corals to prosper on soft substrates or under high rates of sedimentation where sedentary forms are likely to be overturned or buried.

Chapter 12 Palaeoecology and Sedimentary history of the Coralline Crag

12.1 Coralline Crag facies
12.2 Geographical distribution of Coralline Crag facies
12.3 The London Clay surface
12.4 Vertical distribution of Coralline Crag facies
12.5 Depositional history of the Coralline Crag
12.6 Depth of the Coralline Crag Sea
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12.8 Post-depositional history of the Coralline Crag
12.9 Summary

Chapter 12 Palaeoecology and Sedimentary history of the Coralline Crag

12.1 Coralline Crag Facies

From study of the sedimentary structures, sedimentary petrology and granulometry and macrofossil faunas, the Coralline Crag can be divided into a number of distinct environmental facies.

a) Facies A1

This facies is exhibited only in the outcrop in the Tattingstone Valley which represents the most south-westerly exposure of the Coralline Crag. The sediments and fauna are described in detail in Chapter 7 but in general this facies at locality 2 is characterised by:

a) A lack of recognisable physical sedimentary structures.

b) A very high terrigenous sediment content (acid insolubles between 17 and 57% of the sediment).

c) A fine sediment ($< {}^{+}4\phi$) content between 3 and 7% (possibly higher due to errors introduced by sampling technique: see Chapter 7).

d) Mean grain-size of the terrigenous sediment fraction of between ${}^{+}1.96\phi$ and ${}^{+}2.45\phi$.

e) Values of $\phi\sigma_1$ of between 0.77 to 0.98 for the terrigenous sediment fraction Mean = 0.87 (moderately sorted)

f) A general lack of <u>in situ</u> fauna. Skeletal fragments of molluscs and bryozoans are generally comminuted and abraded.

This facies probably represents a sublittoral deposit formed close to the palaeo-shoreline. The large quantity of terrigenous material was derived from the breakup of preexisting deposits which may have been the contemporaneous sediments of the 'boxstones'. The absence of sedimentary structures may be due to extensive reworking by oscillatory bottom currents due to wave action in the nearshore zone which also restricted the development of a benthic fauna.

b) Facies A2

This facies can be seen in exposures at Ramsholt (locality 3), Rockhall Wood (locality 5 and the lowermost part of the exposures at localities 4 and 6), Gedgrave (localities 7, 8) and Sudbourne (locality 16). This facies is characterised by:

a) A lack of recognisable sedimentary structures probably as a result of extensive bioturbation.

b) High terrigenous sediment content (acid insolubles between 15 and 40% by weight).

c) Very high content of silt/clay-sized sediment constituting between 19 and 35% of the sediment by weight.

d) Mean grain-size of between $^{+}1.90\phi$ and $^{+}2.34\phi$; average = $^{+}2.12\phi$.

e) Values of $\phi\sigma_i$ of between 0.60 and 0.97 for the terrigenous sediment fraction. Mean = 0.83 (moderately sorted).

f) Well preserved, abundant *in situ* macrofauna. Many fossils are apparently restricted to this facies eg *Multifascigera* sp nov, *Balanus concavus*, *Pyrgomina anglica* and *Cryptangia woodii* (see Chapter 9) some bivalves eg *Glycymeris* are found *in situ* with both valves articulated.

This facies represents a more offshore area than facies A1 with a fully marine fauna including bryozoans, echinoderms and corals. The high fine sediment content is probably due to derivation from facies lying in an upcurrent direction.

c) Facies A3

This facies is seen overlying Facies A2 with an erosional basal contact at Rockhall Wood (localities 4 and 6). Its relationship with facies B is unknown but it differs from that facies in many respects. Only 1 sample from this facies was examined in detail.

a) Small-scale trough cross-stratification with frequent silt drapes on the foresets.

b) A high terrigenous content of approximately 26% acid insolubles by weight.

c) A silt/clay content of about 4%.

d) Mean grain-size of $^{+}1.70\phi$ for the terrigenous sediment fraction.

e) A value of $\phi\sigma_1$ of 0.62 (moderately sorted).

f) The fauna of this facies appears to have been derived from facies A2 below. Large broken fragments of the bryozoan *Metrarabdotos monilifera* are very abundant in this facies.

This facies reflects the deepening water during the Coralline Crag transgression. It has some features in common with facies B but differs from that facies in having apparently derived most of the included skeletal debris from facies A which it overlies unconformably.

d) Facies B

This facies is well exposed at numerous localities

(localities 9, 11,12,13,14,18,19,20,21,22,23,24,25,27, and 30). It is characterised by:

a) Large-scale cross-stratification.

b) A variable terrigenous content increasing from around 15% acid insolubles by weight at the northernmost locality to around 35% at the southernmost locality.

c) Silt/clay content of between 3 and 8%.

d) Mean grain-size (ϕMz) of between $^{+}1.35\phi$ and $^{+}2.06\phi$ for the terrigenous sediment fraction.

e) Values of $\phi\sigma_i$ of between 0.32 and 0.58. Mean = 0.43 (well sorted).

f) A low diversity of demonstrably *in situ* fauna. The fauna probably included the bryozoans '*Eschara*' *pertusa* and *Biflustra savartii* (see Chapter 10).

This sandwave facies probably represents an offshore sandbank formed under the action of relatively strong currents and may be comparable to modern sandbanks such as those off the coast of Norfolk.

e) *Facies C*

This facies is best seen around the town of Aldeburgh but stretches southward along the eastern margin of the Coralline Crag surface outcrop.

a) Horizontal and low angle stratification.

b) A low content of terrigenous sediment (acid insolubles between 6 and 23%, Mean = 12.8%).

c) A fine sediment ($< {}^{+}4\phi$) content of between 3 and 8%.

d) Mean grain-size of the terrigenous sediment fraction of between $^{+}1.57\phi$ and $^{+}2.05\phi$.

e) Values of $\phi\sigma_i$ of between 0.30 and 0.76 for the

Facies	Sedimentary structures	ϕMz*	$\phi\sigma_i$ *	% acid* insolubles	% silt/clay*	Fauna
A1	None recognisable Destroyed by ?wave action/ ?bioturbation	2.09	1.00	40.1	3.6	Low diversity in situ fauna skeletal material mostly transported, comminuted and abraded. No in situ bryozoans.
A2	None recognisable Destroyed by ?wave action/ ?bioturbation	2.12	0.83	24.3	24.1	Diverse in situ fauna mostly suspension feeders. Epifaunal bryozoans occasionally present.
A3	Small-scale trough cross-stratification with frequent silt drapes	1.70	0.62	25.8	3.7	Low diversity ?in situ fauna. Skeletal material mostly broken and transported. Broken colonies of Metrarabdotos monilifera very abundant.
B	Large-scale tabular or trough cross-stratification. No silt drapes	1.81	0.43	22.8	5.04	Low diversity ?in situ fauna. Skeletal material mostly transported, comminuted and abraded. In situ bryozoans dominated by 'Eschara' pertusa and Biflustra savartii
C	Variable horizontal or gently dipping stratification. Abundant burrows. Frequent silt drapes.	1.84	0.51	12.8	4.97	Diverse in situ fauna mostly suspension feeders. Rich epifauna of encrusting bryozoans. Large globose cyclostome colonies common.

*mean values

Table 20 Summary of characteristic features of Coralline Crag Facies terrigenous sediment fraction. Mean = 0.51 (moderately sorted).

f) Well preserved, abundant in situ macrofauna. Bryozoans are the major sediment contributor and include abundant colonies of Meandropora and Blumenbachium. Diverse encrusting epifauna on large bivalve shells and frequent evidence of contemporary bioerosion by Cliona.

This facies was probably to the seaward side of facies B. There is less evidence of the action of strong current activity. This facies was characterised by a winnowed but stable bioclastic sediment which was colonised by a diverse benthic fauna.

12.2 Geographical distribution of Coralline Crag facies

The geographical distribution of the facies described above is shown in figure 31. It will be noticed that the majority of the area of the main outcrop (cf. figure 2) is covered by deposits of facies B. Facies A (A1, A2, A3) lies to the southwest of facies B while facies C is located to the northeast of facies B in the area around Aldeburgh. Facies A1 is found only around Tattingstone. Facies A2 is unconformably overlain by A3 at Rockhall Wood (localities 4 and 6) whilst at Gedgrave (locality 7) this facies is unconformably overlain by facies B. The nature of the relationship between facies B and C is not known at present.

12.3 The London Clay surface

The Coralline Crag is assumed to rest everywhere on an erosional London Clay surface. As yet there is no evidence from boreholes that any other bed, apart from the basal phosphorite deposit, is present between these two formations.

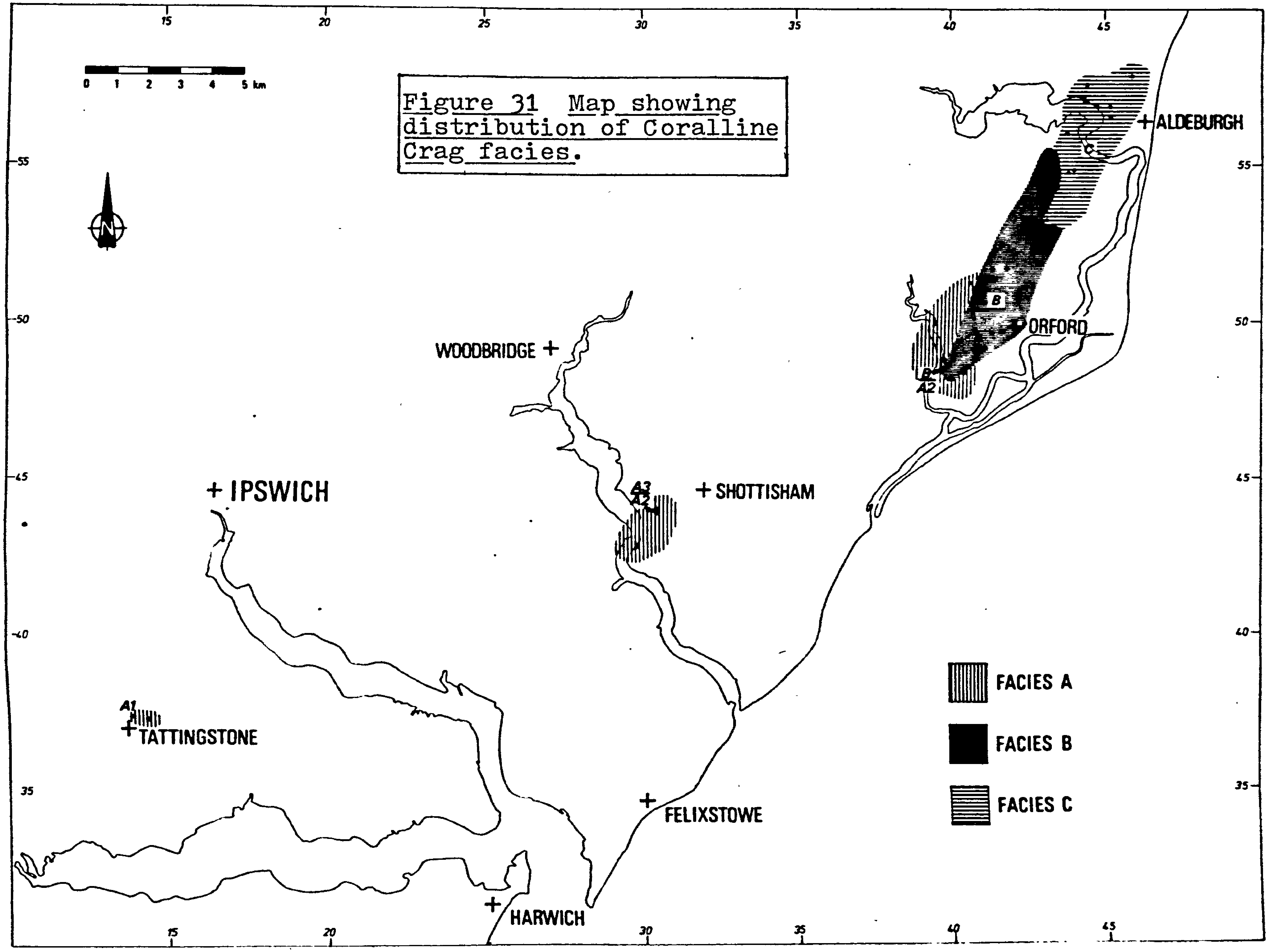


Figure 31 Map showing distribution of Coralline Crag facies.

The Miocene 'Trimley Formation' is presumed to have been winnowed away before Coralline Crag deposition leaving only the lithified 'boxstones' as evidence of its former existence. Study of the London Clay surface morphology is therefore important in consideration of the surface over which the Coralline Crag sea transgressed and of the shape of the Coralline Crag basin.

Harmer (1898) was the first to examine the London Clay surface beneath the Coralline Crag. He made a number of borings around the south west extremity of the main outcrop of the Coralline Crag and came to the conclusion that the London Clay surface dipped gently away to the north (see figure 32). Harmer's study was limited as the maximum depth to which he was able to bore was 31 feet (9.4 m) (Harmer 1898; p. 333). Had he been able to bore deeper he may have discovered that the London Clay surface rose again a few kilometres to the north.

Since the time of Harmer the morphology of the London Clay surface in the study area has been examined in greater detail (Woodland, 1946., Carr, 1967., Allender and Hollyer, 1972, 1973., and Hollyer, 1974). From the data given by these authors Dixon (1979) compiled a map of the London Clay surface for much of the area to the east of Ipswich. His map with amendments taken from Carr (1967), Carr and Baker (1968) and Carr (1971) is shown in figure 33. A more simplified metricated, version of this map is shown in figure 34. A vertical section along the Coralline Crag outcrop is shown in figure 35. It is clear that there is a general depression in the height of the London Clay surface in a north-easterly direction. It

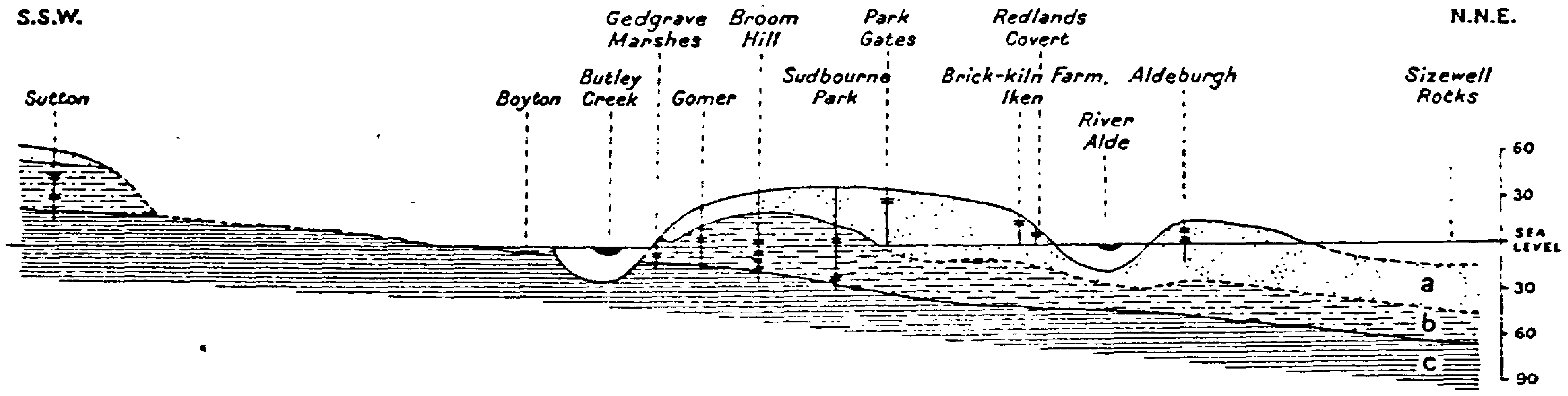


Figure 32 Section showing Coralline Crag on London Clay between Sutton (Rockhall Wood) and Sizewell Rocks. a = "Ferruginous rock" b = shelly sand C = London Clay (after Harmer, 1898)

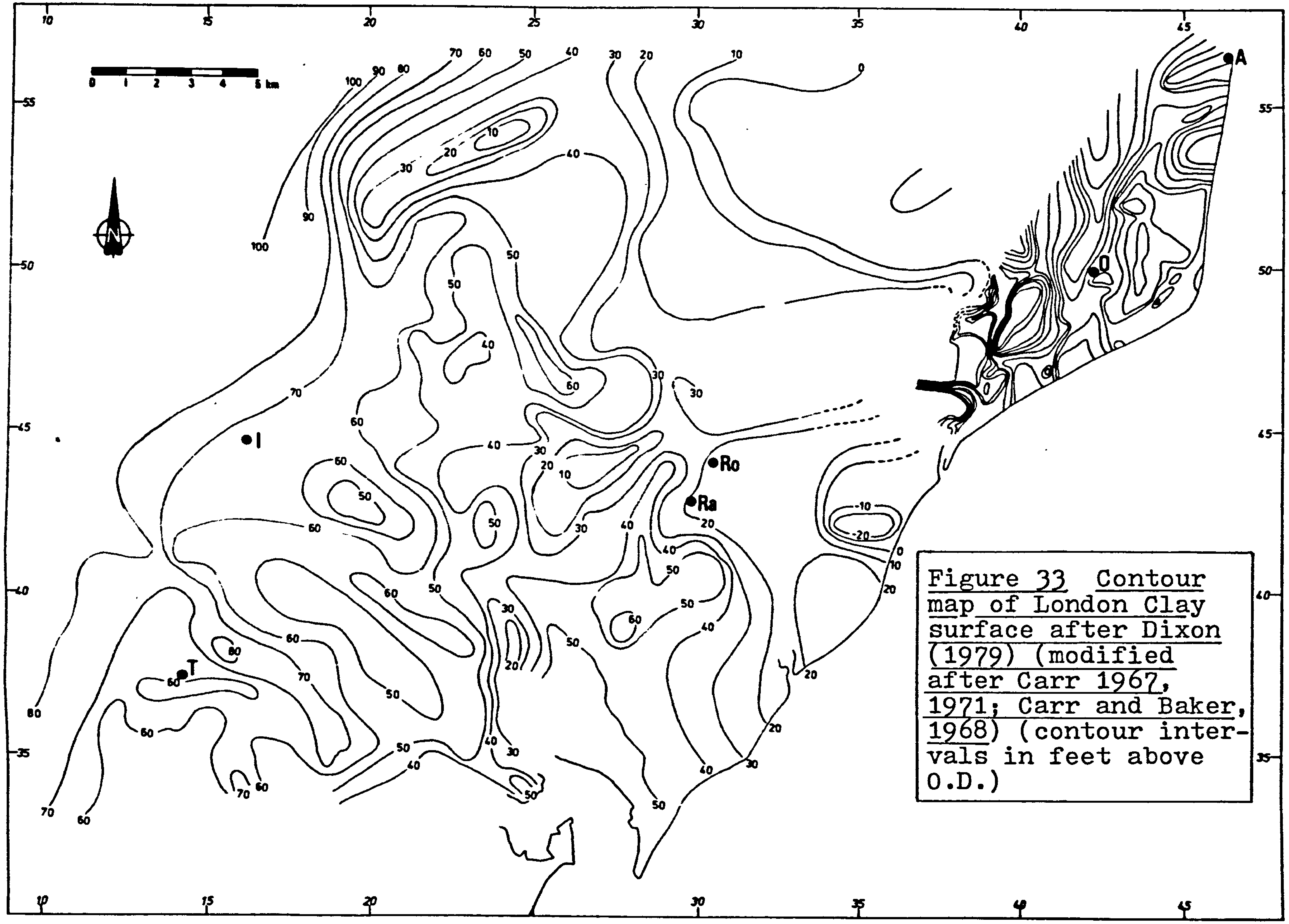


Figure 33 Contour map of London Clay surface after Dixon (1979) (modified after Carr 1967, 1971; Carr and Baker, 1968) (contour intervals in feet above O.D.)

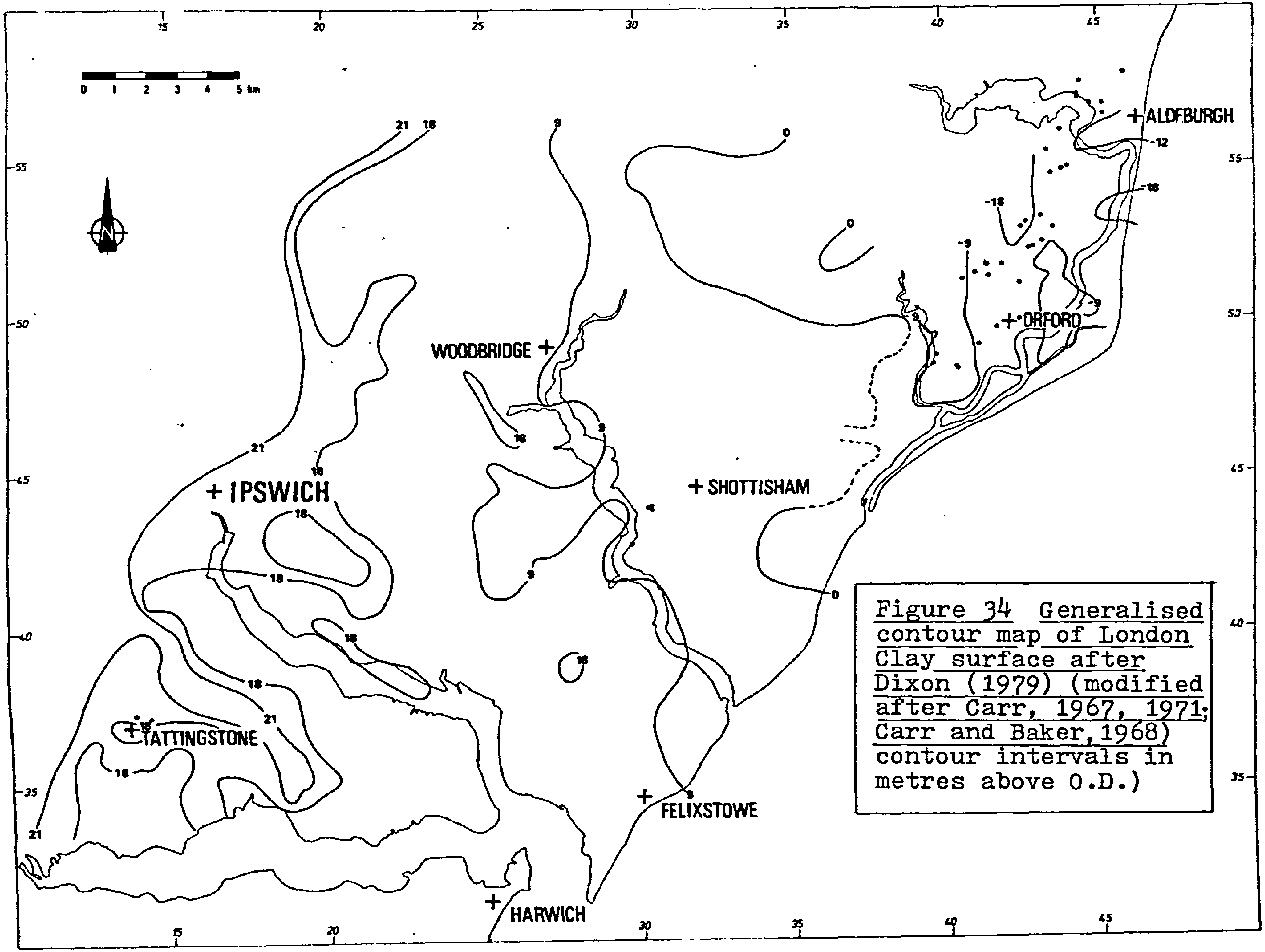


Figure 34 Generalised contour map of London Clay surface after Dixon (1979) (modified after Carr, 1967, 1971; Carr and Baker, 1968) contour intervals in metres above O.D.)

Figure 35 Vertical section through Coralline Crag outcrop. (Coralline Crag in black) Length of section illustrated is approximately 40 km.

must, however, be remembered in attempting to reconstruct the original Pliocene basin topography that the London Clay surface may have been extensively altered in its morphology by erosion in post-Pliocene times (Carr, 1967). Only that part of the London Clay surface which directly underlies the surface outcrop outline of the Coralline Crag can be said to be pre-Pliocene with any degree of certainty. Despite this limitation it is still possible to ascertain that the London Clay surface over which the Coralline Crag sea transgressed was characterised by the presence of numerous ridges and troughs on a surface which had a general dip towards the north and north-east. Possible post-Pliocene tectonic movements may also have affected this dip (see Chapter 14).

12.4 Vertical distribution of Coralline Crag facies

From section 12.2 it is clear that the Coralline Crag facies have distinct geographical distributions in terms of present day surface exposures. In order to more accurately assess the horizontal and vertical relationships of the individual exposures and thus eliminate the effects on distribution caused by present day topography each locality was accurately levelled and the height of elevation above Ordnance Datum determined. This data could then be used in conjunction with data for the topography of the London Clay surface to draw vertical sections through the Coralline Crag outcrop. One such section is shown in figure 36 with the line of section indicated in figure 37.

12.5 Depositional history of the Coralline Crag

Combining this model of horizontal and vertical facies distributions with data from sedimentary structures and

Figure 36 Horizontal and vertical distribution of measured Coralline Crag sections. Line of section is indicated in figure 37. Inferred facies relationship is shown.

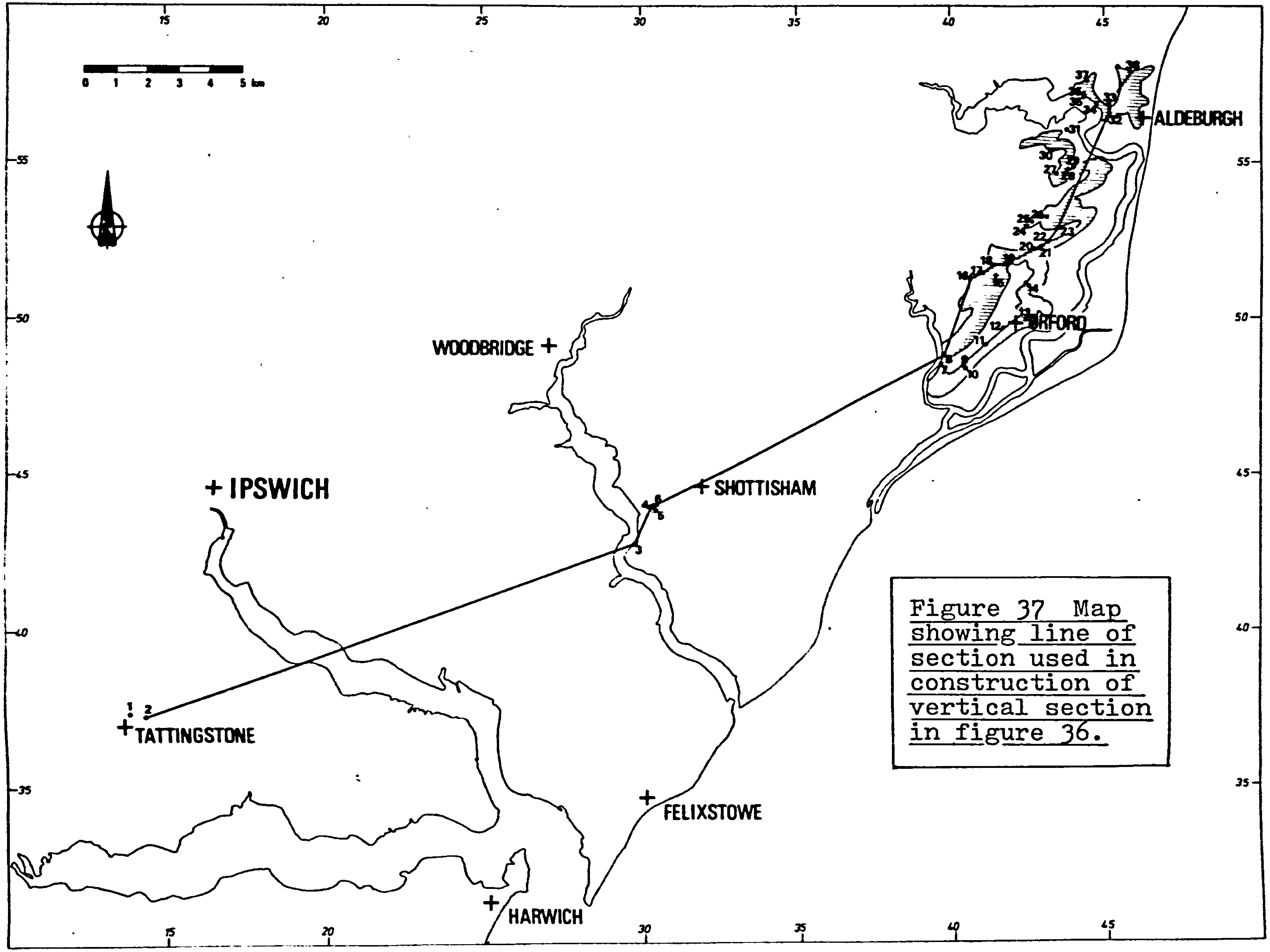


Figure 37 Map showing line of section used in construction of vertical section in figure 36.

faunal distributions it is possible to reconstruct environmental conditions during the deposition of the Coralline Crag.

From the study of cross-stratification (Chapter 5) and the distribution of bryozoan faunas (Chapter 10) it is clear that much of the Coralline Crag was deposited under conditons of strong currents with a net flow direction to the southwest. These currents were due to a strong tidal flow probably parallel to the palaeo-coastline. Although tidal currents are bidirectional, rectilinear or rotary they develop essentially unidirectional sediment transport paths due to:

a) The inequality of maximum strength and duration of tidal flood and ebb velocities.

b) The tendency for ebb and flood currents to follow mutually exclusive transport paths.

c) The lag effect associated with a rotating tide which delays the entrainment of sediment.

d) The tendency for a single tidal current direction to be enhanced by other currents such as wind-driven currents (Johnson, 1978).

Anderton (1976) has described the sequence of facies along a typical tidal transport path. In this model a zone of erosion with winnowed pebble lags and broad, shallow channels gives way downcurrent to large and then small sandwaves, continuous flat bedded and rippled sand, sand patches in mud and finally to continuous mud. The downcurrent decrease in sandwave height within the sandwave zone has also been described from the North Sea by Stride (1970).

This model (Anderton, 1976; Figure 18) seems to correspond quite well with the observed lateral distribution of Coralline

Crag facies. Thus facies C, a winnowed bioclastic deposit lies upcurrent of facies B, interpreted as being deposited by a zone of sandwaves, which in turn lies upcurrent of a much siltier facies (facies A2). Large sandwaves (facies B) may also be seen to lie upcurrent of smaller sandwaves or megaripples (facies A3).

Material from facies C was probably entrained and transported southwestward along a sediment transport path and the finer material eventually deposited in facies A2. This transport may also have been responsible for the relatively increased abundance of barnacle plates in the southwestern localities (particularly at Tattingstone, locality 2). Barnacle plates are particularly robust and thus could withstand prolonged transportation with subsequent concentration into sediments at the end of the transport path.

In studies of modern shelf sediments the facies observed are forming contemporaneously in different areas of the shelf. In the study of fossil deposits any model of deposition will have to take into account the movement horizontally and ultimately vertically of these facies.

Nio (1976) in a study of some European fossil sandwave complexes recognised a vertical sequence of facies which were characteristic of transgressive sandwave complexes. The stages involved in the formation of this sequence were:

1) Flooding of the land area drowning existing river valley and/or depressions of the existing topography with the predominance of estuarine and tidal flat sedimentation.
2) Within the esturaries and depressions smaller sandwaves (initial sandwave facies) can be formed.

3) With a protracted transgression sandwaves of larger dimensions can be formed. Current direction variations are restricted to a narrow spread within the sandwave facies.

4) In the advanced stage of the transgression confined flow conditions decrease and migration of sandwaves occurs only during periods of enhanced current activity eg during storms.

5) With further deepening of the basin lower energy conditions cause sedimentation on the slopes and troughs (slope facies) to be dominant.

6) During the maximum stage of the transgression flattening of the existing topography occurs and no further up-building of the sandwave can occur.

These six stages would be expected at a single point with the passage of time. The facies would be expected to migrate landwards and thus overstep facies earlier in the time sequence. Certain aspects of Nio's model can be seen in the sequence of Coralline Crag facies. For example, the silty inshore facies (facies A2) is overlain unconformably by small sandwaves (facies A3) which presumably developed in deeper waters. However, the incomplete nature of the Coralline Crag outcrop and the complexity introduced by contemporaneous erosion surfaces make direct comparisons with Nio's model difficult.

Nio believed sandwave formation to be a characteristic phase of marine transgressions but their occurrence is limited vertically and horizontally within the transgressive sequence. The sandwaves of the Coralline Crag, as evidenced by large-scale cross-stratification also show a restricted distribution.

The observed distribution may of course have been substantially affected by post-Pliocene erosion. Coralline Crag sediments with large-scale cross-stratification may formerly have been much more widely distributed than the present day elongate facies outcrop pattern would suggest.

It is, however, believed (see section 12.8) that the present day distribution of cross-stratified sediments approximates to the original depositional zone of the sandwave complex.

From the observed facies distributions it is possible to propose at least two alternative models for deposition of the Coralline Crag.

Model A

Sandwave field (facies B) migrating shoreward with increasing water depth. Facies A forming earlier in transgression (pre-sandwave) and lying inshore of facies B. Facies C forming later in transgression (post-sandwave) from degeneration of sandwave complex and lying offshore and in deeper water where currents were less strong.

A vertical section through such a sequence is shown in figure 38. This model would explain such important features as:

a) the source of the finely comminuted and abraded carbonate debris in facies C which is in association with large well-preserved, unabraded skeletal material, the abraded bioclastic sand having been derived from the degradation of the sandwave field when water depths became too great and currents too weak for active upbuilding of sandwaves.

b) The concentration of phosphorite nodules below facies C at Red House Farm Reservoir (locality 28) which could

Figure 38 Vertical section through hypothetical reconstruction of Coralline Crag deposits Facies nomenclature after Nio (1976). Black arrows indicate current direction.

be explained in terms of an internal erosion surface due to winnowing of sediments of the sandwave complex.

Model B

An alternative model is envisaged with a linear offshore sandbank (facies B) lying parallel to the coastline during Coralline Crag times. The sandbank was an area of raised topography on the seafloor thus causing tidal currents to rapidly increase over the crest of the sandbank. Facies C would have been on the offshore side of this sandbank in deeper water and therefore in an area of weaker currents. This model differs from Model A then, in that the differences between the facies are more a consequence of the seabed topography at a single time than of changing water depth with time. However, even with this model a landwards migration of facies would be expected with the offshore facies tending to overstep more nearshore facies.

The presence of a linear sandbank in the Coralline Crag sea appears to be supported by the following observations.

a) The linear shape of the outcrop of the sandwave facies (see discussion in section 12.8).

b) The narrow spread of direction of foreset dips parallel to the direction of elongation of the outcrop.

c) Possible swing of sandwave migration direction towards crest of sandbank at some localities (see figure 8) as noted by Caston and Stride (1970) for sand transport on modern sandbanks off the Norfolk coast.

A comparison with modern sandbanks was also suggested by Harmer (1910; p 93) who believed that the Coralline Crag had been deposited as submarine shell banks "under the influence of tidal currents from the south-west (sic)....in a sea of moderate depth, probably at no great distance from the then existing shore and parallel to it".

12.6 Depth of the Coralline Crag Sea

Many estimates have been made of the depth of the sea under which the Coralline Crag was deposited. These estimates have ranged from less than 10 m (Van Voorthuysen, 1954) to over 300 m (Prestwich, 1871a). Precise estimation of palaeo-water depths for any geological formation is not usually possible. Benthonic organisms are usually substrate specific and are found over wide ranges of depth. Similarly sedimentary structures may be found to occur in various water depths and are more dependant on local conditions of currents and sediment type than bathymetry. The effects and extent of transportation of skeletal fragments must also be considered when attempting to infer palaeoecological conditions from an allochthonous fauna. Nevertheless, when the total evidence from both organisms, sedimentary structures and facies is considered a rough estimate of water depth can be attempted.

a) Evidence from organisms

Prestwich (1871a ;p 135) on the basis of the presence of certain so-called deep water molluscs and the bryozoans Idmonea and Retepora proposed that part of the Coralline Crag at least had been deposited in deep water, in places as great as 1000 feet (305 m). Harmer (1910; p 93) disputed this and wrote "Neither the fauna of the Coralline Crag nor the sediment composing it give any indication of deep-sea conditions...." He gave a water depth of 15-50 fathoms (27-91 m) (Harmer 1898, p 244) and pointed out that a transgression of the magnitude suggested by Prestwich would have inundated the greater part of Eastern England. Certainly there is no evidence of such an extensive transgression during Pliocene times. Reid (1890; p 39) gave a depth of deposition of 40-60 fathoms (73-110 m) stating that a lesser depth would have encouraged "....a larger proportion of littoral and plant-eating species". As has been already stated (Chapter 9) evidence of the existence of plants in the Coralline Crag is scanty and inconclusive although other factors than depth, such as water turbidity may be important in limiting their distribution. Wilkinson (1980) on the basis of the ostracod fauna thought the Coralline Crag Sea was much shallower and gave a maximum depth of 20 m.

Depth is of course only one of a complex series of interrelated factors which may limit the distribution of an organism. Temperature and salinity become increasingly important in shallow waters. McAlester and Rhoads (1967) pointed out that stenothermal forms of bivalve tend to live in deeper waters where temperature fluctuations are less. Euryhaline or brackish stenohaline forms tend to occur in relatively shallow, near-shore waters. They also observed that deep vertical burrowing types of bivalve are characteristic of very shallow subtidal sediments, whereas near-surface horizontal burrowing predominates in deep water, subtidal sediments. The most important deep burrowers are <u>Dosinia</u>, <u>Lutraria</u>, <u>Cumingia</u>, <u>Macoma</u>, <u>Solen</u>, <u>Ensis</u>, <u>Mya</u>, <u>Barnea</u>, <u>Thracia</u> and most <u>Lucinidae</u>.

In the Coralline Crag the molluscs tend to be of the shallow burrowing type such as Venus, Glycymeris, Cardita or epifaunal like Chlamys, Pecten, Anomia and Ostrea. The deep burrowing forms listed above are not common in the Coralline Crag but some are very common in the Red Crag. The Coralline Crag is characterised by the abundant bryozoans and occasional corals which are intolerant of temperature and salinity fluctuations. The presence of the bryozoan Cupuladria canariensis in the Coralline Crag would appear to indicate that deposition was not in the littoral zone. Stach (1936; p 63) wrote, 'their free mode of life prohibits their existence in the littoral zone where wave action is strongly felt'. Lagaaij (1963; p 187) was able to conclude that 'the lunulitiform Bryozoa thus seem to be confined to the stable small-particle bottoms below wave base'.

In general therefore it can be said that the Coralline Crag fauna does not indicate deposition in the very shallow near-shore zone. Conversely there is no evidence of very great water depths. Evidence of boring algae is abundant in shell material in the Coralline Crag (see Chapter 8) indicative of water depths of less than 50 metres (Bathurst, 1967). Therefore evidence from the Coralline Crag fauna would indicate deposition in water depths of probably at least 10 metres and less than 50 metres. It should be remembered however that different facies of the Coralline Crag may have been deposited under different water depths.

b. Evidence from sedimentary structures

As already discussed (Chapter 5) sedimentary structures such as cross-stratification may only serve to indicate a minimum water depth and thicknesses of cross-sets should not be used as an absolute indicator of depth of deposition. Using the formula of Allen (1968b) a minimum depth of 4.5 metres is indicated for deposition in facies A3 and a minimum depth of 16 metres for facies B although water depths may have been substantially greater.

McCave (1971) has described how water depth may be a limiting factor on the formation of sandwaves on the sea-bed. He concluded that high wave effectiveness in the nearshore zone prevented sandwave formation and was responsible for the shoreward maximum extent of sandwaves off the Belgian/Dutch coast of 18 m water depth. McCave added, however, that "These conclusions apply only to the nearshore zone and not to the crests of sandbanks which are frequently shallower than 18 m and yet are often capped by megaripples and small sand waves. Current strength and intensity of sand transport is very high at bank crests, and the balance between wave and current action is different from that in the nearshore zone".

The presence of large quantities of fine sediment in facies A2 could be thought of as indicating deposition in depths below effective wave base. However McCave (1971) wrote "The simple existence of a zone of high wave activity does not inhibit deposition of mud when concentrations are high. Mud may be deposited in regions of both fairly strong tidal currents (surface velocity 1.5 knots) and high wave activity at the bed".

From the evidence given above it is unlikely that sedimentary structures in themselves can provide an accurate estimate of water depth in the Coralline Crag sea.

12.7 Temperature of the Coralline Crag Sea

Estimates of the temperature of the Coralline Crag sea arise mainly from study of the fauna and especially from certain stenothermal species. As early as 1842 Wood noted the composition of the fauna was "approximating that of the coast of Portugal". Most subsequent studies concurred with this view. Harmer (1910; p93) wrote of the Coralline Crag: "The molluscan fauna of this stage gives no indication of any climatal changes, pointing throughout to warmer.... conditions than now obtain, such as those of the Mediterranean or the Azores". Many comparisons were made between the Coralline Crag molluscan fauna and that of the Mediterranean e.g. Prestwich (1871a), Wood (1874), Harmer, (1896, 1898,1902) (see Chapter 9.7) These comparisons were based on percentages of living species only found in more southern regions than the British Isles at the present time. The characteristic genera of this 'southern' fauna included the molluscs Panopea, Pholadomya, Chama, Hinnites, Erycinella, Scintilla, Nucinella, Sigaretus, Pyramidella(?) Fossarus(?) Cancellaria, Cassidaria, Terebra, Pyrula and Voluta, and the brachiopod Lingula (Wood 1874; p196).

General conclusions on the temperature regime can be drawn from the overall composition of the carbonate secreting fauna. In general, aragonite secreting organisms are more common in warmer waters (Lowenstam,1954). In cold waters, such as those of Alaska, the carbonate sands are nearly all calcitic in composition except for some molluscs and rare corals (Hoskin & Nelson, 1969). In the Coralline Crag a substantial proportion of the carbonate skeletal material is aragonitic indicating warmer waters than those of present day Alaska. Lees and Buller (1972) believed the composition of the carbonate secreting faunas were characteristic of the temperature regime. Thus, temperate waters were characterised by the association of Molluscs, benthonic Foraminifera, echinoderms, bryozoans, barnacles, ostracods, calcareous spicule bearing sponges, tube secreting worms, ahermatypic corals and calcareous red algae. Warm waters (minimum 14-15°C mean 23°C) were characterised by hermatypic corals, calcareous green algae while bryozoans formed only a minor component and barnacles were never significant contributors to the fauna. With the exception of calcareous red algae and calcareous spicule bearing sponges, the "temperate water association of Lees and Buller would appear to be the same as that of the Coralline Crag.

More specific conclusions on the temperature of the Coralline Crag sea can be deduced from present day distributions of stenothermal species. One such species is the bryozoan Cupuladria canariensis which is fairly common in the Coralline Crag. This species is only found in waters between 12 and 32°C at the present time. Its distribution appears to be limited by the 14°C surface isocryme (Lagaaij, 1963; p189). Lagaaij believed thatthis isocryme would have followed the line of the present day 5°C surface isocryme into the area of the North Sea (figure 44). This would have allowed for a migration route for this species from the Atlantic around the north of Scotland and into the southern North Sea Pliocene deposits without the necessity for a direct seaway from the North Sea to the English Channel to the south (see chapter 14).

Thus, if C. canariensis had a similar temperature tolerance during the Pliocene as at the present time winter surface water temperature would have been 14°C or greater.

The bryozoan Metrarabdotos was used by Cheetham (1967) as a warm water indicator. M. monilifera is very abundant in the Coralline Crag (see Chapter 11). Cheetham gave the observation that where they occur, fossil and Recent species of Metrarabdotos are the dominant bryozoans in both size and abundance of colonies as evidence that the generic niche was very narrow. M. tenue, which has comparable erect arborescent colonies to M. monilifera and is believed to have occupied the same niche, is limited by the 20°C surface isocryme at the present time. Cheetham concluded (p.106) "The northern limit of the geographic distribution of Metrarabdotos has probably been the northern boundary of the tropical marine climatic zone throughout late Palaeogene and Neogene time". The minimum surface water temperature for the Coralline Crag would thus appear to be rather higher than that suggested by Lagaaij (1963).

Strauch (1968) used a more empirical approach to determine palaeo-water temperatures. Hiatella arctica is an exceptionally eurythermal and very long lived mussel species which grows to a larger size in cooler waters. Strauch used observed variation of shell size in Recent specimens of H. arctica under different conditions of temperature to interpret water temperatures from fossil specimens. Specimens from the Coralline Crag yielded an annual range of temperatures from 13.5°C-24°C although he admitted that "the summer figure seems a little high". It will be noted that the lower figure corresponds very well with the minimum of 14°C implied by the presence of Cupuladria canariensis (Lagaaij, 1963). A value of 14°C also corresponds to the minimum surface water temperature off southern Portugal (Sverdrup et al 1942) and would therefore confirm the conclusions of Wood (1842) derived from the molluscan faunas. The Mediterranean has a similar minimum surface water temperature but has a higher maximum of approximately 26°C compared with 20°C off southern Portugal. The greater range of temperature is related to the relatively shallow, restricted circulation in the Mediterranean.

It would appear therefore that the Coralline Crag was deposited in warm temperate waters probably with an annual minimum surface water temperature of about 14°C and a summer maximum of about 20°C comparable with present day conditions off the south of Portugal.

12.8 Post-depositional history of the Coralline Crag

In the period of regression which followed deposition of the Coralline Crag, the sediments were probably exposed to the action of meteoric waters (see Chapter 8). The coarser, silt-free sediments of facies A3, B and C had a greater porosity and were therefore more susceptible to the percolation of slightly acid meteoric waters than the siltier sediments of facies A2. The result of this free percolation was the leaching of metastable aragonite grains from the sediment and redeposition of the carbonate as cement on calcitic grains. This cementation clearly predated the deposition of the overlying Red Crag as lithified blocks and boulders of Coralline Crag are occasionally found in the more recent deposit. The result of this lithification is that cemented Coralline Crag sediments have a much greater surface outcrop area than uncemented sediments. Where uncemented sediments are found they are often overlain by cemented sediments which have served to protect them from erosion.

It is believed that much of the Coralline Crag deposits have been removed by later, but pre-Red Crag, erosion but that mostly uncemented sediments were removed. Therefore the present day surface outcrop of cemented sediments ie facies A3, B and C probably closely represent their original maximum geographic extent. The elongate shape of the outcrop of facies B could therefore be reasonably supposed to have been an original feature of that facies. This would support a linear sandbank interpretation for this facies.

Another interesting feature of facies B is its relatively greater elevation than adjacent facies. Thus, facies B forms a topographic ridge running from Gedgrave in the south to Iken in the north. Adjacent sediments of facies C, although also cemented and presumably resistant to erosion, are seen to be topographically lower. The topographic elevation of the sandwave facies could also be original and would also support a sandbank interpretation.

A similar interpretation was applied by Gullentops (1957) in consideration of the orgin of some elongate hills in Hageland, south east of Antwerp, Belgium. The hills are between roughly 1 and 5 km long, although some are much longer, and owe their existence to elongate outcrops of Diestien sandstone. The length of the hills compares with a length of 8 km for the Coralline Crag ridge between Gedgrave (locality 7) and Iken (locality 30). Gullentops drew an analogy between the Diestien outcrop and modern offshore banks off the coast of Belgium.

In the case of the Coralline Crag, Harmer (1910; p 93) drew attention to the possible link between the outcrop shape and the shape of modern offshore sandbanks.

12.9 Summary

While much palaeoenvironmental evidence is either lacking or open to alternative interpretations a sequence of deposition for the Coralline Crag can be proposed.

a) Transgression commencing across undulose, erosional London Clay surface (figure 39, A) with some erosion of London Clay and reworking of residual deposits (the Crag phosphorite deposit) and possible winnowing of a Miocene sand deposit (The 'Trimley Formation').

b) Initial lag gravel provides substrate for some bryozoan encrusters.

c) Further transgression results in formation of islands and low promontories (figure 39, B) which may have sheltered the marine inlets and allowed fine-grained carbonate derived from further offshore to be deposited. High carbonate sediments in such a nearshore environment would require minimal terrigenous input from the land and/or very rapid carbonate deposition. The fact that the terrigenous sediment content decreases up the carbonate sequence seems to imply that input was effected during the early stages of the transgression possibly from contemporaneous reworking and that input from rivers was minimal.

d) With further deepening of water tidal currents flowing

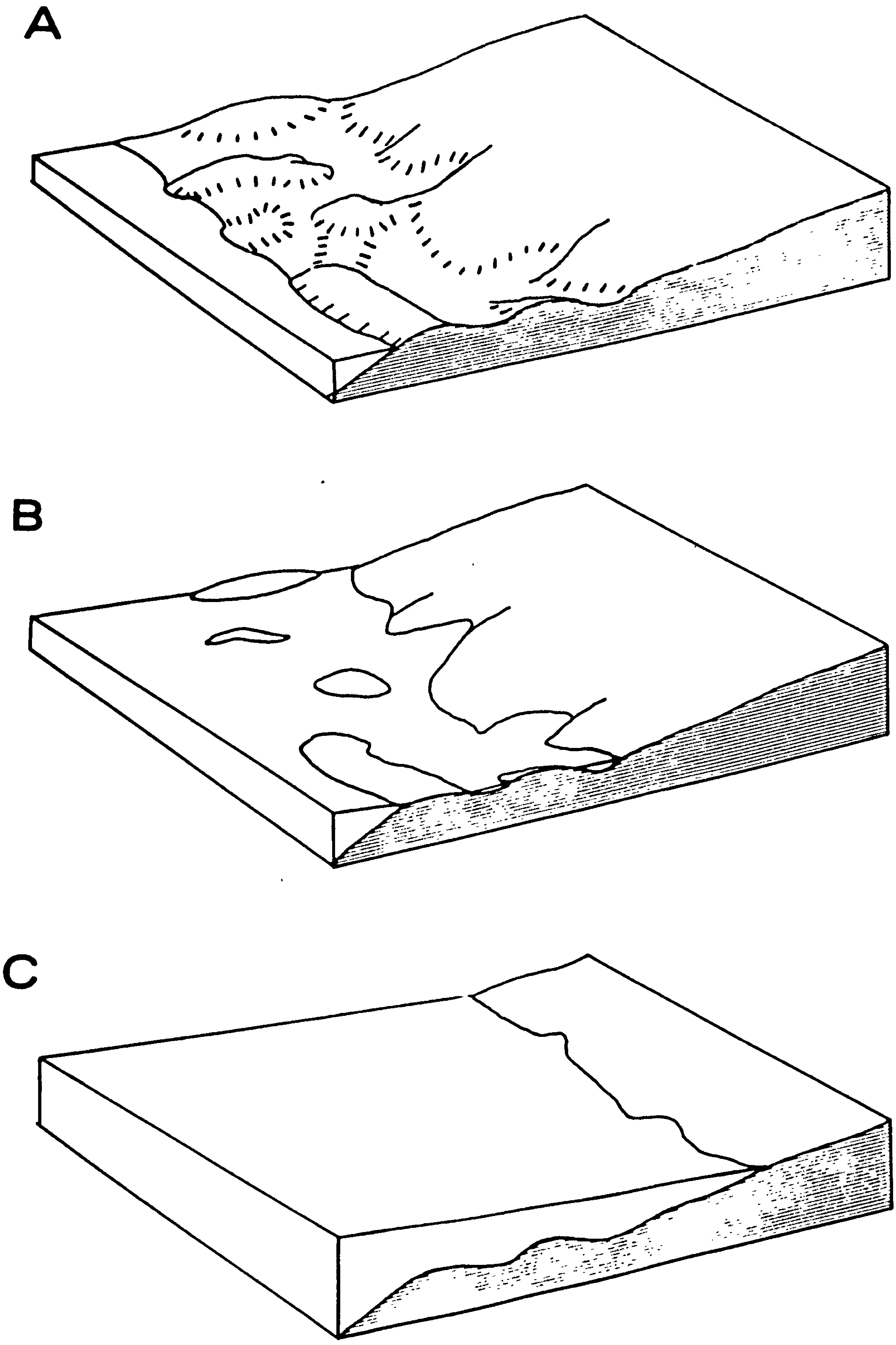


Figure 39 Three stages in the inundation of the eroded London Clay topography by the Coralline Crag sea showing changes of coastline morphology.

across earlier deposited sediment resulted in the formation of small sandwaves.

e) With time and increase in water depth the zone of sandwaves migrated landwards and began upbuilding in the form of an offshore linear sandbank. Restricted water flow over the crest of the bank led to increased current velocities, increased sandwave height and more rapid transport of sediment.

f) At the maximum extent of transgression this sandbank lay parallel to the shoreline with siltier carbonate sediments lying on the landward side and winnowed carbonate sediments on the seaward side. Carbonate skeletal material was transported from the offshore zone, along the sandbank and was eventually deposited in an abraded and comminuted condition in the nearshore zone. Each area had its own in situ fauna which was primarily dependant on the nature and stability of the sediment. The currents, which flowed dominantly to the south west, were probably tidal but may have been reinforced by wave generated currents particularly during storms. At the maximum extent of transgression the shore of the Coralline Crag sea was probably along the line of rapid increase in slope caused locally by the outcrop of the Chalk (figure 39, C) and was therefore just inland of the Coralline Crag outcrop at Tattingstone.

g) During a period of regression the Coralline Crag sediments were exposed to the action of subaerial diagenesis which preferentially cemented the porous cross-stratified sediments of the sandwave facies and the coarse winnowed sediments of facies C. The siltier sediments were not cemented and were mostly subsequently eroded possibly during the transgression of the Red Crag as many Coralline Crag fossils are known to have been derived into the later formation (Wood, 1859).

Chapter 13

Correlation of Miocene and Pliocene deposits of the Southern North Sea Basin

Chapter 13

Correlation of Miocene and Pliocene deposits of the Southern North Sea Basin

13.1 Introduction

"The confusion....is not so much a question of synchronism but the difficulty to understand the exact stratigraphical meaning of the local names used in the countries around the North Sea" (Van Voorthuysen, 1957). This point, stressed by Van Voorthuysen, has been the key factor in stratigraphical correlation within the Neogene deposits of the North Sea basin. Work in this area has a long history stretching back to the early part of the 19th century. Stratigraphical correlations were often made between deposits of widely differing ages and the problem has been exacerbated by the different usages of terms by different authors (see below).

This chapter deals specifically with the correlation of the Miocene and Pliocene deposits of the East of England i.e. the Lenham Beds, the 'Trimley Formation' and the Coralline Crag, with deposits in the Netherlands and Belgium. These deposits are fairly close in geographical terms and represent parts of a single sedimentary basin. Correlations with deposits from different sedimentary basins, however, is fraught with difficulties. Such correlations are primarily made on the basis of floras or faunas which even at the present time can be seen to vary widely according to regional or even local climatic conditions. Without a complete understanding of the regional variations of climate during the Neogene and the distributions of land and sea, with their effects on water currents and climate, correlations between geographically remote localities are liable to serve no great purpose. The subdivisions of these Neogene Formations are temporally short and thus do not encompass any global faunal changes which could be used as markers. Radiometric dating of such recent deposits is subject to wide fluctuations such that the error within a single radiometric age date will be greater than the length of the whole period which is to be subdivided (see Funnell, 1964).

For these reasons this study will be mostly confined to correlations between the Miocene and Pliocene formations of the Southern North Sea Basin. Even within this single basin of deposition dramatic variations in facies type and fauna have existed contemporaneously in different areas. Correlations made by authors between the Coralline Crag and the Mediterranean type sections of Pliocene and Pleistocene will, however, also be mentioned.

13.2 Correlation of the Trimley Formation ('boxstones')

Preservation of most of the molluscs as moulds within the 'boxstones' makes identification difficult. Most identified species have long stratigraphic ranges and broad ecological tolerances. The vertebrate remains are usually abraded and their identification is often indeterminate. These problems are compounded by the historical confusion of stratigraphical nomenclature already mentioned. The problems are increased by the lack of recent corroborative evidence of faunas and facies types from localities and sections which are no longer accessible.

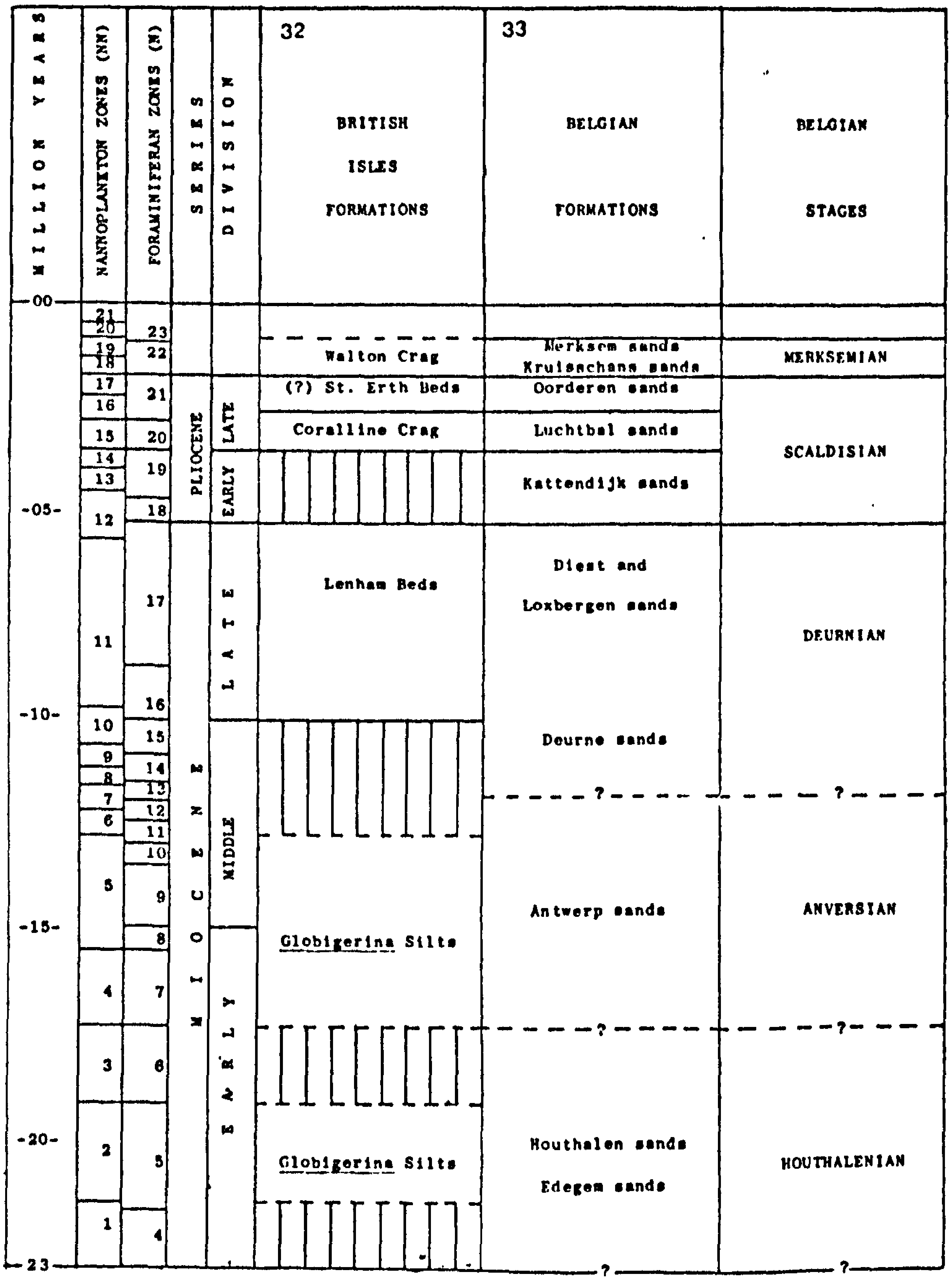
Most correlations have been made with the Neogene sequence in Belgium. The stratigraphy of the Belgian Neogene has been summarised by de Heinzelin and Glibert (1957) (see Figure 40) Tavernier and de Heinzelin (1961) and Curry et al (1978) (see Figure 41).

One of the first accounts which attempted to correlate the 'boxstone' fauna with deposits of the continent was by Lyell (1852) who described the "Antwerp Crag" Formation around Antwerp, Belgium. He subdivided this Formation into a Lower Crag or Crag noir, a Middle Crag or Crag gris and an Upper Crag or Yellow Crag (see Figure 42). He also described (p.282) "....an argillaceous sand with numerous ball-like concretions of clay-stone in which were casts of large Bivalves, chiefly of Pectunculus (P. variabilis?), and others... each of which had served as the nucleus of a nodule", from a locality near Berchem, south of Antwerp. Fish vertebrae, shark teeth and many unabraded cetacean bones were also found in this deposit. He attributed the sands seen in this section to the Antwerp Crag with no qualification and regarded the cetaceans as "truly characteristic of the Antwerp Crag". He concluded that the source for the cetacean remains found in the Crag phosphorite deposit was of Antwerp Crag age although he admitted that local facies variations might affect correlation of the various Antwerp Crag beds.

Since that time the deposits which Lyell grouped as "Antwerp Crag" have been shown to be rather heterogeneous in age (see figure 42). In a table (p.279) Lyell (1852) placed the "Antwerp Crag" in the Scaldesian [= Scaldisien] system overlying the Sands of Diest which belong in the

Pliocene	SC_{2c}	Horizons à *Melampus pyramidalis*	Zone à *Neptunea contraria*	SCALDISIEN
	SC_{2b}	Horizons de Kallo		
	SC_{2a}	Horizons du Luchtbal à *Pecten gerardi*		
	SC_1	Horizon de Kattendijk sables à *Isocardia cor*	Zone à *Isocardia cor*	
Upper Miocene	D_2	ex-Casterlien	Zone à *Terebratula perforata*	DIESTIEN/ DEURNIEN
	D_1			
Upper Middle Miocene	An2	Sables noirs d'Anvers à *Pectunculus pilosus* (= *Glycymeris deshayesi*)		ANVERSIEN
	An1	Sables d'Edeghem à *Panopaea menardi*		
Lower Middle Miocene	Bd2	Sables du Limbourg (Limburgien)		BOLDERIEN
	Bd1c	Horizon du Bolderberg (Boldérien)		
	Bd1b	Horizon de Houthalen (Houthaléen)		
	Bd1a	Gravier d'Eelsloo à *Lamna cattica*		

Figure 40 Neogene stratigraphy in Belgium
from: Lexique Stratigraphique International.
Europe fasc 4 a VII (1957)



<u>Figure 41</u>

<u>Correlation of British and Belgian marine Neogene Formations</u> (after Curry <u>et al</u>, 1978).

Figure 42 Correlation of the Antwerp Crag (Lyell, 1852)

	Lyell (1852)		Lankester (1865)	Lankester (1868., 1870)	Van den Broeck (in Harmer 1898)	Lagaaij (1952)	De Heinzelin & Glibert (1957)
A N T W E R P C R A G	Yellow Crag (Upper Crag)	Scaldesien		Scaldisien			
	Crag gris (Middle Crag)		Middle Crag *			Diestian	
	Crag noir (Lower Crag)			Black Crag (= Diestien of Dumont) *	Diestien (of Dumont) *		Anversien (Upper Middle Miocene)
	Bolderien				Bolderien *		

*proposed sources of cetaceans found in Crag phosphorite deposit

Diestien system.

Lankester (1865b; pp.150-151) pointed out the strong similarity of the 'boxstone' fauna to the "Middle Crag of Antwerp" as this deposit was found to contain teeth of Carcharodon megalodon* as well as abundant cetacean bones. He later believed (Lankester 1868, 1870) that these fossils were derived into the Antwerp Crag from another source which he thought to be Diestien in age. Lankester (1869) observed that Isocardia lunulata, a mollusc commonly found in 'boxstones' but not in either the Coralline or Red Crags, was also common in Diestien beds on the continent. He recognised, however, that facies differences in shallow marine environments hamper accurate correlations. He also believed the 'boxstones' and the Lenham Beds of Kent to be equivalent in age.

It is essential to note here that Lankester (1868, 1870) equated the Diestien with the 'Crag noir' or'Black Crag' of Antwerp as described by Lyell (1852) (see figure 42). He equated the Scaldisien, however, with the 'Yellow Crag' of Antwerp and not the whole of the Antwerp Crag as Lyell had done. This usage of the term'Diestien' has led to much subsequent confusion. Dumont (1839) described the Diest sands as underlying the Antwerp Crag but Lyell (1852; p.294) expressed doubts as to the validity of this conclusion. The Diestien of Dumont was incorporated into the new system Anversien in 1879 (Tavernier and de Heinzelin, 1961). The Diestien of modern usage is a more recent deposit of

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* C. megalodon is now assigned to the genus Procarcharodon (A. Longbottom pers comm, 1981)

upper Miocene age (see figure 40). Thus the 'Diestien' of early authors refers to the 'Crag noir' of Antwerp which is now believed to be Anversien in age (De Heinzelin and Glibert, 1957; Tavernier and de Heinzelin, 1961). De Heinzelin and Glibert (1957; p.12) listed the typical molluscs of the Anversien; Isocardia lunulata, Nucula haesendoncki and Conus dujardini are also found in the 'boxstone' fauna (Bell 1911, 1915, 1917). Tavernier and de Heinzelin (1961) divided the Anversien into an upper division: Sables d'Anvers (à Pectunculus pilosus), and a lower division: Sables d'Edegem (à Panopaea menardi). Both these zonal fossils are found in 'boxstones' (Bell 1911, 1915, 1917).

Harmer (1898) quoted Van den Broeck and listed the cetaceans Hoplocetus crassidens, Herpocetus scaldiensis and Squalodon anwerpiensis, which are all found in the Crag phosphorite deposit,

as occurring in the Bolderien of Antwerp together with species of Diestien age. The term 'Diestien' here is probably equivalent to the 'Crag noir' of Antwerp and not to the 'Diestien' of the rest of Harmer's paper.

In a study of the petrology of the 'boxstones' Boswell (1915) made the following observations.

a) 'Boxstones' have a rich and characteristic mineral assemblage.

b) Glauconite is very rare in 'boxstones' but common in Belgian 'Diestien' deposits. This may be due to the diagenetic removal of glauconite as seen in the Antwerp Crag.

c) The mineral assemblage is rather different to that of the Lenham beds.

Most authors have correlated the 'boxstones' with beds which are now believed to be Miocene in age. Bell (1915, 1917), however, believed that the 'boxstones' were of greater age and derived from Rupelien (Oligocene) deposits.

The majority of the available evidence indicates that the 'Trimley Formation', and thus the 'boxstones' and the phosphogenic episode which resulted in their formation, is Miocene in age and can be tentatively correlated with the Sables noir d'Anvers (= Black Crag of Antwerp, = Diestien of early authors) which is now considered to be Anversien (Upper Middle Miocene) in age (De Heinzelin and Glibert, 1957).

13.3 The Gedgravian and Boytonian stages

Harmer (1900a) proposed a classification of the Crag deposits of the East of England in order to facilitate comparisons with European stages. The Coralline Crag was assigned to the Gedgravian stage. The stage took its name from the village of Gedgrave; "Gedgrave is the only locality in the Crag district where none but Coralline Crag deposits occur" (Harmer, 1900b; p.707). Thus the term 'Gedgravian' was synonymous with the Coralline Crag.

Bell (1911; p.11) later proposed a division of the Coralline Crag into a lower, Gedgravian zone and an upper 'Boytonian' zone which he recognised as containing a mixture of Coralline Crag and Red Crag molluscan species. The 'Boytonian' zone, named after the locality at Boyton, has remained a source of controversy ever since (Baden-Powell, 1960; Cambridge, 1977). Bell (1911; p.11) described the section at Boyton: "The principal section was at Boyton, where it was worked for coprolite, a bed of a very few inches resting at the base of about 18 inches of a whitish or cream-coloured Crag, which in turn was capped by another thin band or seam of the same product, the Red Crag overlying all". In this he appears to describe Red Crag overlying Coralline Crag, each deposit with a thin basal phosphorite deposit. He described the fauna as consisting of a mixture of Red and Coralline Crag species and then claimed that similar heterogeneous faunas existed at Ramsholt, Waldringfield, Bawdsey and in the basement bed at Walton-on-Naze. He considered that the Boytonian fauna was intermediate between the Red and Coralline Crags thus making "....the break between the Coralline and Red Crags of little importance...." He went on to list (p.15) the characteristic fossils of the Boyton zone and later extended this faunal list (Bell, 1912).

Bell's observations are even more peculiar in the light of a note in a paper by Wood and Harmer (1877; p.120) on the excavations at Boyton Marshes which reads; "Mr Bell....tells me that in the excavations referred to, about 18 inches of Coralline-Crag are overlain by some Red Crag, and that, in working, the labourers mix the two together...." Whitaker (1885; footnote on p.28) attributed this communication to A. Bell, the author of the 1911 and 1912 papers. Harmer (1898; p.333) also believed that the mixing of the faunas was due to the excavation and wrote "The shells obtained by the coprolite-diggers were so mixed that it was impossible to say certainly from which formation they had been derived".

Despite this initial criticism, Harmer eventually adopted the idea of a distinct "Boytonian zone" with a fauna intermediate to the two crags (Harmer, 1914-1925; pp 4,5,62 and 492) and classified it as an upper zone of the Coralline Crag (Harmer, 1914-1925; p.5).

Despite a general rejection of the validity of the Boytonian zone since that time the usage of the term has persisted (Van Voorthuysen, 1957; p.264). Cambridge (1977) suggested that certain derivative species in the Red Crag e.g. Angulus benedeni and Pecten westendorpianus, which are unknown in the Coralline Crag, may have been derived from Boytonian age deposits. He further suggested that the Boytonian could be correlated with the sands of Kallo. In view of the total absence of positive evidence for the existence of a 'Boytonian' zone in the East of England it is curious that these views have persisted for so long.

13.4 Correlation of the Coralline Crag

a) Introduction

Before attempting to correlate the Coralline Crag (Gedgravian) with horizons in the successions of Belgium and Holland it is necessary to review the nomenclature which has been used to subdivide those sequences. As was the case in the preceding section this is often a matter of establishing each author's usage of a particular term which, for instance, may include beds in one stage which a subsequent author may include in a different stage. The Belgian succession is well known and it is with these deposits that attempts at correlation have been concentrated. The two stages in the Belgian succesion which are of importance in the history of correlation of the Coralline Crag are the Diestien (now Deurnien) and the Scaldisien.

b) The Diestien and Scaldisien stages in Belgium (figure 43) The Diestien stage mentioned here, it should be noted, is not equivalent to the Diestien (of Dumont) which is mentioned in the section on correlation of the 'Trimley Formation', this being a somewhat older deposit. Reid (1890), in an early attempt at correlation of the East Anglian Crag Formations, suggested that the Coralline Crag was equivalent to the Sables à *Isocardia cor* which at that time were part of the Belgian Diestien. Harmer (1900a, 1900b, 1910, 1918) while still maintaining equivalence with the 'zone à *Isocardia cor*' placed this division in the Casterlien stage. This latter stage name is now obsolete (De Heinzelin and Glibert, 1957) and should not be used. Lagaaij (1952; p.206), on the basis of a study of the bryozoan faunas of the southern North Sea basin wrote ".... I do not hesitate to correlate the Scaldisian of Belgium with the Gedgravian (Coralline Crag) of East Anglia, as 84% of the Scaldisian forms [of bryozoans] occur in the Coralline Crag". Lagaaij's material, however, which had been sent to him from the Belgian Institute of Natural Science in Brussels as typical "Scaldisian", was in fact from a Bryozoa facies of the 'zone à *Isocardia cor*' which Lagaaij at that time considered to be Diestien and therefore older (Van Voorthuysen, 1957; p.264). Glibert and De Heinzelin (1955) later proposed that the 'zone à *Isocardia cor*' should in fact be included within the Scaldisien after all. Thus, the lower Diestien 'zone à Terebratula perforata' became the Deurnien with the Upper Diestien 'zone à Isocardia cor' as the base of the Scaldisien, the term Diestien being discontinued.

Van Voorthuysen (1957) objected to this arrangement as he claimed that this now meant that the Plio-Pleistocene boundary, which he had placed at the top of the 'zone à Isocardia cor', now split the Scaldisien stage. However later authors (Tavernier and De Heinzelin, 1961; Curry et al, 1978) have placed the Plio-Pleistocene boundary at the top of the Scaldisien with the Mio-Pliocene boundary at the base of the Kattendijk Sands ('zone à Isocardia cor'), the Scaldisien thus occupying the whole of the Pliocene in the Southern North Sea area (see figure 41).

Figure 43 summarises the major changes in stratigraphical nomenclature of the Anversien, Deurnien (ex Diestien) and Scaldisien stages in Belgium since the work of Lagaaij (1952). Each column represents the relative positioning of individual formations in these three stages by a particular author. The positions of the Mio-Pliocene and Plio-Pleistocene boundaries as interpreted by these authors are also indicated. Non-anglicised spellings of stage names i.e. ending -ien rather than -ian, have been used in this section except where the author specifically used the anglicised form.

When attempting to correlate a formation like the Coralline Crag with the Belgian sequence it is best

Lagaaij (1952)	Glibert & De Heinzelin (1955)	De Heinzelin (1956)	De Heinzelin & Glibert (1957)	Van Voorthuysen (1957)	Tavernier & De Heinzelin (1961)	Cambridge (1977)	Curry et al (1978)	Belgian Stages
xxxxxxxxxxxxxxx Scàldisian	- - - - - - - - zone à Isocardia cor ooooooooooooo	xxxxxxxxxxxxxx Sables de Kallo (N. contraria) Horizons du Luchtbal (Pecten gerardi) Sables du Kattendijk (Isocardia cor) ooooooooooooo	xxxxxxxxxxxxxx Horizons de Kallo Horizons du Luchtbal (à P.gerardi) zone à Neptunea contraria Horizons du Kattendijk (Isocardia cor) ooooooooooooo	zone à Aloidis complanata (Sables de Merxem) zone à Neptunea contraria xxxxxxxxxx zone à Isocardia cor ooooooooooooo	xxxxxxxxxxxxxxx Sables de Kallo (N. contraria) Sables du Luchtbal Sables du Kattendijk (Isocardia cor) ooooooooooooo	Sands of Kruisschans Sands of Kallo Sands of Luchtbal Sands of Kattendijk ooooooooooooo	xxxxxxxxxxxxxx Oorderen Sands Luchtbal Sands Kattendijk Sands ooooooooooooo	SCALDISIEN
zone à Isocardia cor ooooooooooooo zone à Terebratula perforata	Sables à Terebratules (= Sables de Diest = Sables de Deurne)		Zone à Terebratula perforata	Sables à Terebratula perforata	Sables de Grobbendonk Sables de Deurne (T.perforata)	Sands of Deurne	Diest and Loxbergen Sands Deurne Sands	DEURNIEN (DIESTIEN)
		Sables d'Anvers Sables d'Edegem	Sables noirs d'Anvers à Pectunculus pilosus Sables d'Edeghem à Panopaea menardi		Sables d'Anvers (P.pilosus) Sables d'Edegem (P.menardi) Gravier de Burcht	Sands of Antwerp	Antwerp Sands	ANVERSIEN

oooo Mio-Pliocene boundary
XXXX Plio-Pleistocene boundary

Figure 43 Stratigraphical subdivision of Belgian Neogene deposits since 1952 done at the level of similarities of fauna and flora of individual deposits and thus avoid the complication of placing of these horizons within stages whose boundaries are prone to fluctuations according to an individual author's interpretation.

c) Correlation with the Belgian sequence

Irrespective of the stage in which the formation was placed the overwhelming consensus of opinion in the published literature is for the equivalence of the Coralline Crag and the Belgian 'zone à Isocardia cor' on the basis of molluscs (Reid, 1890., Harmer, 1900a, 1900b, 1910, 1918) and on the basis of bryozoans Lagaaij, 1952; see preceding section). Van Voorthuysen (1954) correlated the Coralline Crag with the 'zone à Isocardia humana' (= Isocardia cor). More recently the stratigraphical position of the Coralline Crag has been discussed by Cambridge (1977). He believed the Coralline Crag to be equivalent to the Belgian Sands of Luchtbal which overlie the sands of Kattendijk ('zone à Isocardia cor') in the Antwerp region of Belgium. Bryozoans are abundant in the Luchtbal sands and Pseudamusium gerardi (= Pecten gerardi = Chlamys gerardi), which is also fairly common in the Coralline Crag, is described as the most typical fossil. Andrew and West (1977) have described a pollen assemblage obtained from the Coralline Crag at Raydon Hall about 1 km east of Orford. The assemblage shows the presence of a mainly coniferous forest flora with a number of exotic genera of Eastern Asian/North American affinity including Sequoia-type, Sciadopitys and Taxodium type. They acknowledged the difficulties of interpretation of pollen assemblages within shallow marine deposits and tentatively suggested the assemblage to be Brunssumian in age. The Brunssumian continental stage has been correlated with the lower part of the formation of Oosterhout of Holland (Zagwijn and Staalduinen, 1975) which has in turn been correlated with the Antwerp Crag of Luchtbal (Laga, 1972). Wilkinson (1980) in a study on the ostracods and Foraminifera of the Coralline Crag correlated these faunas with those of the Sables of Kattendijk and Luchtbal of Antwerp. Evidence suggests therefore that the Coralline Crag may be correlated with the Sables de Kattendijk or the Sables of Luchtbal of the region around Antwerp and which are Lower to Middle Pliocene in age. A more definite conclusion awaits more detailed work particularly on the microfaunas.

d) Correlation with the Dutch sequence

Zagwijn and Doppert (1978) correlated the Coralline Crag with certain facies in the Oosterhout Formation of Holland rich in molluscan shells and bryozoans which they termed the 'Coralline Crag facies'.

e) Correlation with other areas

Correlation of the Coralline Crag with deposits in other sedimentary basins have been made in the past despite the problems involved. Reid (1890) and Burrows (1895a) both considered that the Coralline Crag was equivalent in age to Plaisancian deposits of the Mediterranean. They also thought that the younger Crags could be correlated with the deeper water Astian stage of Italy. Harmer (1900b, p.707) doubted whether the Coralline Crag was as old as the Plaisancian and correlated the Gedgravian with the Italian Astian. This idea was discussed in more detail by Baden-Powell (1953, 1955a, 1955b and 1960) and proposed that correlation was possible using species of *Turritella*. He believed that *T. tricarinata*, which is common in both the Coralline Crag and Astian deposits, had evolved into *T. communis* which is found in the Red Crag and Calabrian deposits. He based his correlation on the similar climatic sequence of the two areas and on the fact that both the Coralline Crag and Astian deposits precede the sudden appearance of *Neptunea contraria*. The usage of the speciation of an infaunal gastropod for correlation between two areas of presumably widely differing climatic conditions is unlikely to be of any real value in attempted correlations between the North Sea basin and the Mediterranean. Wilkinson (1980), on the basis of the ostracod faunas, believed that the Coralline Crag could be correlated with the *Leptocythere bacescoi* zone of the middle part of the Pliocene in Italy. This ostracod zone contains the Astian stage of other authors.

13.5 Correlation of the Lenham Beds

The Lenham beds are the only other formation demonstrably of Miocene or Pliocene age which is found in the East of England and was deposited in the depositional basin at the Southern end of the North Sea. The association in the literature of the Lenham Beds with the 'boxstones' of the Trimley formation and the evidence yielded by the present vertical elevation of the Lenham Beds on earth movements in the Southern North Sea in Mio-Pliocene times makes it worth briefly considering their stratigraphic position relative to the other Neogene deposits already discussed. Reid (1890) considered that the Lenham Beds and the Coralline Crag were both of equivalent age to the 'sable à _Isocardia cor_' of Belgium. Harmer (1900b, 1910, 1918) referred the Lenham Beds (Lenhamian) to the zone à _Arca diluvii_ and correlated this Formation with the Diestien'zone à _Terebratula grandis_' (= Sands of Louvain and Diest). Lagaaij (1952) correlated the Lenham beds with his lower Diestien 'zone à _Terebratula perforata_' which was later to become the Deurnien stage of Glibert and De Heinzelin (1955) and Van Voorthuysen (1957) (= Zone à _Terebratules_ = Zone à _Ditrupa_ of Van Voorthuysen, 1954) (see Figure 43). Double (1924), in a study of the mineral components of the Crag sediments,noted (p.353) that the mineral assemblages of the Lenham Beds and the 'Diestian' were very similar, both containing abundant monazite and sillimanite.

On current evidence the Lenham Beds can be correlated with the part, at least, of the Deurnien stage of Belgium and which is Middle - Late Miocene in age (Curry _et al_ 1978) (see figure 41).

13.6 Correlation of the St. Erth Beds

The age of the St. Erth Beds of Cornwall have long been a subject of controversy. For more details on the subject of correlation of the St. Erth Beds,which are possibly of

Pliocene age, the reader is referred to Mitchell (1965) and Mitchell _et al_ (1973).

Chapter 14

Earth Movements in the Southern North Sea basin in Miocene and Pliocene times

Chapter 14

Earth Movements in the Southern North Sea basin in Miocene and Pliocene times

14.1 Introduction

During the Caenozoic in the Southern North Sea area, sea level is known to have risen above and fallen below the present sea level. Most of the evidence for these fluctuations is found in Pleistocene deposits where marine and estuarine sediments, including beaches, are found far above present sea level and from freshwater sediments, beaches and valley systems which are now submerged (West, 1972). Data for Miocene and Pliocene deposits in the East of England is less complete but the Lenham Beds (Diestien) are found to lie 162 - 183 m above present sea level (Wooldridge, 1927). The Coralline Crag shows a much smaller elevation relative to present sea leavel of up to only 17 m (Tattingstone). The real difficulty involved with determining sea level fluctuations comes from identifying whether they arise, for example, from a real raising of sea level or from a lowering of the land relative to sea level.

Southeast England is, in general, south of the limit of Pleistocene glaciations and there is no evidence for a glacial isostatic uplift since the last glaciation (West, 1972). There is however very substantial evidence for subsidence during the Pleistocene in the southern part of the North Sea basin of which southeast England forms the southwestern margin.

The eustatic component of relative sea level fluctuations is much more difficult to determine. Carter (1978) produced evidence for a late Miocene eustatic global sea level fall.

In all studies there are difficulties caused by the absence of any certain datum level. That is, whether any part of the Earth's crust have remained stable for long enough for it to be used as a reference point for the study of eustatic sea level changes. Thus, while the component of change derived from eustatic sea level fluctuations should not be ignored, it seems clear that local tectonic movement was an important factor in the evolution of the southern North Sea in Miocene - Pleistocene times.

14.2 Faunal evidence

Early work on Crag faunas (particularly molluscs) made mention of 'barriers' to the basins of deposition of the various Crags. These 'barriers' were held to be responsible for the absence of so-called 'northern' or 'southern' forms of mollusc at various stages of Crag deposition.

Wood (1874; p.193-194) proposed that a land barrier existed during Red Crag times which cut off the North Sea basin from the south but that this barrier did not exist during Coralline times. Harmer (1896b, p.752-754) additionally proposed that a barrier existed to the North of the Crag basin during Coralline Crag times preventing influx of 'northern' forms of mollusc. This barrier was later removed but replaced by one to the south preventing influx of 'southern' forms of mollusc into the Red Crag basin. Gradual elevation of this southern barrier supposedly led to a migration of the southern limit of the basin northwards and a regressive shallowing of the Red Crag Sea.

Lagaaij (1963; p.194), on the other hand, indicated that the

North Sea basin was closed to the south during Pliocene (Coralline Crag) times and that warm water species were able to reach the land-locked basin by a path around the North of Scotland. He cited (p.196) the modern finds of a loggerhead turtle and a flying fish as indications of the fact that the Gulf Stream can carry tropical and subtropical marine organisms along this route. He proposed that the Pliocene 14°C surface isocryme followed the present 5°C surface isocryme (see figure 44) which bends southwards into the North Sea basin. Thus he felt temperature distribution in the Pliocene sea to have been an important factor influencing migration of warmer water fauna into the East Anglian area despite a land barrier which blocked free connection to the Atlantic via the English Channel. Zagwijn and Doppert (1978) produced a series of palaeogeographic maps for the southern North Sea basin in Neogene and Quaternary times. These maps show closure of North Sea basin from the south from Late Miocene to 'Middle Pleistocene' times and are therefore consistent with Lagaaij's argument.

14.3 Tectonic evidence

Thus the question arises of how, where, when, and for how long a period of time did land barriers exist during the Neogene of the North Sea basin? Both eustatic sea level changes and regional subsidence and uplift are possible causes of changes in the distributions of land and sea.

The Lenham Beds of Kent were thought to have been deposited in a sea of between 20 fathoms (36.5 m) (Reid, 1886, p.342) and 40 fathoms (73 m) depth (Monckton, 1902). Allowing for the difficulties involved in any estimations of water depth

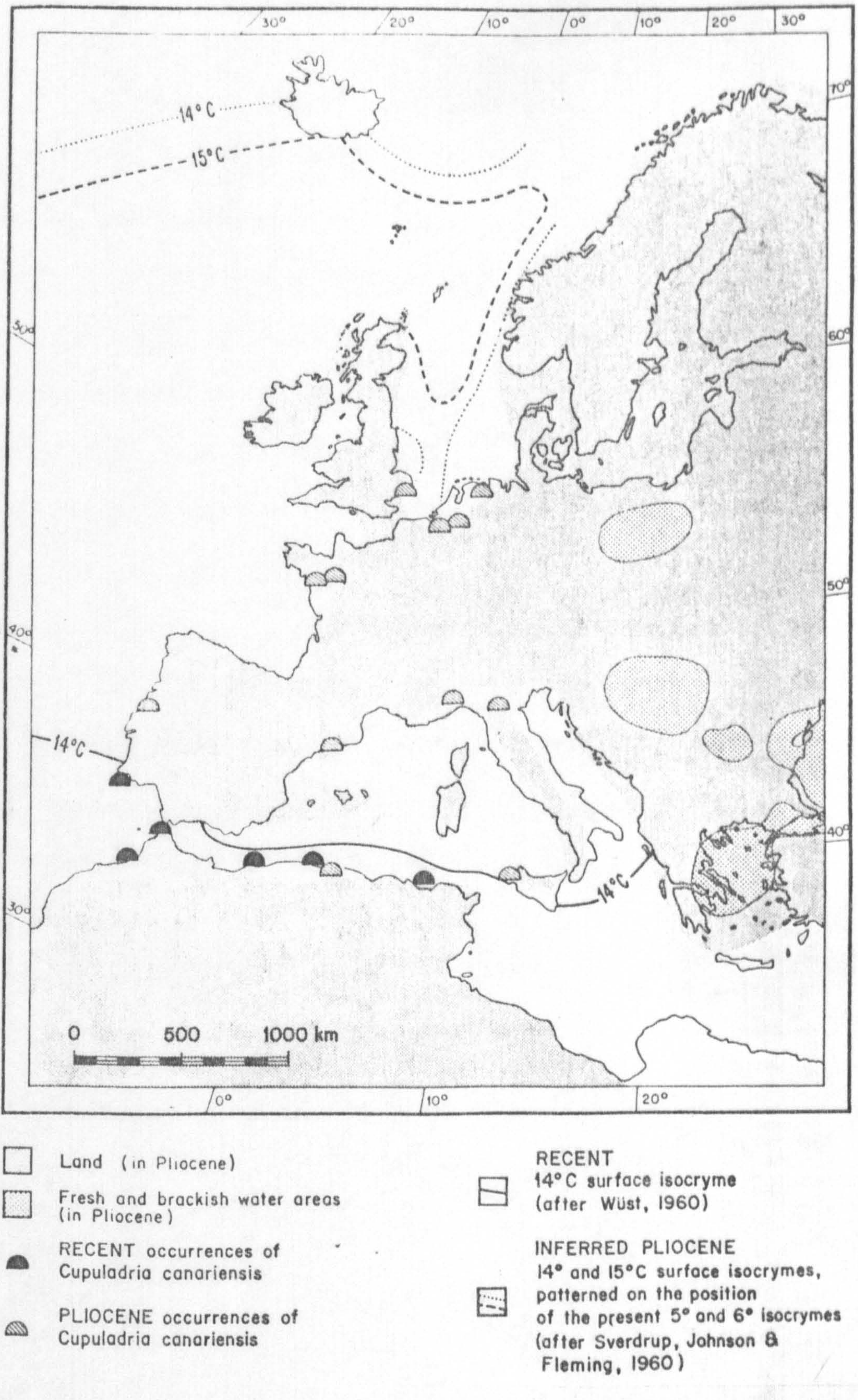

Figure 44 Shift of sea water temperatures in the Eastern Atlantic and Mediterranean since the Pliocene (after Lagaaij, 1963).

derived from study of molluscan faunas (see Chapter 9) and taking the more conservative estimate, this would mean a difference of 800 feet (244 m) between modern sea levels and those of the Diestien. A eustatic transgression of this scale would inundate much of southern England. Clearly local tectonic uplift has been a major cause of the present day elevated position of the Lenham Beds. Pliocene and Pleistocene deposits at Utrecht on the other hand are found at depths of 1143 feet (348 m) and consist of shallow water deposits (Reid, 1886). Between Belgium and Holland there is a 900 m relative change in vertical position of Pliocene and Pleistocene beds over a lateral distance of only 200 km (Van Voorthuysen, 1954). This points to a continued, largely syndepositional depression throughout Pliocene and Pleistocene times on the Eastern flank of the North Sea basin.

These facts led Harmer (1896b, 1898, 1910) to believe that processes of uplift and subsidence were the cause of the appearance and disappearance of land barriers. Harmer (1910; p.94) wrote: "The tectonic movement of upheaval and subsidence....seems to have obtained its maximum development along a line drawn from Kent to Amsterdam. Its influence may be traced in East Anglia, but it died out in that direction the result being, first the shallowing of the Coralline area, and afterwards the gradual retreat of the Crag Sea towards the north". In this account, however, he takes no account of the period of regression between the deposition of Coralline Crag and Red Crag, implying a steady northwards regression since Lenham Beds (Diestien) times. While admitting that elevation of the Lenham Beds has occurred, he proposed a southern connection of the Coralline Crag basin with the English Channel across the southern counties of England (Harmer, 1896b; p.752). Some authors have also followed this explanation (e.g. Stamp, 1936) but others feel that there was no southern connection (e.g. Lagaaij, 1963) in Pliocene times.

14.4 Tectonic hisory of the Neogene south-western North Sea

a) Anversien("Trimley Formation")

Little is known of the local conditions during deposition of Anversien deposits (The "Trimley Formation") in the East of England. Monckton (1902; p.520) thought that deposition occurred during the same period of regional depression during which the Lenham Beds were deposited. Boswell (1915; p.203-204) has remarked that the restricted distribution of 'boxstones' corresponds to an anticlinal axis which was active during Eocene - Pliocene times but did not comment on the significance of this correspondence.

b) Diestien (Lenham Beds)

Wooldridge (1927; p.131) in a detailed study described the Diestien Sea as "....a gulf or channel roughly coextensive with the London Basin, as defined by the present Chalk escarpments...." The Diestien deposits "rest on a wave-cut platform inclined towards the axial line of the syncline". The syncline was formed by pre-Diestien warping along an axis of Charnian trend. He believed the slope of the platform to be largely original but stated "Nevertheless there appears to have been slight post-Diestien uplift along the Wealden axis, with complementary deepening of the London Syncline". Van Voorthuysen (1954), however, wrote "....the epeirogenic movement which took place during Pliocene time in this southern part of the North Sea Basin has not been affected by the tectonic highs and basins of minor tectonic magnitude, already existing in Pre-Pliocene time".

Abbott (1916; p.182) had proposed that the uplift of the Eastern England area "....reveals in the most striking manner the evidence that the earth's movements have travelled as waves" with a deepening of the basin immediately in front of a 'wave' of uplift which travelled northwards from the time of the deposition of the Lenham Beds. Thus as the wave moved northwards, so depressions, and thus transgressions, would be followed by uplift and consequent regression. He claimed (p.186) that the Lenham Beds of the South Downs revealed a more ancient fauna than those of the North Downs in support of his theory.

c) <u>Gedgravian</u> (Coralline Crag)

Harmer (1896b) believed that the general sloping of the sub-Coralline Crag London Clay surface was evidence of post-depositional uplift to the south-west of that deposit. He therefore did not consider that the uplift, and thus the slope, might be pre-depositional. Harmer (1898; p.315) thought that this uplift resulted in the formation of cliffs of Diestien deposits on the southern limits of the Coralline Crag basin and wrote, "It is difficult, therefore, from a stratigraphical point of view, to find any other source for the boxstones than the older Pliocene sandstones of the South of England".

Bell (1911) expressed similar views but thought that a channel had existed which cut through upraised Diestien deposits from the south-west and thus connected the Coralline Crag basin with the English Channel. As described elsewhere in the present study (Chapter 13) the 'boxstones' were derived from a more ancient deposit than the Lenham Beds which is probably of Anversien age. Boswell (1915) recognised an anticlinal axis with a line of greatest uplift roughly along the present line of the Stour in a NW-SE direction and wrote (p.203) "It seems probable that slight uplift was taking place in the central area during deposition [of the London Clay], and sagging and sedimentation on each side of it, but it was not until post-London Clay times that the movement became very marked". He felt that deposition of the Coralline Crag took place on the north-eastern limb of this anticlinal structure. He noted that the distribution of 'boxstones' within the crags corresponds with the area of maximum uplift but does not comment on the significance of this observation. Van Voorthuysen (1954) also noted this axis as a hinge line of change of direction of strike of the Chalk and Lower Tertiaries of East Anglia.

14.5 Summary and Conclusions

Local tectonic uplift and subsidence were important factors in the distribution of Neogene deposits in the Southern North Sea basin. The scanty evidence has been variously interpreted in attempts to explain the changing faunas during this period. Early workers proposed land "barriers" which were periodically raised and lowered allowing either 'northern' or 'southern' forms of mollusc into the basin. These early discussions took little or no account of eustatic changes of sea level which have undoubtedly contributed to the changes in the geographical distribution of land and sea. Whilst eustatic sea level changes might be expected to fluctuate over relatively short periods of time, large scale tectonic movements are probably more gradual and continuous. Thus it is probable that since Diestien times, at least, the North Sea basin has been progressively tilted to the North with the raising of its southern margin (The Wealden axis). This resulted in the raising of the Lenham Beds to their position of 207 m above present sea level and the creation of a landlocked marine basin open to the north in early Pliocene times. Eustatic sea level changes and further minor amounts of uplift and subsidence resulted in periodic transgressions across the East of England. One of these transgressions resulted in the deposition of the Coralline Crag and a later more extensive transgression deposited the Red Crag. The relative roles played by sea level changes and uplift/subsidence are not easily determined. Basin topography has a strong effect on the extent and depth of water during a transgressive phase. This basin topography may be subsequently altered during later tectonic phases. A possible sequence of events which explains the observed stratigraphic sequence is given below. The East Anglian Neogene deposits are generally limited in extent with long stratigraphic breaks between them. This is evidence of their marginal nature to the main North Sea basin. Further work on more complete Neogene sequences of the central southern North Sea may help to elucidate some of the inherent problems in this area.

1. Transgression Eustatic sea level rise.
   Deposition of the Trimley Formation in part of Suffolk. (Anversien)
2. Regression Tectonic uplift along anticlinal axis leading to breakup of Trimley Formation.
3. Transgression Eustatic sea level rise
   Deposition of the Lenham Beds in Kent (Diestien)
4. Regression Tectonic uplift along Wealden axis
5. Transgression Eustatic sea level rise + local subsidence
   Deposition of Coralline Crag in Suffolk on subsiding NE limb of anticlinal axis (Gedgravian)
6. Regression Continued tectonic uplift + eustatic sea level fall. Subaerial lithification of Coralline Crag
7. Transgression Eustatic sea level rise
   Deposition of Red Crag in Suffolk and Essex across anticlinal axis. General flattening of topography
8. Regression Eustatic sea level fall + tectonic uplift during Red Crag times.

Concluding remarks

The Coralline Crag was evidently deposited during a marine transgression of limited geographical extent over part of south-east Suffolk. The general absence of Chalk-derived flints, common in the overlying Red Crag, seems to confirm that the Coralline Crag sea failed to inundate the Chalk outcrop which lies only a few kilometres to the north-west of the Coralline Crag outcrop at Tattingstone.

The Coralline Crag therefore was probably deposited at no great distance, possibly only 10-15 km, from the palaeoshoreline. The land surface over which the sea transgressed was mostly of London Clay, a formation of clays and silts with bands of carbonate, phosphorite and pyritic concretions. Therefore it is interesting that despite this relatively unconsolidated sedimentary bedrock and the hinterland of Cretaceous and Tertiary sediments that a carbonate formation could have been deposited so close to the shoreline. Terrigenous sediment input from the land from rivers and surface runoff must have been very limited not to have "diluted" the carbonate sediment. Carbonate deposits around present day Britain are restricted to those areas with minimal terrigenous input from the land and are often associated with areas of hard bedrock as are the deposits on the Scottish shelf (see Wilson, 1979). Indeed the terrigenous sediment of the Coralline Crag is unlikely to have been derived from the land surface at all but was probably reworked *in situ* from earlier deposited sediments from within the marine basin. Indications that the Coralline Crag was deposited on a slight topographic high on the seabed may in part explain the lack of terrigenous sediment.

The Pliocene Oosterhout Formation of Holland contains possibly comparable lenses of carbonate sediment in a sequence of marine sands and clays described as 'Coralline Crag facies" by Zagwijn and Doppert (1978). Thus,carbonate deposits formed in geographically restricted parts of the basin where conditions were favourable. Elsewhere, terrigenous sedimentation dominated.

It is possible that a similar situation existed in eastern England on the western margin of the southern North Sea basin. The Coralline Crag thus represented geographically restricted lenses of carbonate sediment forming where conditions were favourable in the basin possibly associated with slight topographic highs,with less carbonate-rich sediments deposited elsewhere. Terrigenous facies which are laterally equivalent to the Coralline Crag have yet to be found in this area but ongoing exploration in the southern North Sea may help to prove the Pliocene facies relationships.

Eventually a clear picture may be obtained of the facies distributions of the entire basin which may help to explain what conditions conducive to carbonate deposition existed in the Pliocene which do not exist in the southern North Sea basin today.

One of the major problems in interpreting thanatocoenose fossil assemblages such as those of the Coralline Crag is that of distinguishing transported from _in situ_ components. This thesis has attempted to illustrate the importance of the complementary study of sedimentary facies analysis and detailed faunal analysis. Many benthonic faunas are substrate specific and the substrates themselves are dependant on current strength, wave activity, sedimentation rate and other interrelated factors. Contemporaneous erosion and transportation then serve to overprint primary faunal distributions which must then be deciphered by careful reconstruction of palaeocurrents and sediment transport paths.

Sedimentary facies interpretation in a deposit like the Coralline Crag is far from straightforward. It must be remembered that the preserved outcrop represents a "frozen" fragment of what was once a dynamically active sedimentary regime. Consideration of the sequence of events at a point in space has to be considered within the broader perspective of the whole sedimentary basin. Thus, for instance, while the deposit was laid down during a transgression, active upbuilding of a carbonate bank may have led to a 'regressive' (a shallowing upward) sequence in the area of the bank. Continued sea level rise led to a landward migration of the shoreline with relative shifts in the position of the facies with time and consequent overprinting and erosion of parts of the sequence. Subsequent diagenesis and erosion of the selected parts of this sequence have been shown to further hamper interpretations.

This thesis has attempted to interpret the palaeoenvironment of deposition of the Coralline Crag of Suffolk. It has tried to show that during such a transgression a complex sequence of facies can be expected both vertically and laterally.

It is hoped that comparisons with present day shelf sediments will be made in the future and that information derived from study of both fossil and Recent sequences may complement one another to increase our understanding of the sedimentary events which mark a marine transgression in a shallow shelf sea.

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1851 Part II(1) Bivalves ; no. 8 4 1-150
1853 Part II(2) Bivalves ; no.24 7 151-216
1857 Part II(3) Bivalves ; no.33 9 217-342
1872 Supplement Univalves ; no. 113 25 1-98
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Plate 1 **Coralline Crag phosphorite deposit**

A Phosphorite deposit at the base of the Coralline Crag at Ramsholt Cliff (locality 3). Phosphorite nodules and large abraded fragments of London Clay carbonate septaria can be seen resting on the erosional surface of the London Clay. Scale is 15cm long.

B Phosphorite deposit at the base of the Coralline Crag at Ramsholt Cliff (locality 3): 1.Phosphorite nodules ; 2. Fragments of carbonate septaria. The junction between the London Clay and Coralline Crag sediment is indicated by a dash at the extreme left.
Scale is 15cm long.

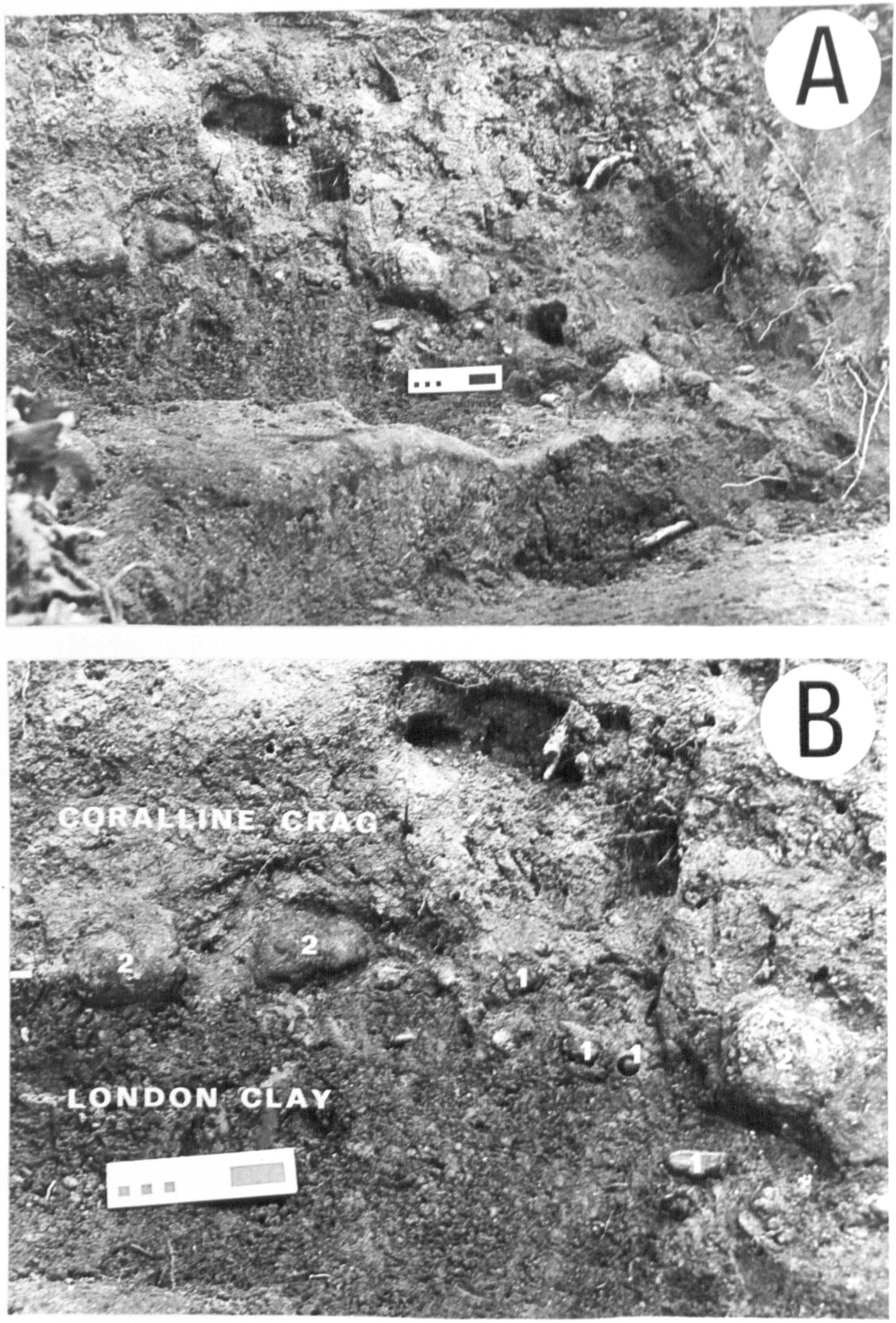

A
B
CORALLINE CRAG
2
2
1
1
1
2
LONDON CLAY
1

Plate 2 **Crag phosphorite nodules**

A Phosphatic nodules (concretions) from the Crag phosphorite deposit at Ramsholt Cliff (locality 3). Note naturally polished surface.

B Dendritic or vermiform markings on the surface of phosphorite nodules. These are believed to be the result of close adherence of modern rootlets. (See Chapter 2) Ramsholt Cliff (locality 3).


1cm
A


1cm
B

Plate 3 London Clay phosphorite concretions and Crag derived equivalents

A Top : Xanthilites bowerbankii Bell . London Clay, Sheppey, Kent. Sedgwick Museum C19374, Walton Collection.

Bottom : Xanthilites bowerbankii Bell . Red Crag, Sutton, Suffolk. Sedgwick Museum C45284.

Scale bar = 1cm

B Top : Hoploparia belli McCoy . London Clay, Sheppey, Kent. Sedgwick Museum C19098.

Bottom : Hoploparia belli McCoy . Red Crag, Felixstowe, Suffolk. Sedgwick Museum C45251.

Scale bar = 1cm

C Top : Lamna obliqua (Agassiz) . London Clay, Sheppey, Kent. Sedgwick Museum C21168.

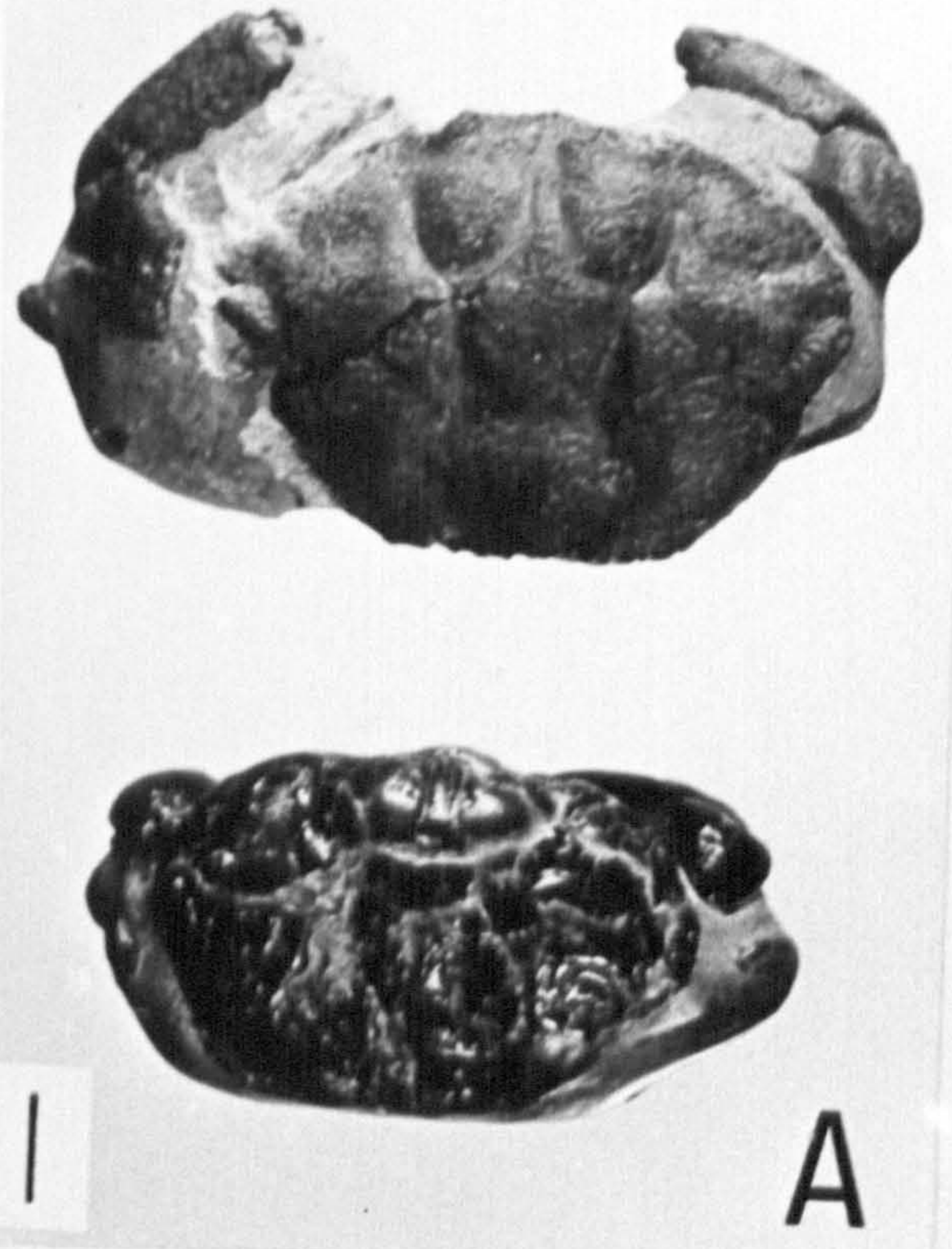
Bottom : Lamna? obliqua (Agassiz) . Red Crag, Felixstowe, Suffolk. Sedgwick Museum C45380.

Scale bar = 1cm

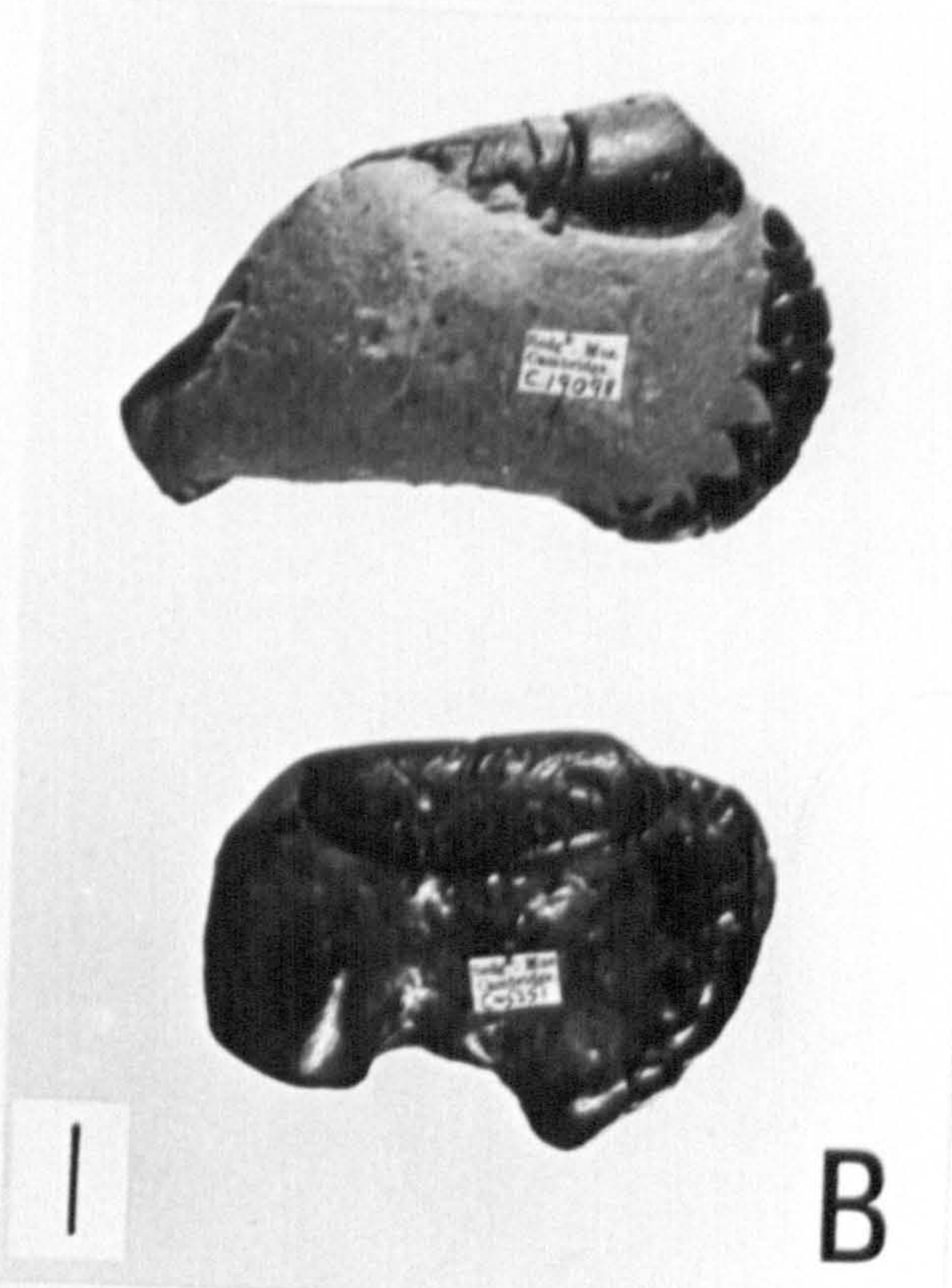
D Top : Odontaspis vertebrae . London Clay, Sheppey, Kent. Sedgwick Museum C21189-21191.

Bottom : Otodus (?=Odontaspis) vertebrae . Red Crag, Sutton, Suffolk. Sedgwick Museum C84894.

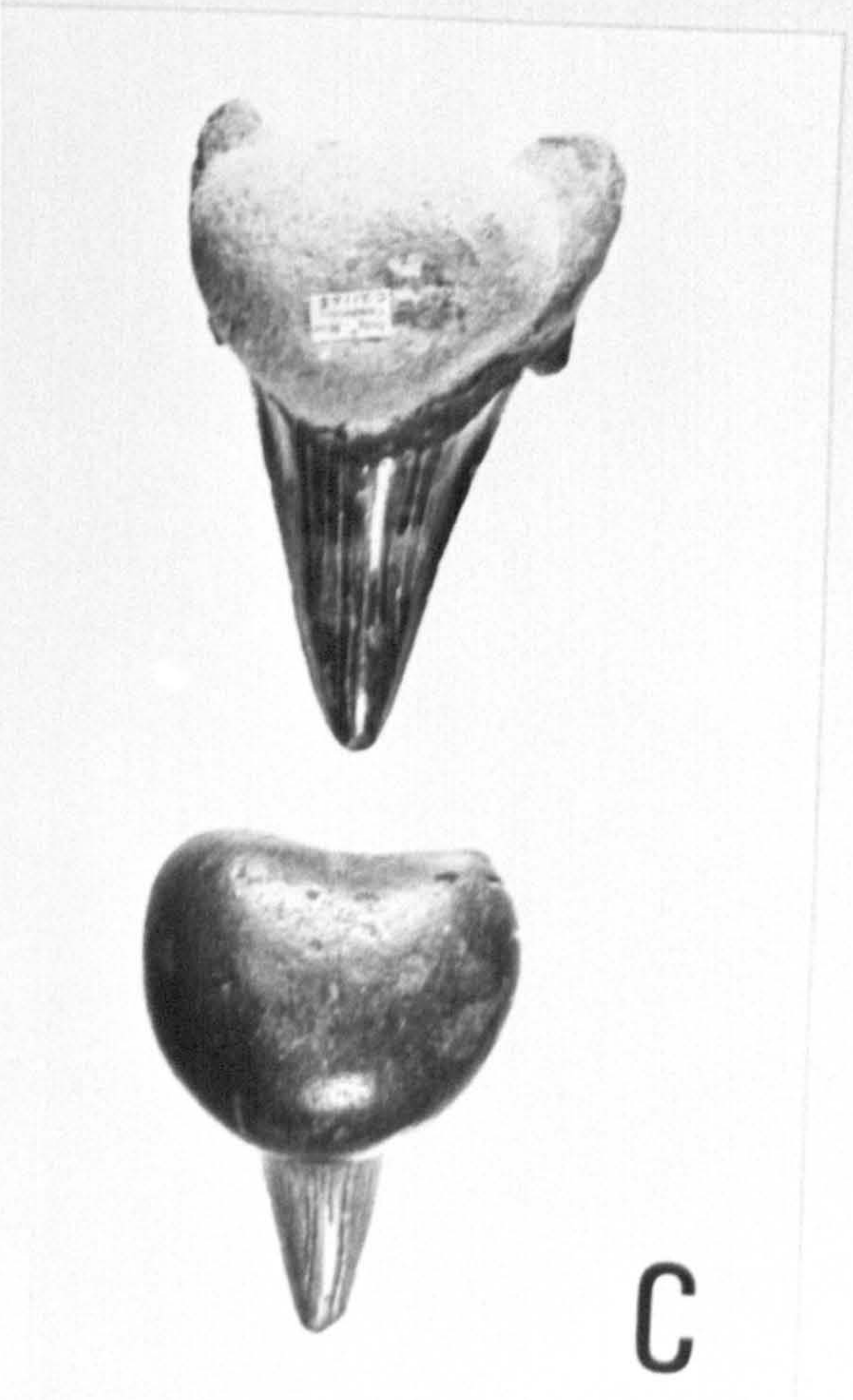
In each example the upper specimen is a concretion around a fossil from the London Clay. The lower specimen is a derived example from the Crag phosphorite deposit.



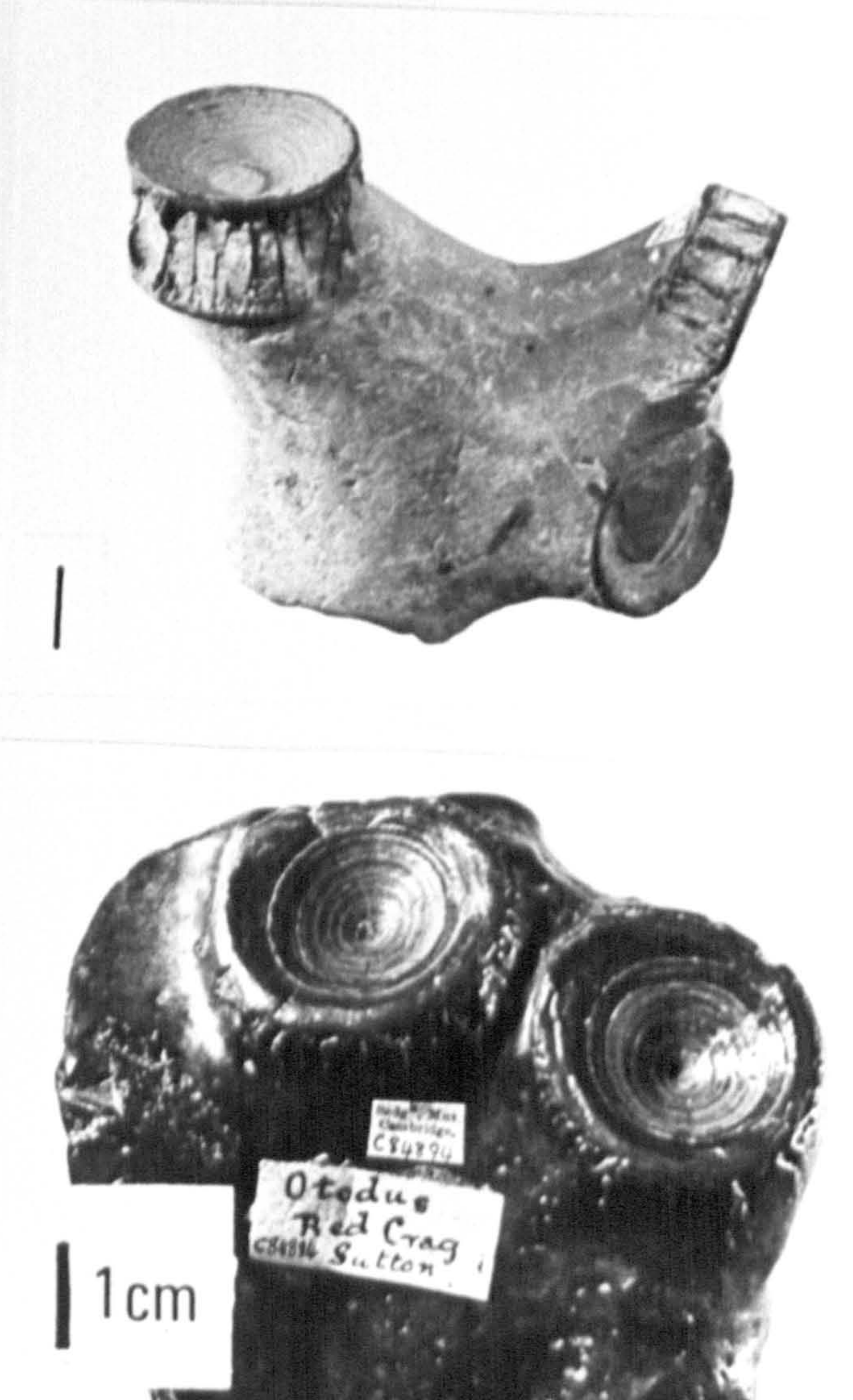
A



B



C



D

Plate 4 **Phosphatised burrows and endolithic borings**

A Phosphatic concretion formed as a burrow infill. Note concentric layering. London Clay, Sheppey, Kent.

B Derived phosphatic concretion from the Red Crag, Bucklesham, Suffolk. Compare with A.

C Polished section of phosphorite nodule showing flask-shaped crypts attributable to the trace fossil genus *Teredolites*. Red Crag, Bawdsey, Suffolk.
Scale bar = 1cm


A
1cm


B
1cm

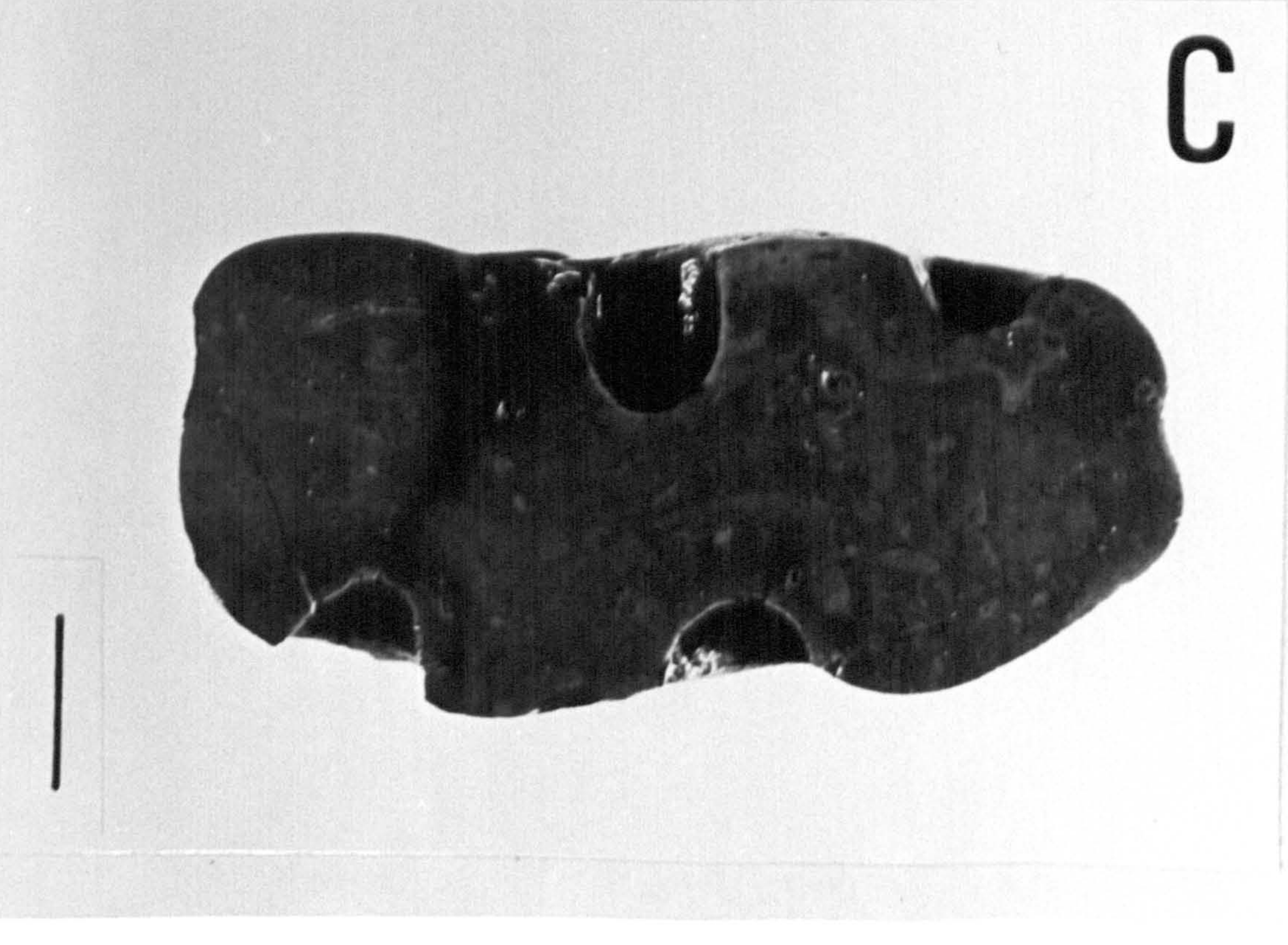

C

Plate 5 Crag phosphorite nodules

A Phosphatised cast of ammonite chamber. cf Tropaeum sp (Lower Cretaceous heteromorph). Source of specimen unknown. Red Crag. Sedgwick Museum C84888.
Scale bar = 1cm

B Spiral phosphorite concretion. Dextral coiling. Ipswich Museum collection.
Scale bar = 1cm


A
C 84888

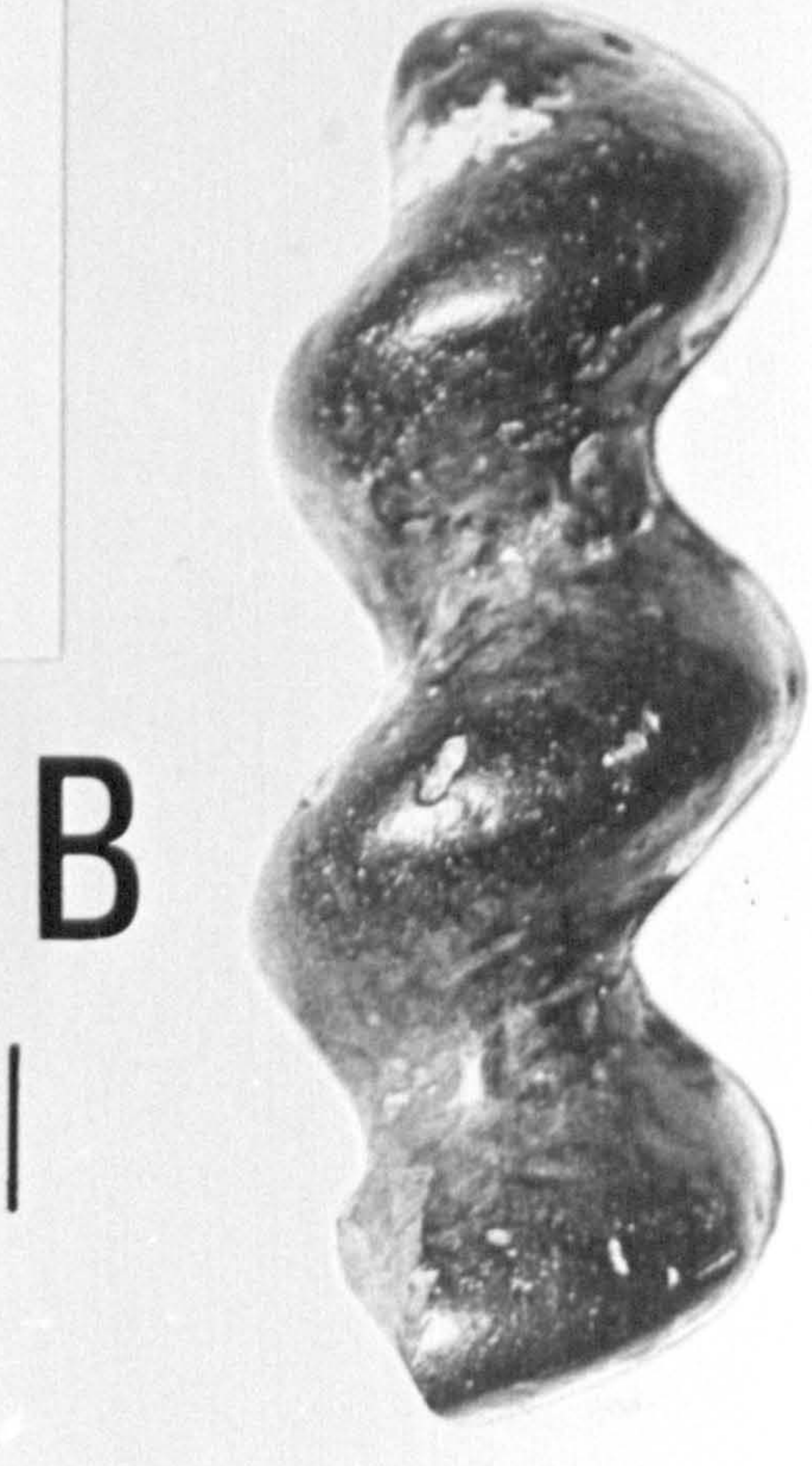

B

Plate 6 Sections of phosphorite concretions and nodules

A Polished section of Crag phosphorite nodule. Septarian veins, initially pyrite in the original London Clay concretion, are now partially infilled with limonite probably derived from pyrite oxidation. Note abundant pellets. Red Crag phosphorite deposit, Bawdsey, Suffolk.
Scale bar = 1cm

B Polished section of London Clay phosphorite concretion showing internal pyrite veins. Veins do not reach the surface of the concretion. Note darker colouration in the centre in the vicinity of the veins and abundant pellets. London Clay, Sheppey, Kent.

C Crag phosphorite nodule showing veins on surface. The outer softer part of the original concretion was removed by abrasion thus exposing the veins. Red Crag phosphorite deposit, Bawdsey, Suffolk.
Scale bar = 1cm

D Thin section of Crag phosphorite nodule showing pellet and a vein, partially infilled with limonite. Vein was originally pyrite.
Scale bar = 500μm

E Thin section of London Clay phosphorite concretion showing pellet of amorphous apatite cut by later diagenetic pyrite vein.
Scale bar = 500μm

F Thin section of Crag phosphorite nodule showing internal structure of pellet. Red Crag phosphorite deposit, Bawdsey, Suffolk.
Scale bar = 500μm

G Thin section of Crag phosphorite nodule showing cluster of pellets. Red Crag phosphorite deposit, Bawdsey, Suffolk.
Scale bar = 500μm

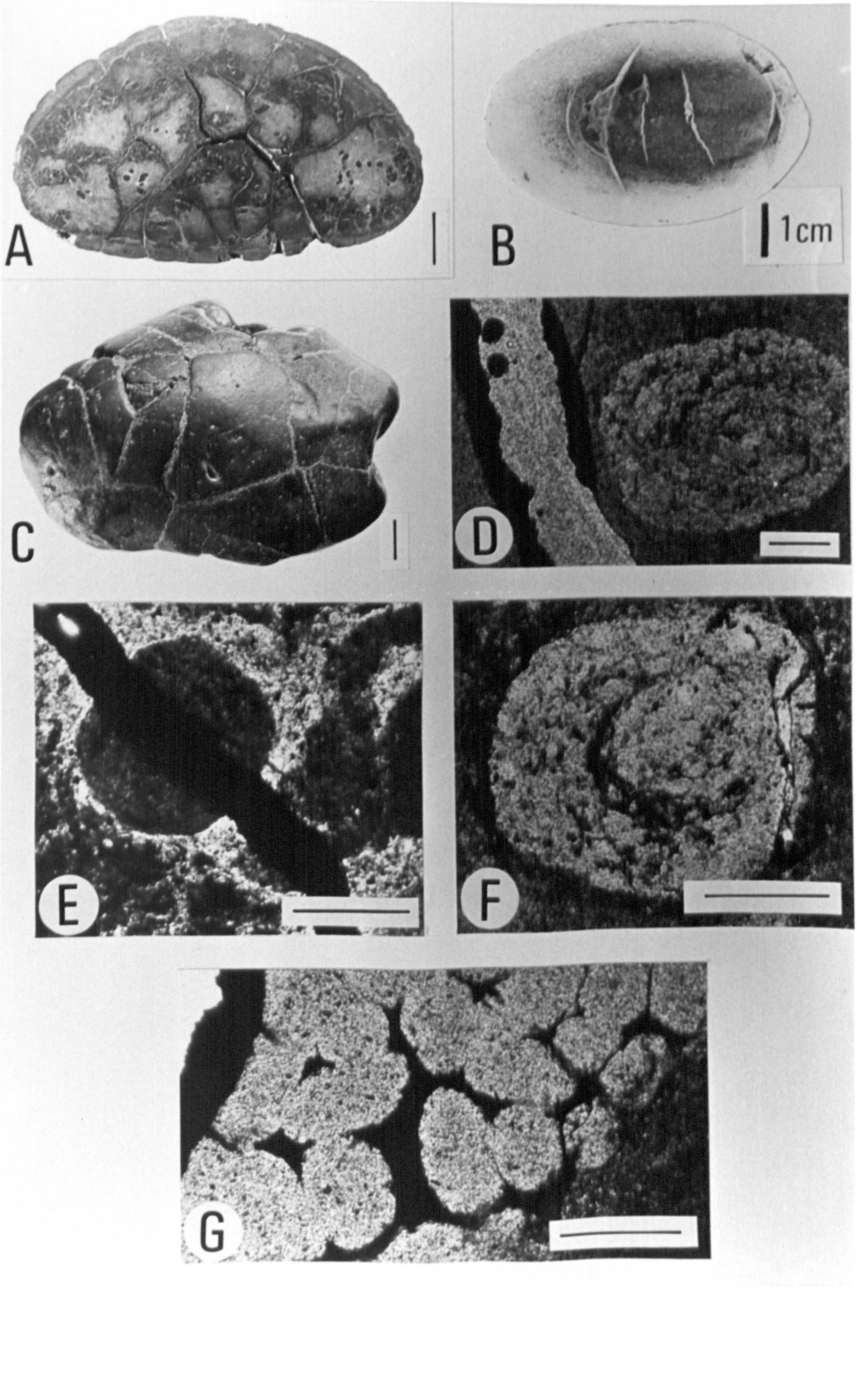

A
B
1cm
C
D
E
F
G

Plate 7

Petrography of 'boxstones'

A-B Thin sections of 'boxstones' showing variation of grain-matrix ratios. A : Matrix typically comprises roughly 50% of the sediment. B : Less commonly the grains may show matrix support.
Scale bars = 500µm

C Thin section of 'boxstone' showing a group of ?faecal pellets composed of amorphous carbonate apatite.
Scale bar = 500µm

D Thin section of 'boxstone' showing pseudomorphism of ostracod valves by high ferroan carbonate.
Scale bar = 500µm

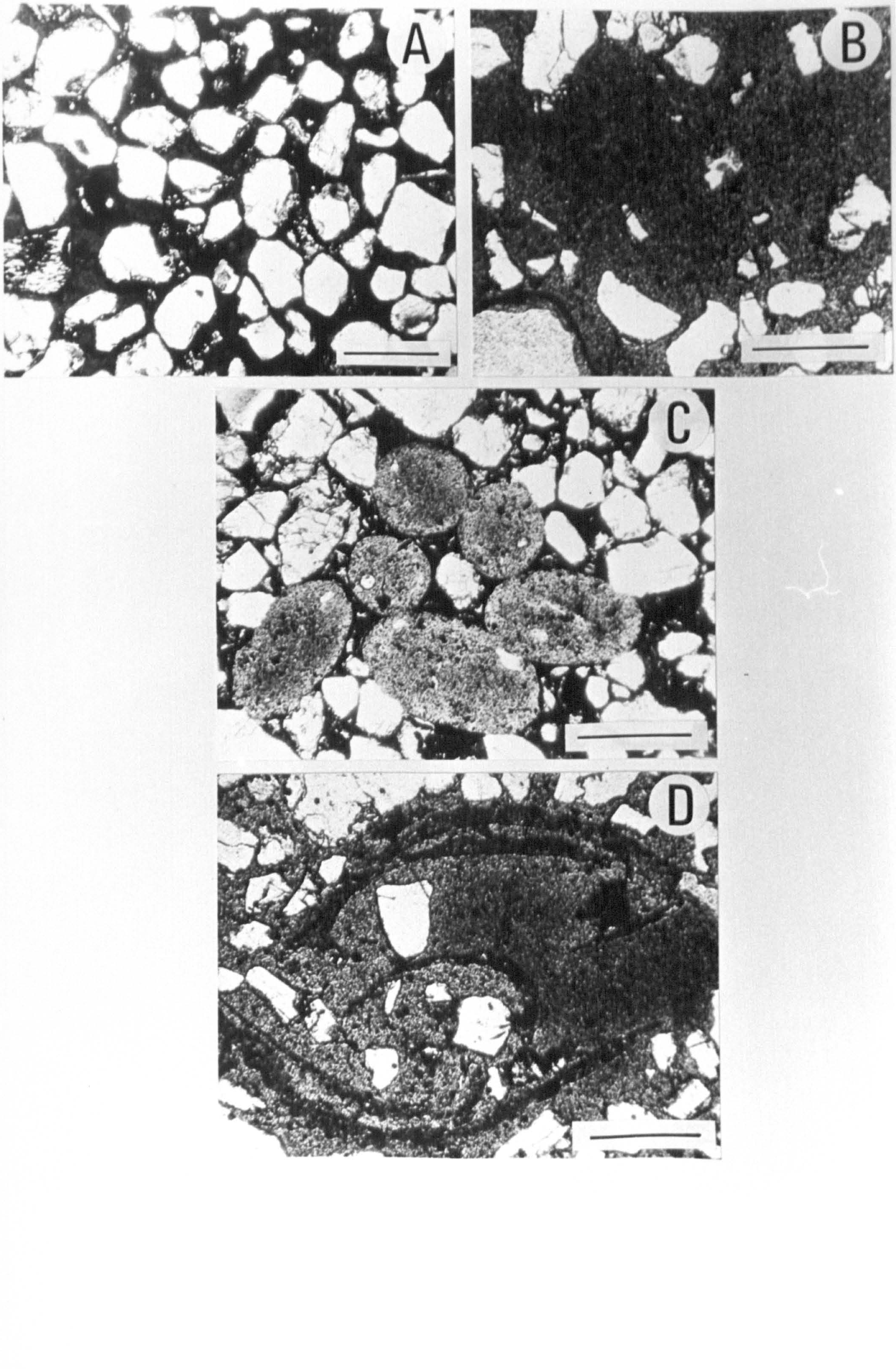

A
B
C
D

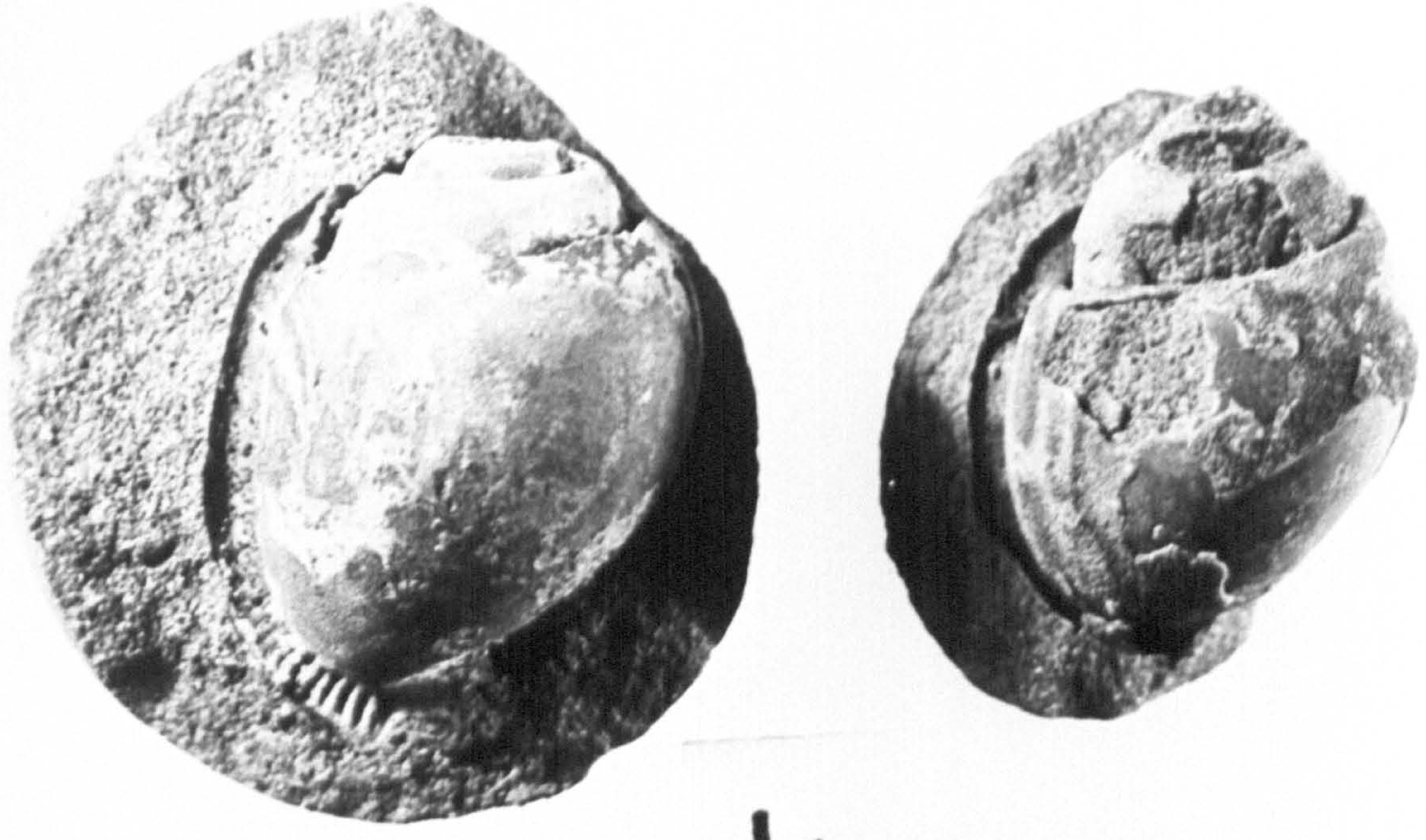
Plate 8

'Boxstone' Mollusca

A *Semicassis saburon* (Bruguière). Suffolk
Left : BMNH G51188 Right : BMNH G51189

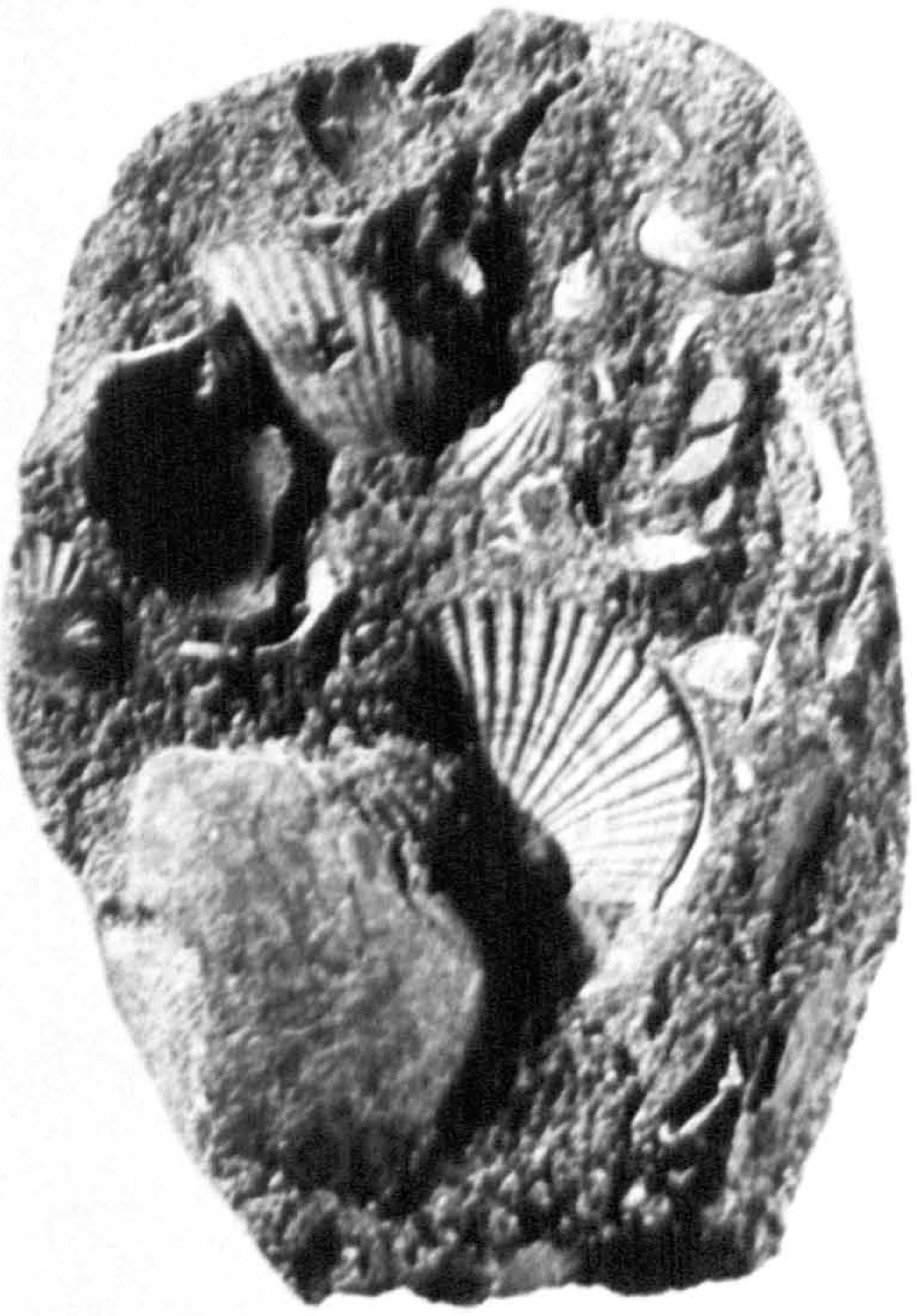
B *Glycymeris glycymeris* (Linné). Suffolk
Sedgwick Museum C48553 Goodman Collection

C Moulds of Molluscan shells on a fractured surface of a 'boxstone'. Suffolk. Sedgwick Museum C84892



A

B



C

Plate 9 Phosphatised shark material

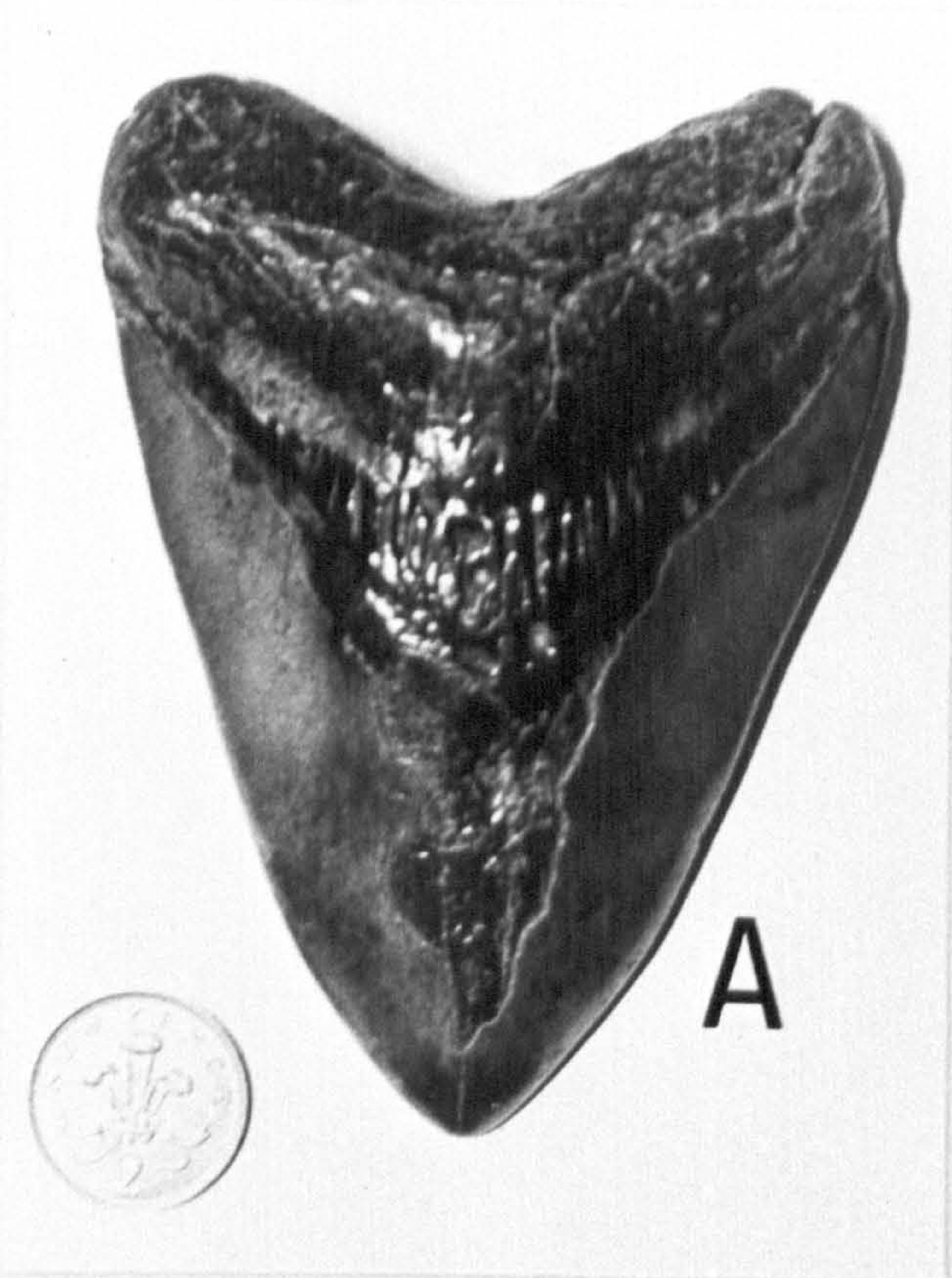
A Procarcharodon megalodon. Tooth. Ipswich Museum Collection. Coin is 26mm diameter.

B Procarcharodon megalodon. Tooth enclosed in 'boxstone' sediment. Ipswich Museum 956-149. Coin is 26mm diameter.

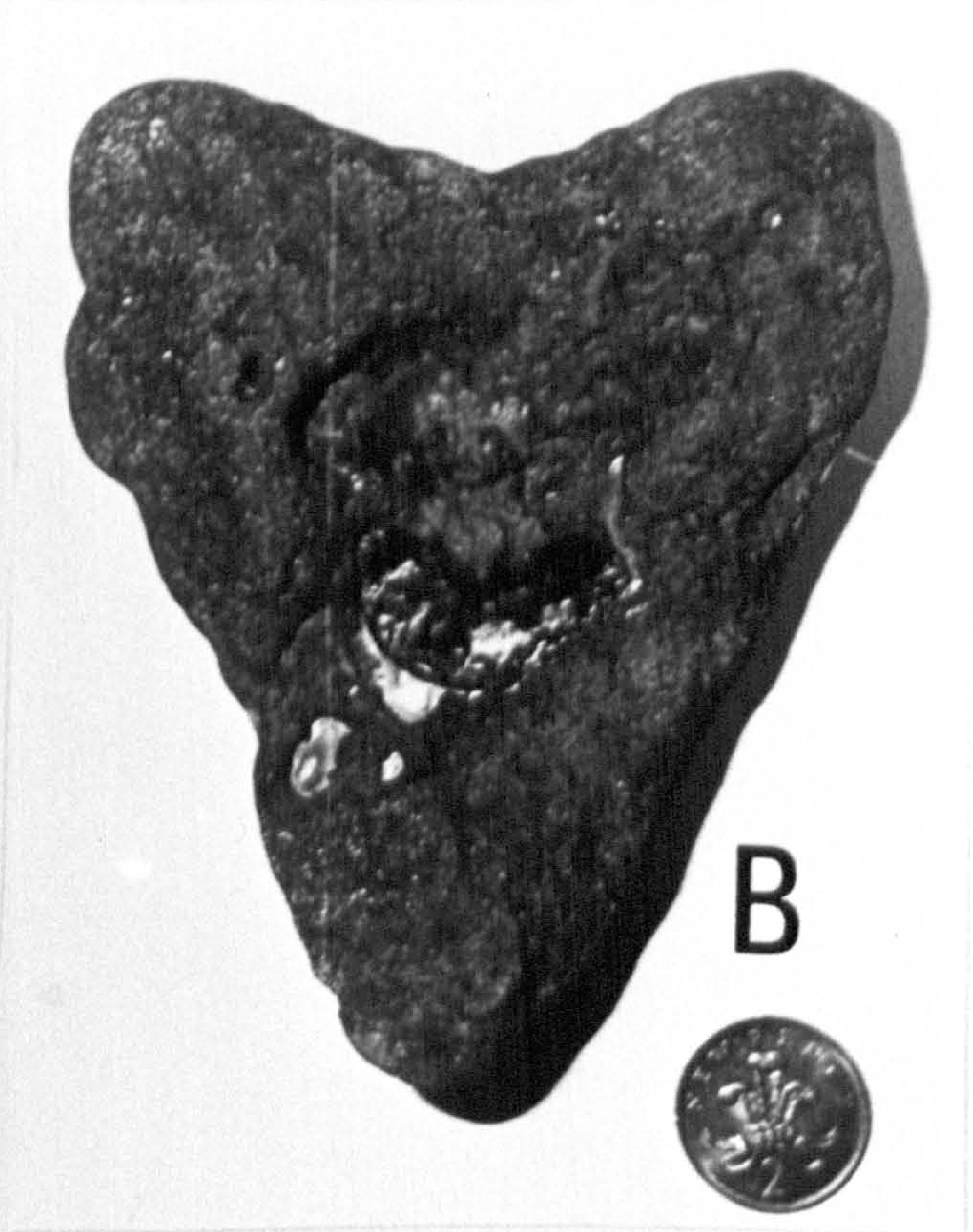
C Procarcharodon megalodon. Tooth. Root enclosed in 'boxstone' sediment. BMNH P47380. Scale bar = 1cm

D Odontaspis sp. Tooth enclosed in 'boxstone' sediment. Ipswich Museum 933-119B 46. Scale bar = 1cm

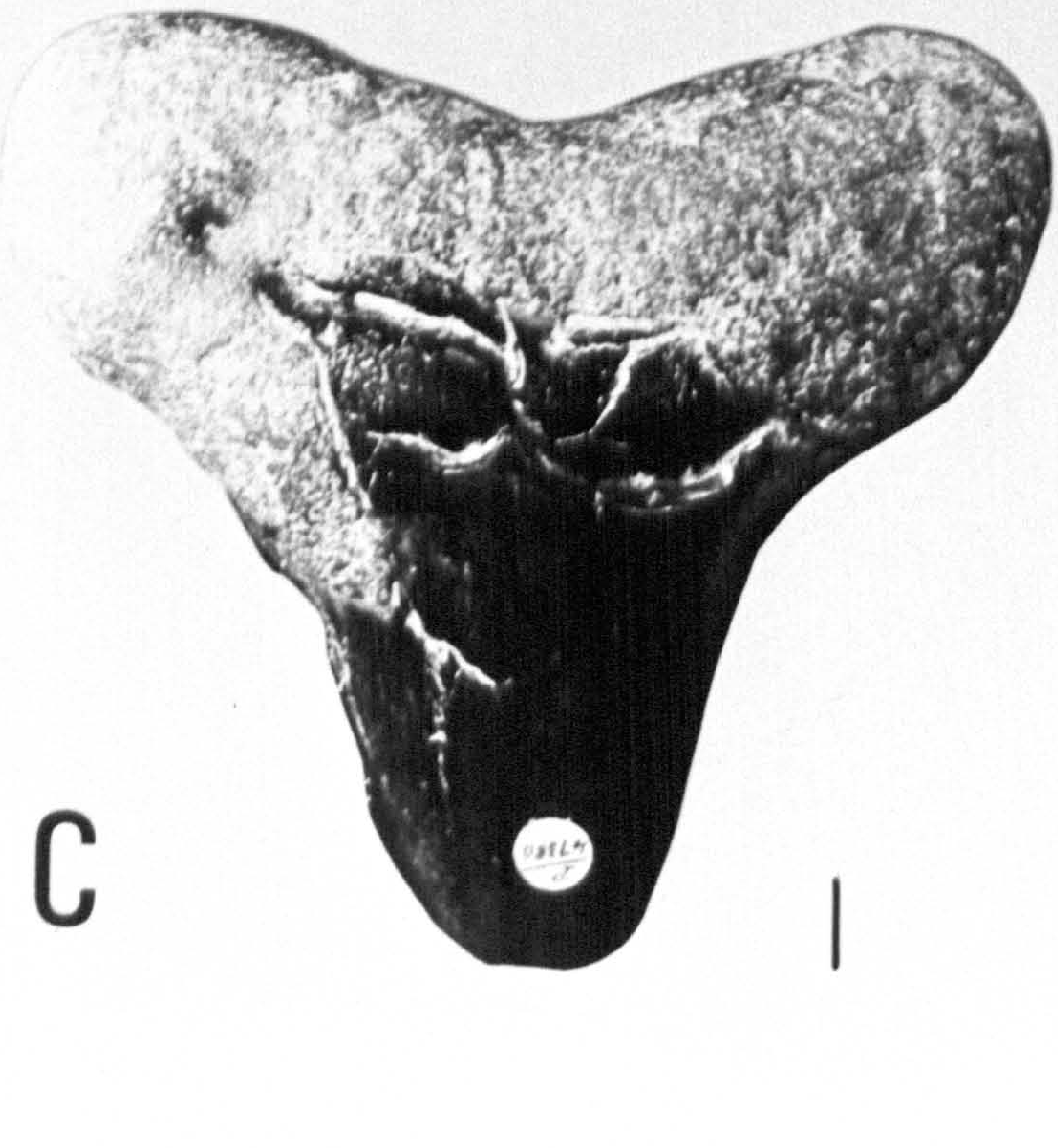
E Procarcharodon megalodon. Vertebra enclosed in 'boxstone' sediment. Ipswich Museum 933-119B 45. Scale bar = 1cm



A



B



C

D

E

Plate 10 Phosphatised Cetacean material

A Large abraded fragment of indeterminate cetacean bone.
Red Crag phosphorite deposit, Bawdsey, Suffolk.
Scale bar = 1cm

B Cetacean tooth (cf *Hoplocetus*). Red Crag, nr. Woodbridge, Suffolk. Sedgwick Museum C84896
Scale bar = 1cm

C Cetacean tooth (*Hoplocetus crassidens*) with adherent 'boxstone' sediment. Ipswich Museum Collection.
Scale bar = 1cm

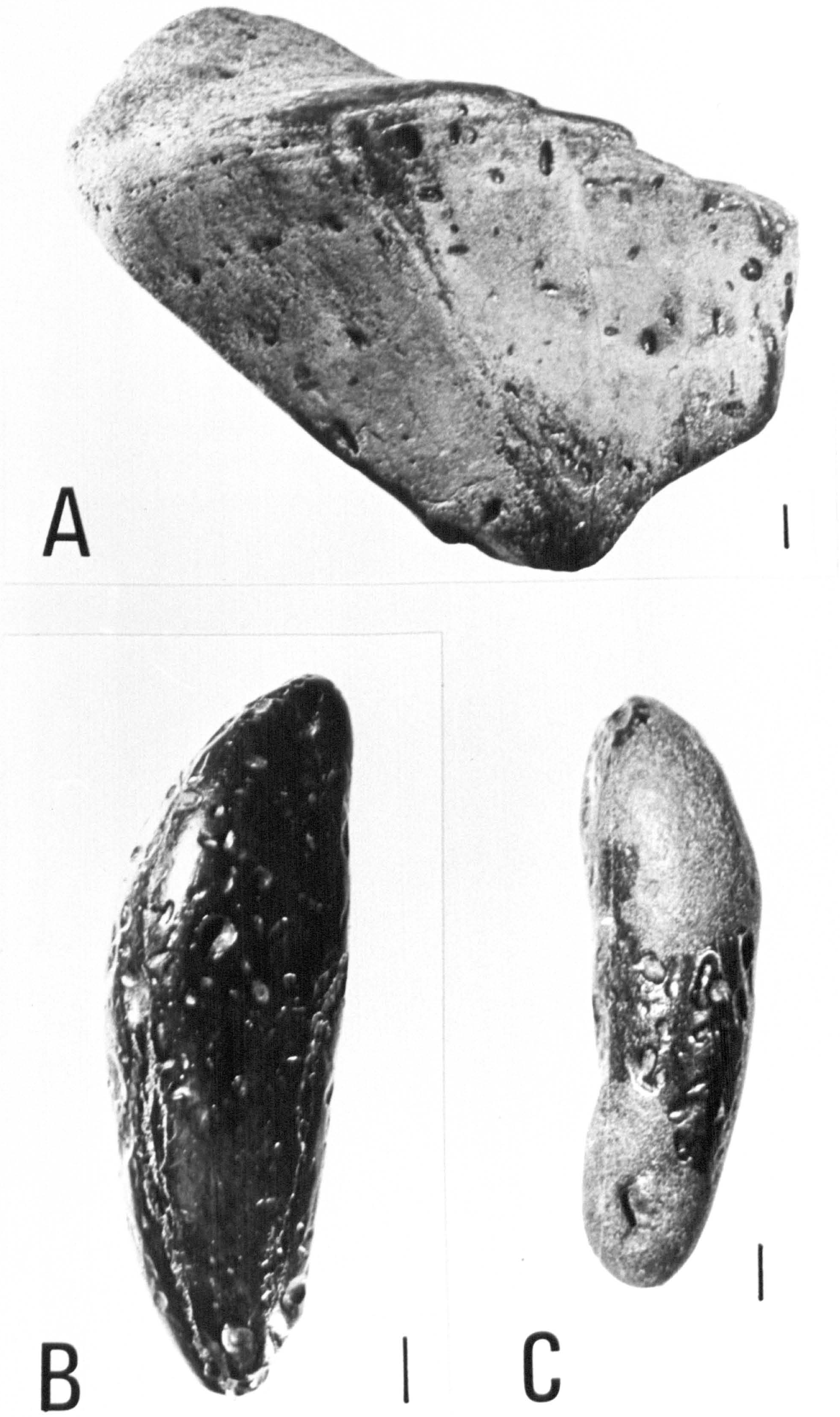

A
B
C

Plate 11

Phosphatised Wood from the Crag Phosphorite Deposit

A Fragment of phosphatised wood. Sedgwick Museum C84891a.
Scale bar = 1cm

B Polished transverse section of phosphatised wood. Note well defined growth rings. Red Crag, Woodbridge, Suffolk.
Sedgwick Museum K5325. E.Charlesworth Collection (1876).

C Thin section of phosphatised wood showing fine presevation of wood tissue and vessels. Sedgwick Museum C84891b.
Scale bar = 500μm

D Thin section of phosphatised wood at higher magnification showing detail of tracheids in transverse section. Apparent pairing is due to longitudinal overlap. Sedgwick Museum C 84891b.
Scale bar = 100μm


A
B
1cm
C
D

Plate 12

Facies A : Sedimentary features

A Bioturbated Coralline Crag sediments with no clearly defined sedimentary structures overlain by Red Crag. Facies A1 .
Tattingstone Hall (locality 2).
Staff graduated in cm.

B Coralline Crag with no well defined sedimentary structures in lower part of face, grading upwards into trough cross-bedded sediments deposited by the migration of megaripples.
Amplitude of megaripples roughly 50cm. Facies A2-A3.
Rockhall Wood (locality 6).
Scale is 1m long.

C Well defined trough cross-bedding produced by migrating megaripples. Foresets often show silt drapes. Large fissure containing reprecipitated calcite at far left. Facies A3.
Rockhall Wood (locality 4).
Scale is 1m long.

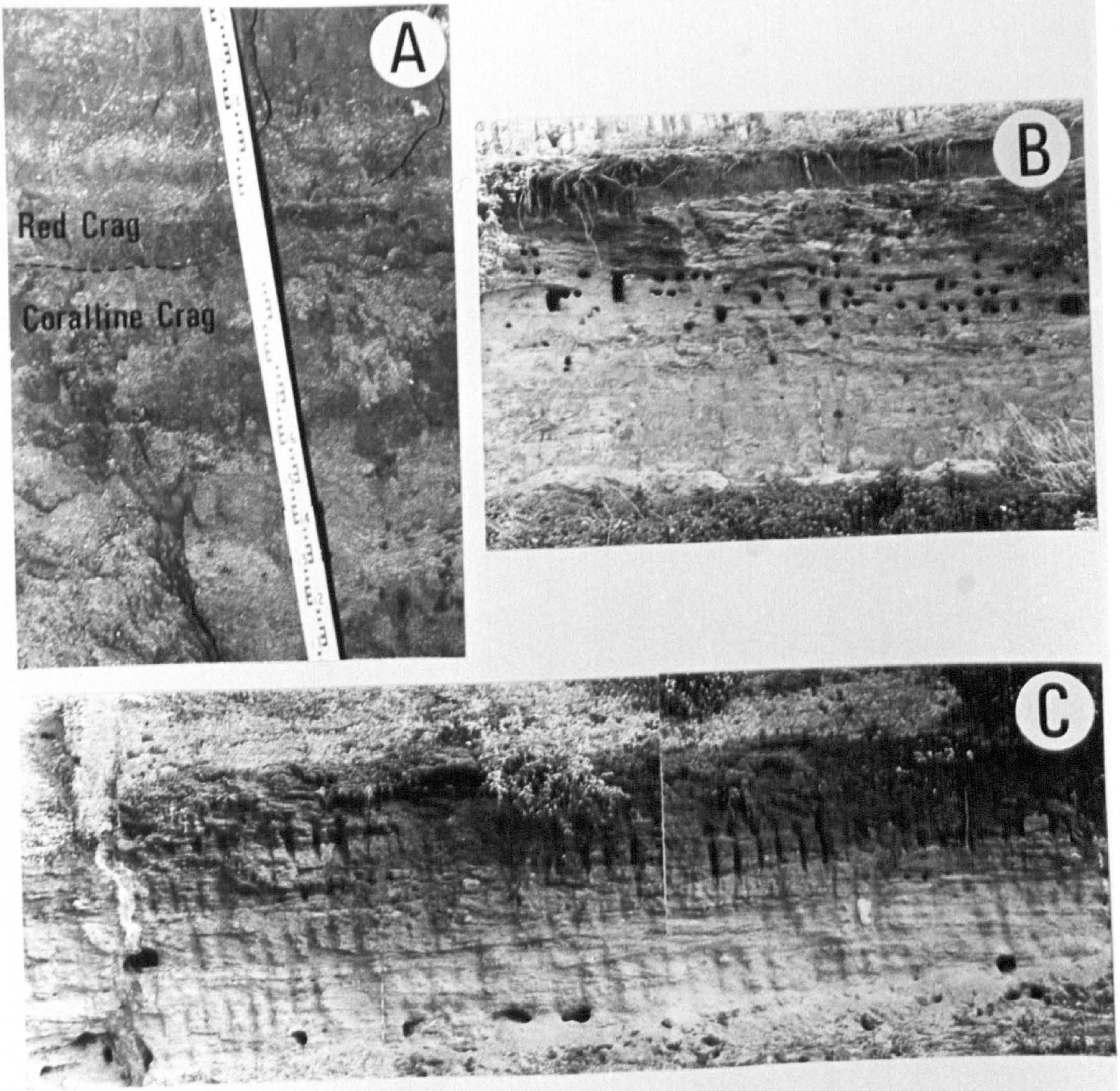

A
Red Crag
Coralline Crag
B
C

Plate 13

Facies B : Sedimentary features

A-B Large-scale cross-bedding produced by the migration of sandwaves with an amplitude of approximately 1-2m.
A : Crag Farm (locality 20). Scale is 1m long.
B : Crag Farm (locality 21). Face is 3m high.

C Section at right angles to section shown in A shows large-scale trough cross-bedding. This indicates that the sandwave front was probably sinuous. Crag Farm (locality 20).
Face is 2m high.

D Angular truncation between two cross-bedded units.
Richmond Farm (locality 11).
Scale is 1m long.

E Individual foreset laminations. Direction of current transport is away from the observer at right angles to the face.
Scale is 30cm long.

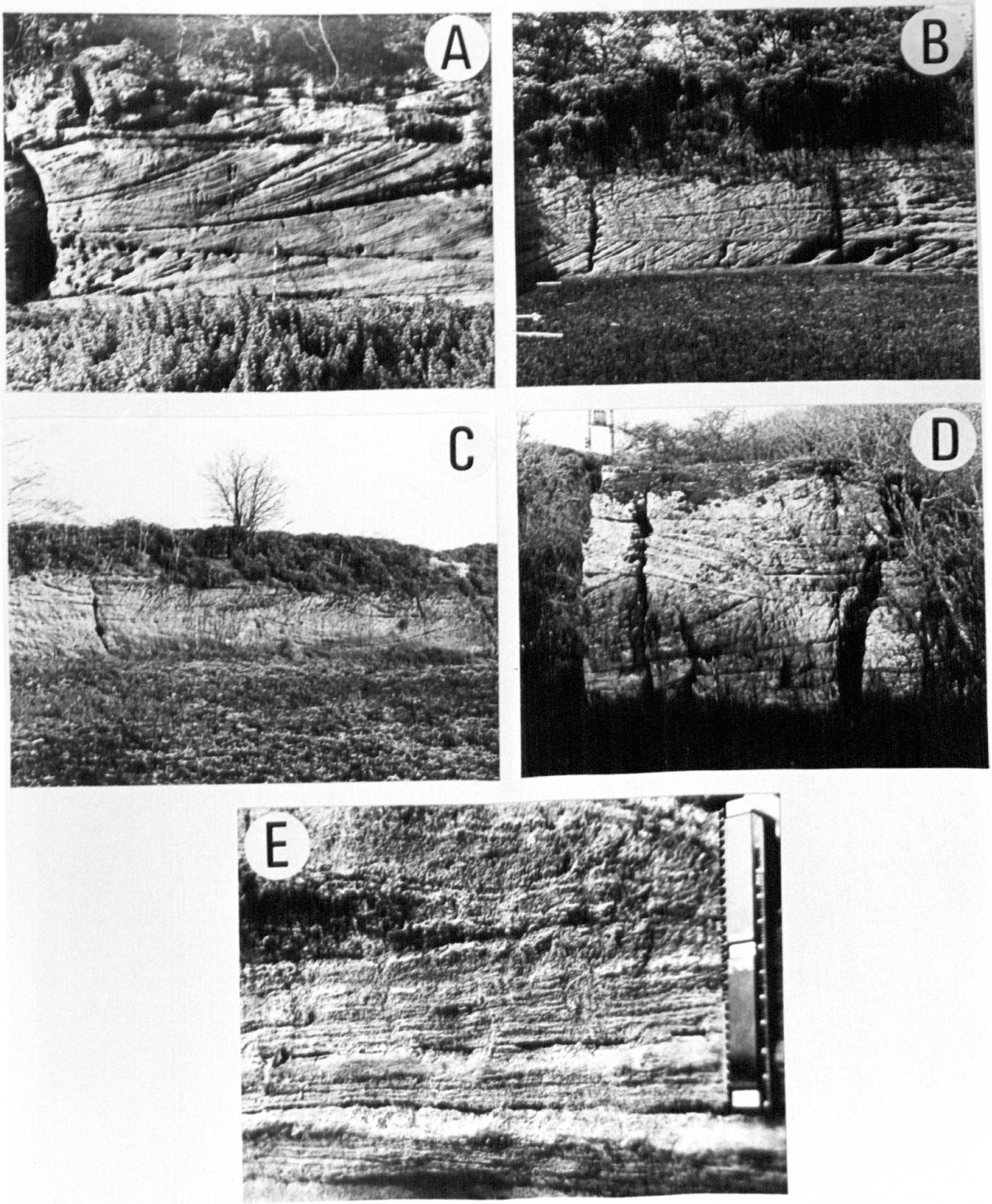

A
B
C
D
E

Plate 14

Facies C Sedimentary features

A Horizontal bedding at Crag Pit Nursery (locality 38). Two solution pipes can be seen extending downwards from the upper surface of the Coralline Crag. The pipes are infilled by the overlying soil.
Scale is 1m long.

B Low angle bedding (dip 6-8°) at Aldeburgh Hall (locality 32).
Scale is 1m long.

C Silt band at Round Hill (locality 36).
Scale is 25cm long.

D Imbrication of shell debris as a result of burrowing activity.
Coin is 28mm diameter.

E-F Intensely bioturbated sediment at Round Hill (locality 36).
Horizontal burrows weathering into relief.
E : Scale is 25cm long
F : Lens cap is 58mm diameter

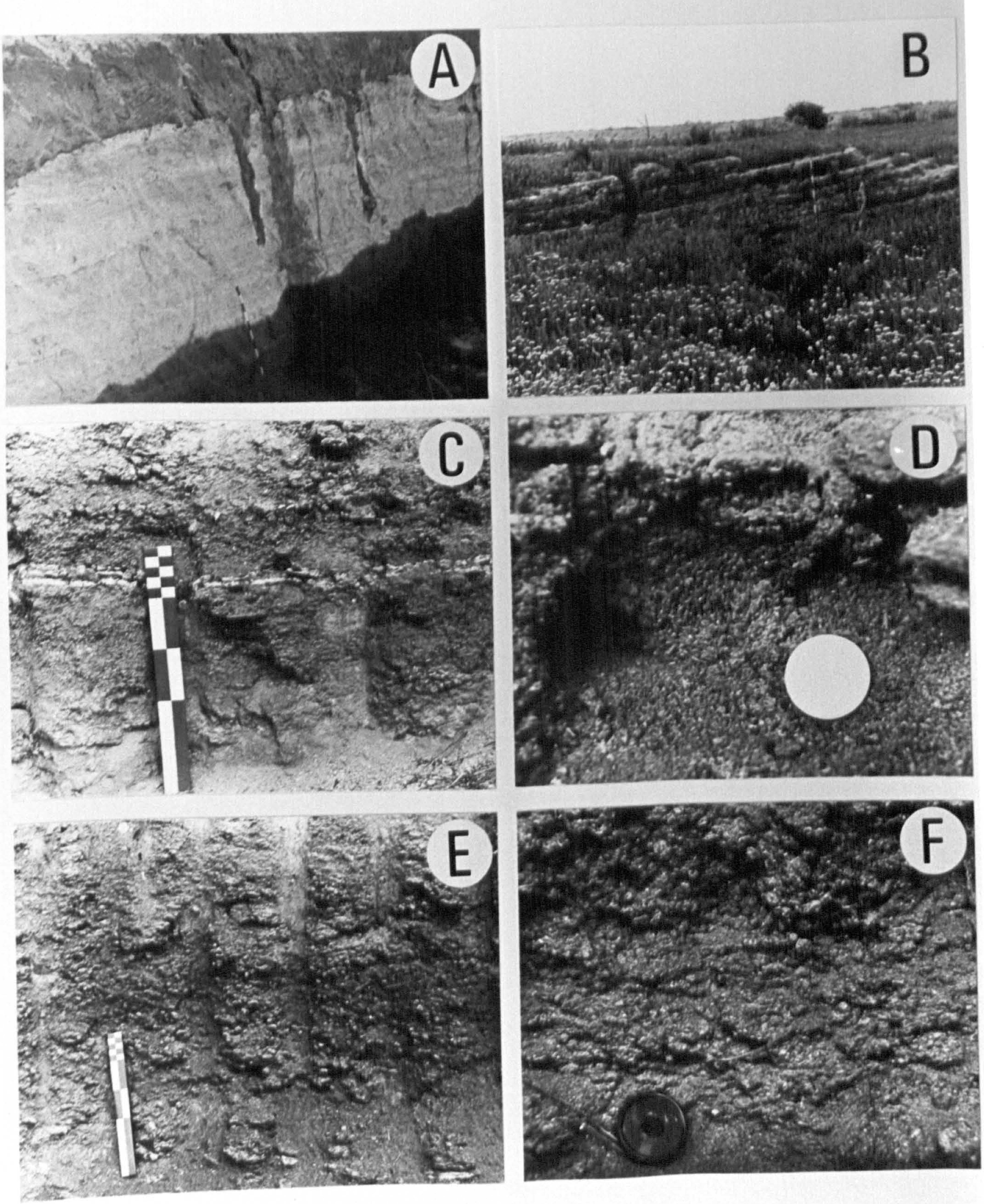

A
B
C
D
E
F

Plate 15

Solution pipes and fissures

A Vertical solution fissures containing reprecipitated calcite in cross-bedded Coralline Crag. Solution has removed aragonitic material from the sediment at this locality. Two straight fissures in the centre of the picture may have developed along vertical joint planes. Fissure to the right is more sinuous. Fissures do not seem to develop along bedding planes. Crag Farm (locality 21).
Hammer is 37 cm long.

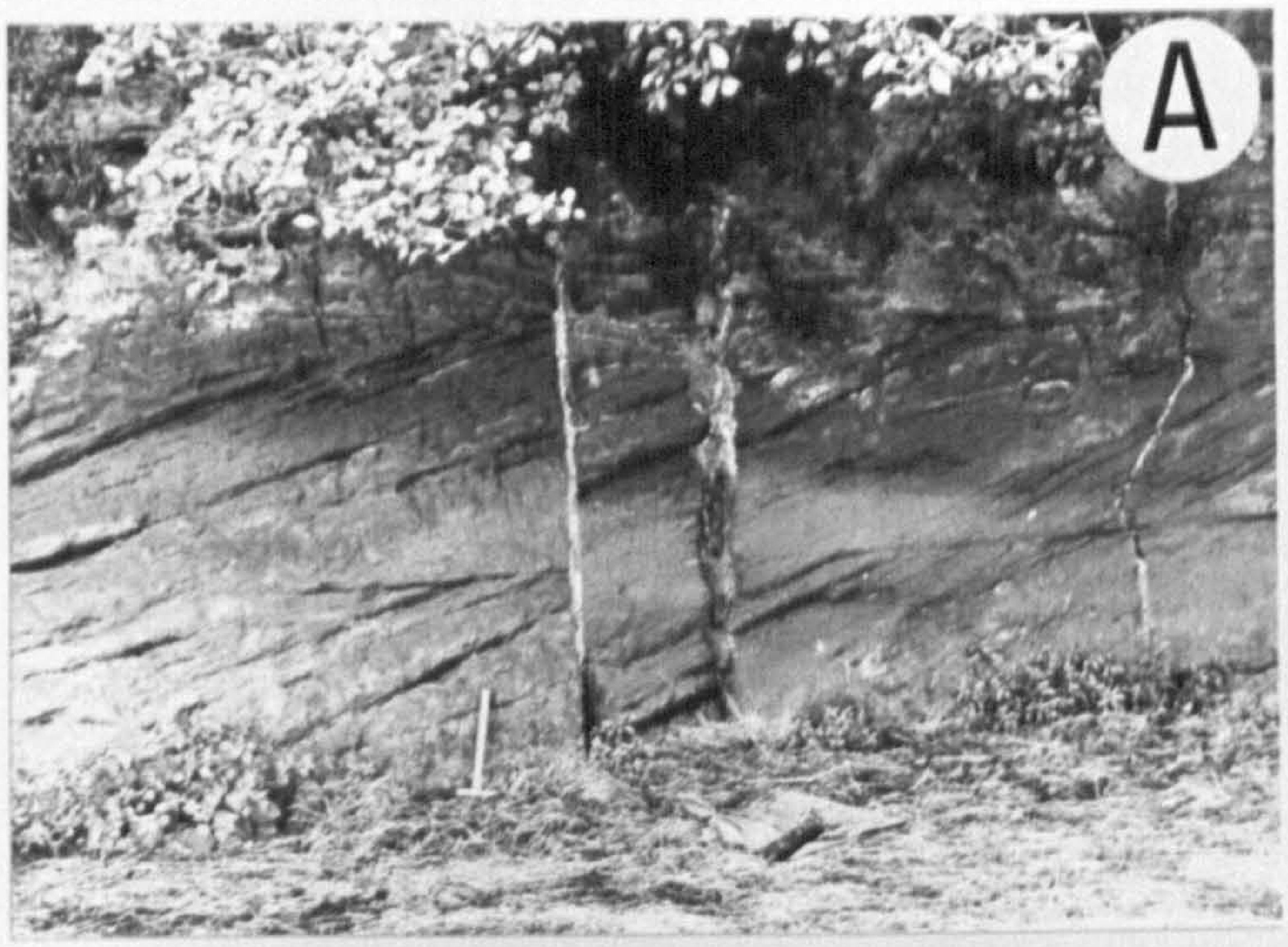
B Small fissure containing reprecipitated calcite. Solution has removed aragonitic material from the sediment at this locality. Gedgrave Cliff (locality 7).
Scale graduated in cm.

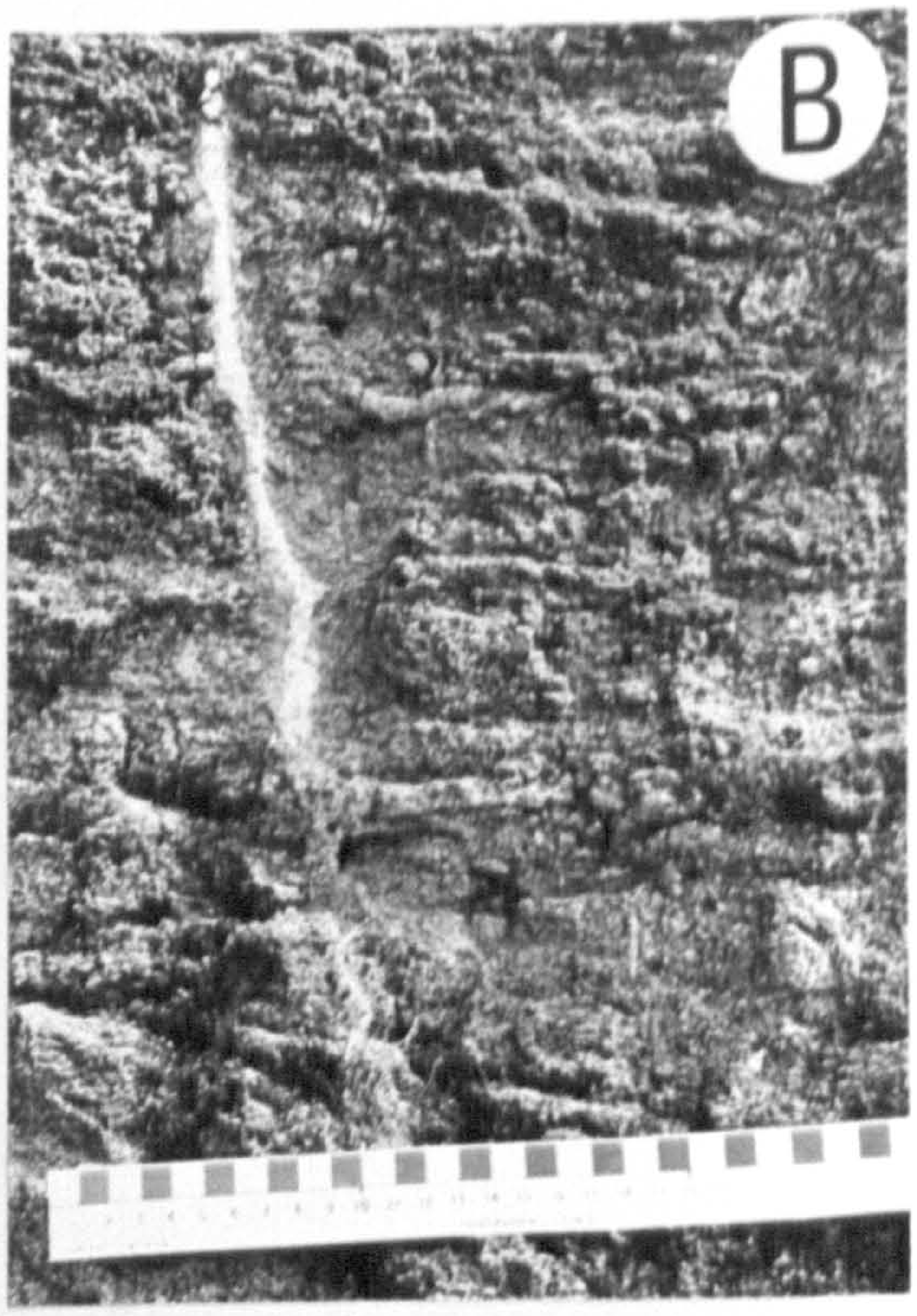
C Sinuous solution fissure containing reprecipitated calcite. Solution has removed aragonitic material from the sediment at this locality. Crag Farm (locality 20).
Scale graduated in 10cm divisions.

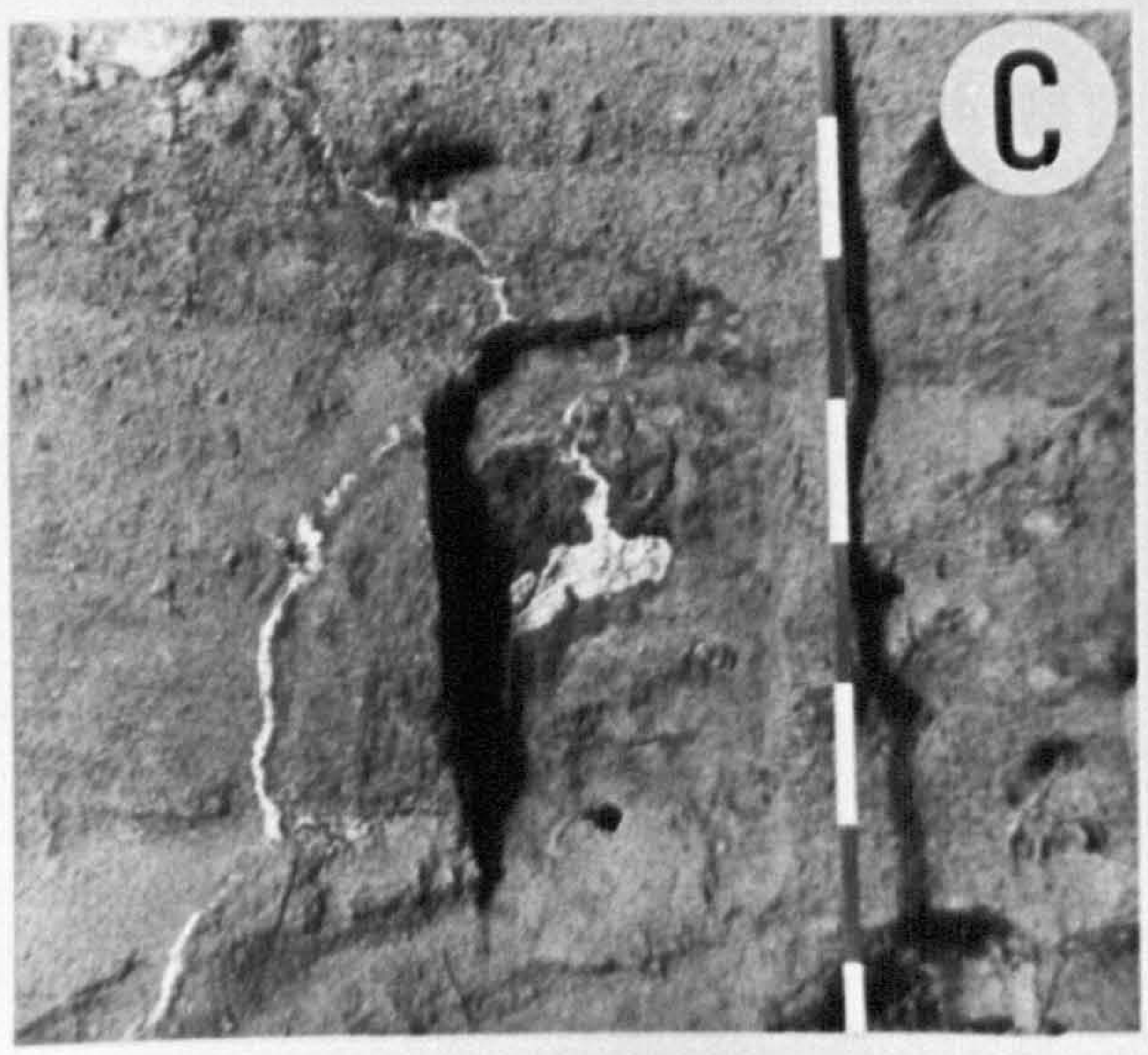
D Solution pipes in horizontally bedded Coralline Crag. Solution has removed aragonitic material from the sediment at this locality. Crag Pit Nursery (locality 38).
Scale is 1m long.

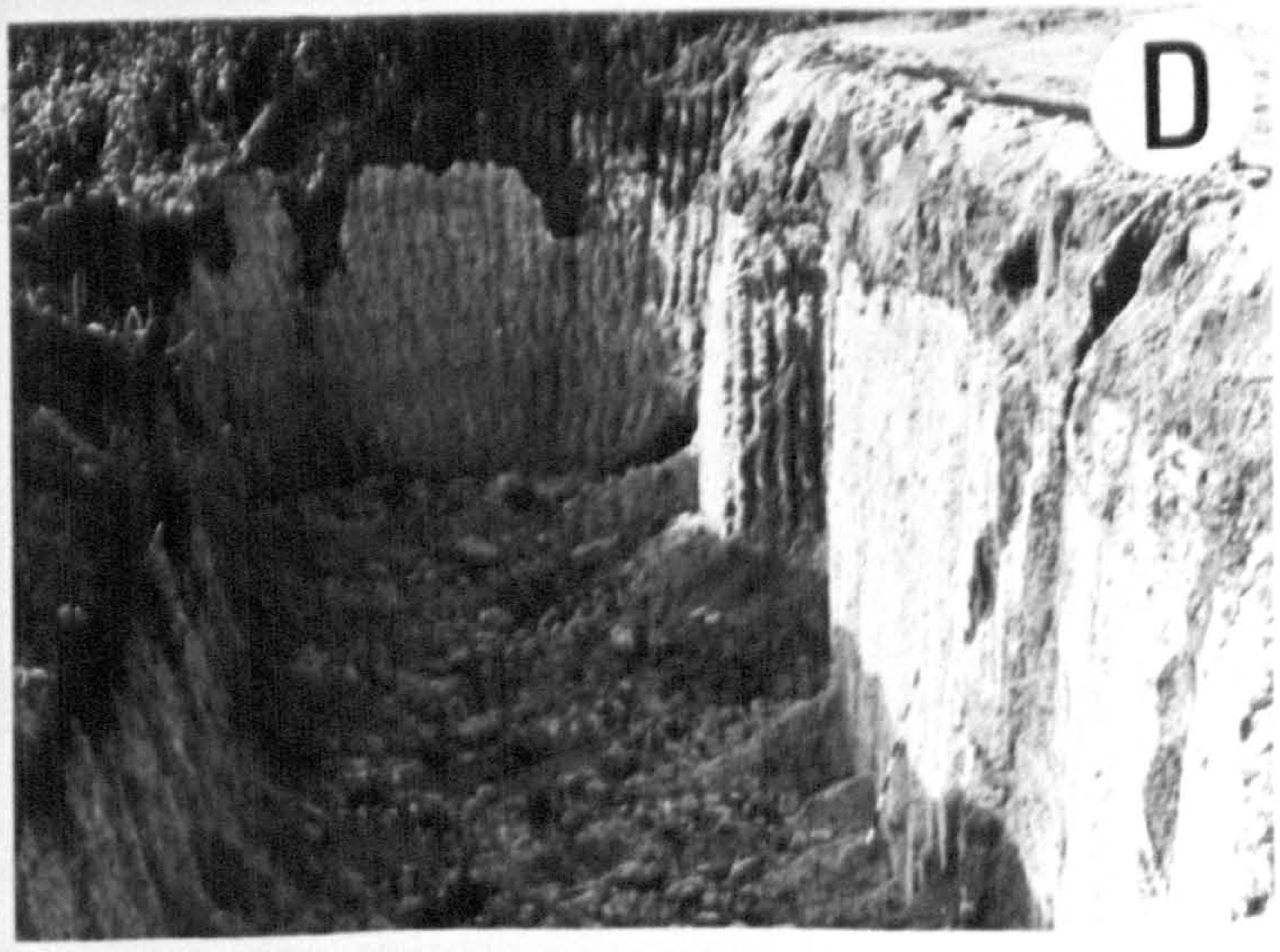
E Coralline Crag with undulose surface and solution pipes. Solution has removed aragonitic material at this locality. Round Hill (locality 36).
Scale is 1m long.

F Solution pipe. There has been no removal of aragonitic material from the Crag at this locality. Compare with A - E. Sudbourne Park (locality 16).
Scale is 1m long.


A


B


C


D


E

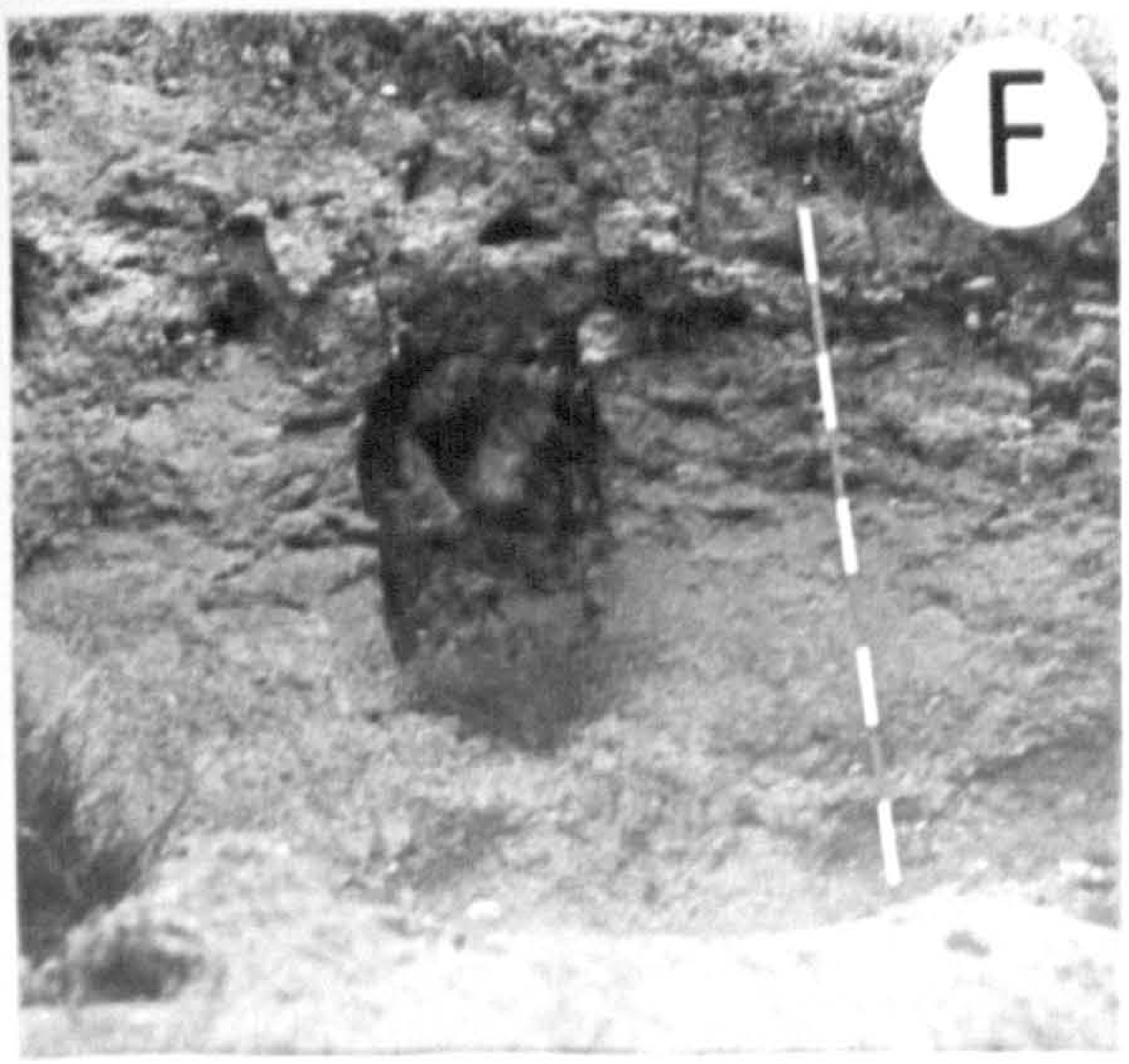

F

Plate 16 Coralline Crag petrography

A Thin section showing granular sparite infilling intergranular pore space. Tattingstone (locality 1).
Scale bar = 250µm

B Thin section showing granular sparite infilling intergranular pore space. Foraminiferid chambers (intragranular pore space) are also infilled by sparite. Tattingstone (locality 1).
Scale bar = 100µm

C Drusy sparite growing on bioclastic fragments into intergranular voids. Note increase in crystal size of mosaic away from grain boundary. Tattingstone (locality 1).
Scale bar = 100µm

D Fibrous sparite on chamber walls of a large bryozoan fragment. Sudbourne Church (locality 19).
Scale bar = 100µm

E Syntaxial calcite rim on echinoderm fragment. Fibrous sparite developed on adjacent molluscan shell fragment.
Aldeburgh Brick Pit (locality 33).
Scale bar = 100µm

F Syntaxial calcite rim on echinoderm fragment.
Aldeburgh Golf Course (locality 37).
Scale bar = 100µm

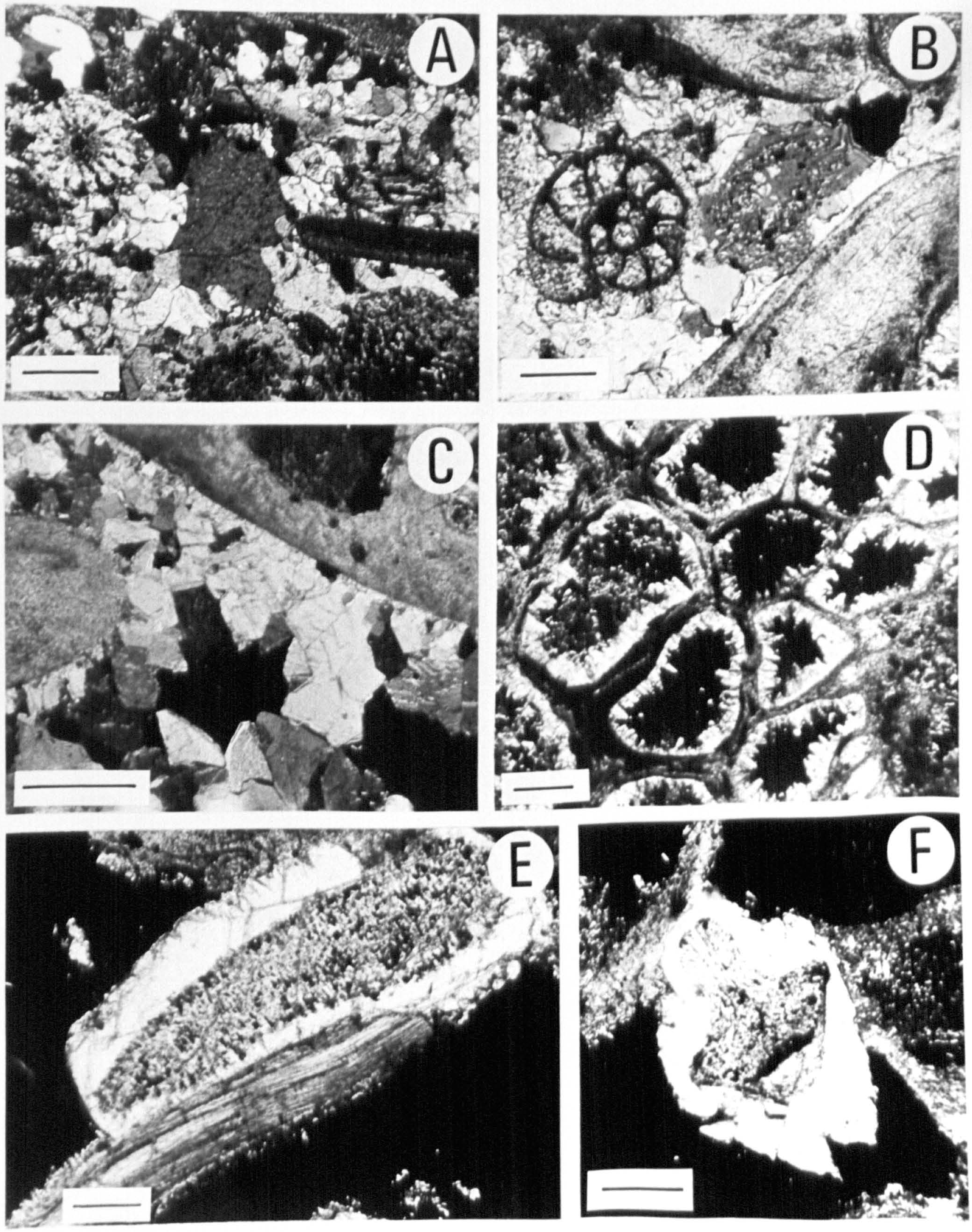
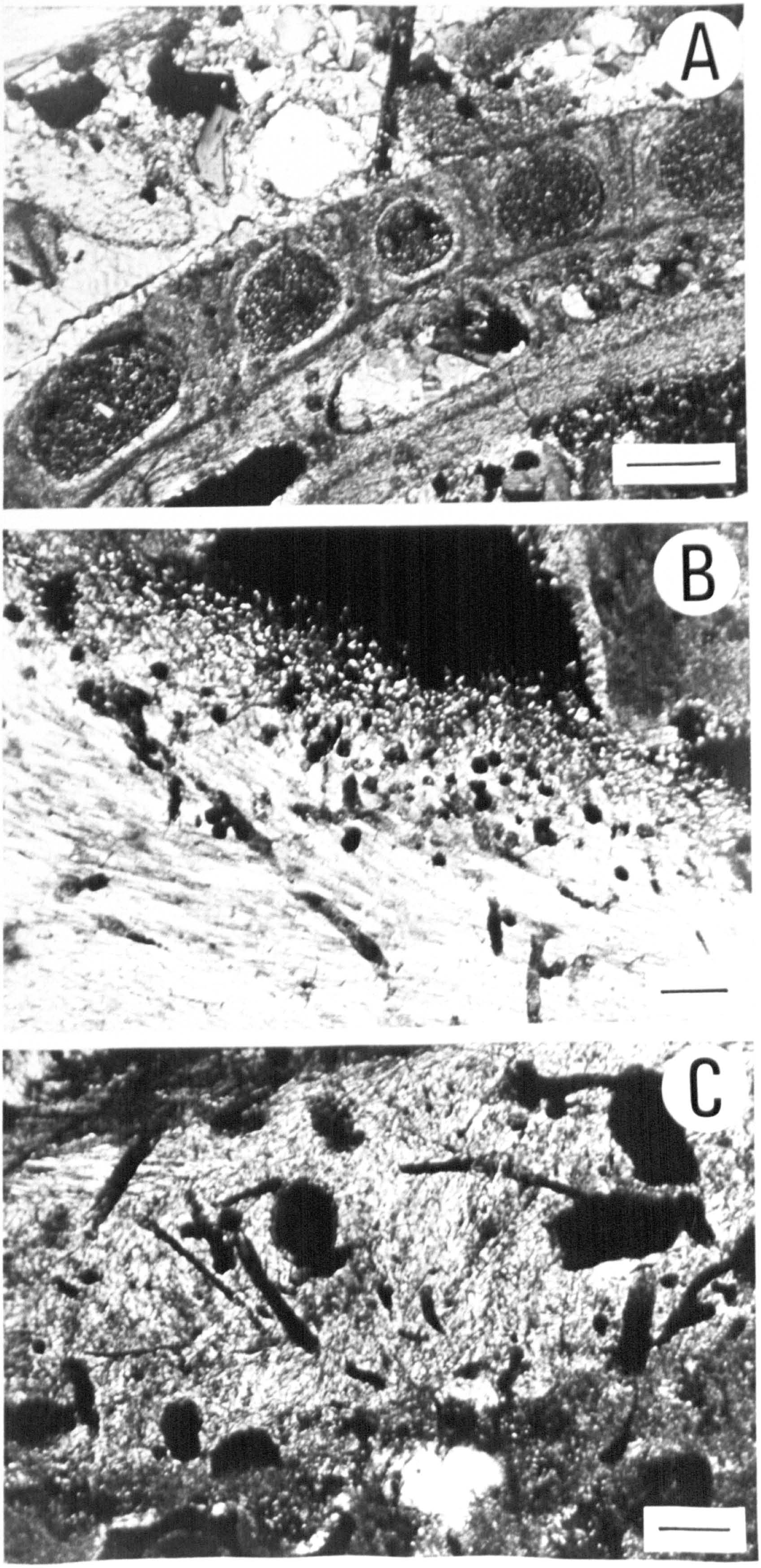

A
B
C
D
E
F

Plate 17

Authigenic glauconite in the Coralline Crag

A Thin section showing authigenic glauconite infilling intragranular pore space within a barnacle skeletal fragment. Tattingstone (locality 1).
Scale bar = 100μm

B–C Thin section showing ?algal borings in molluscan shell. Borings are infilled with iron oxides and ?oxidised glauconite.
B : River Alde (locality 35). Scale bar = 100μm
C : Gedgrave Cliff (locality 7). Scale bar = 100μm


A
B
C

A Concentration of eschariform colonies of Biflustra savartii. These colonies are not in life position but are probably very nearly in situ. Aldeburgh Hall (locality 32).
Scale is 25cm long.

B Eschariform colony of Biflustra savartii. Aldeburgh Hall (locality 32).
Coin is 24mm diameter.

C In situ colony of Cellaria. Aldeburgh Hall (locality 32).
Coin is 24mm diameter.

D Articulated specimen of Cellaria. Locality unknown.
Sedgwick Museum specimen.
Scale bar = 5mm

E Abundant large Cyclostomes and celleporiform Cheilostomes (arrowed) exposed on a bedding plane. Aldeburgh Hall (locality 32).
Scale is 30cm long.

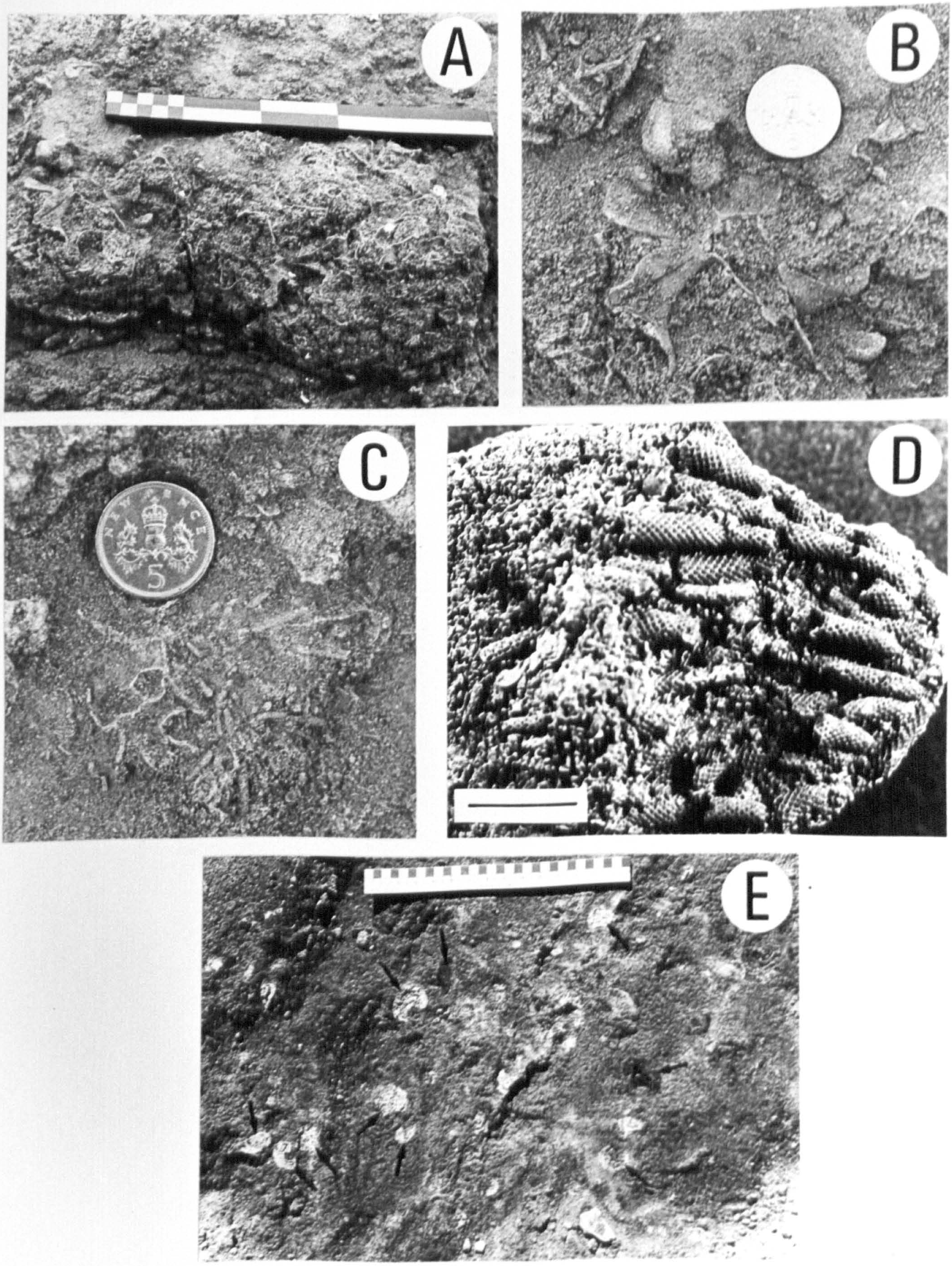

A
B
C
NEW PENCE
5
D
E

Plate 19

Meandropora aurantium (Milne Edwards, 1838)

A Surface view of spheroidal colony. Individual fascicles can be seen. Sedgwick Museum C51085.
Scale bar = 1cm

B Surface view of colony. Note coalescence of fascicles.
Sedgwick Museum C51082 Broom Pit, Gedgrave.
Scale bar = 1cm

C Fractured section of colony showing cyclical growth banding.
Aldeburgh Hall (locality 32).
Scale bar = 1cm

D Fractured section of colony showing detail of fascicles.
Aldeburgh Hall (locality 32).
Scale bar = 5mm

E Colony surface showing ovicells developed between fascicles.
Scale bar = 1cm

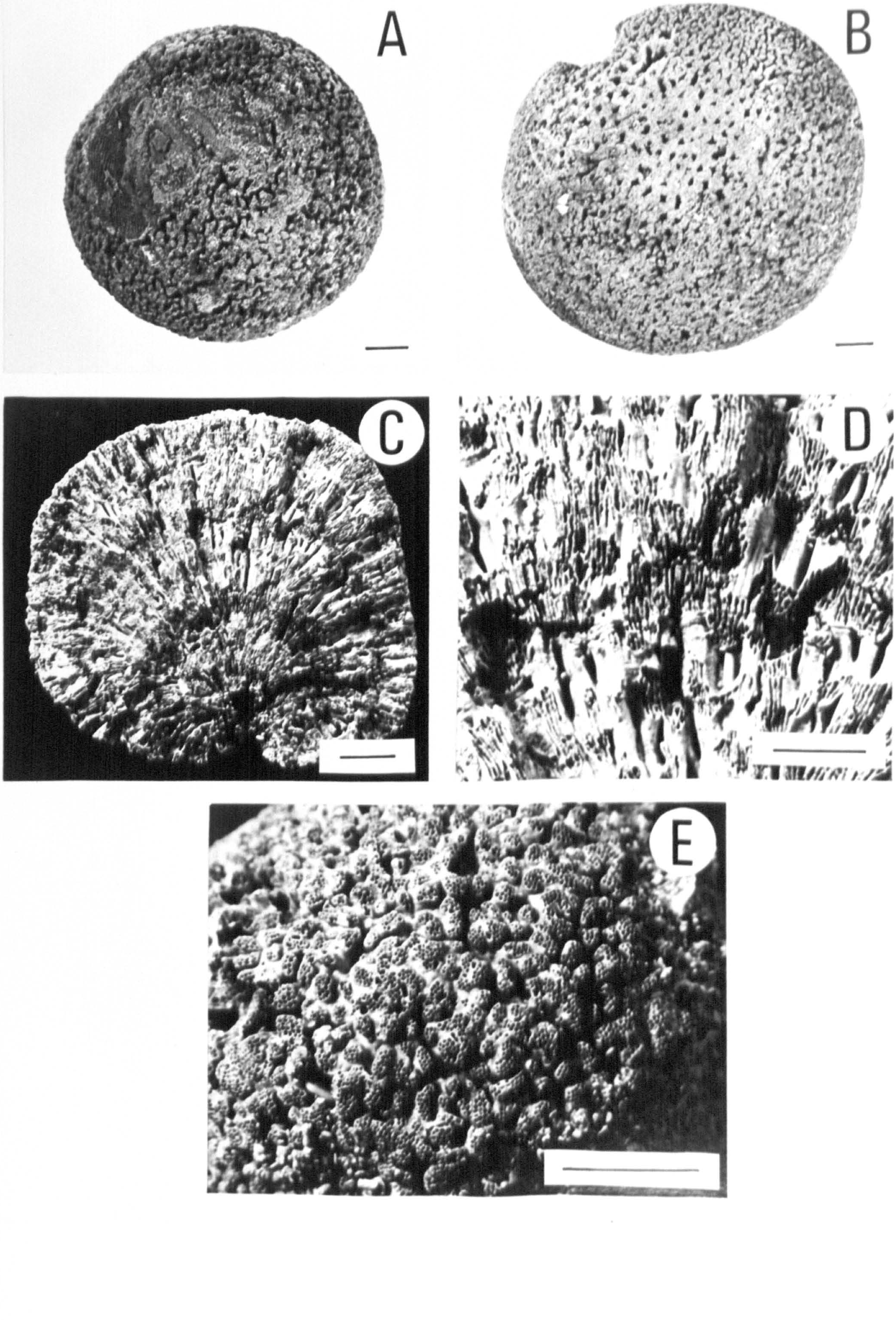

A
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Plate 20

Meandropora tubipora (Busk, 1859)

A Spheroidal colony. Crag Pit Nursery (locality 38).
Scale bar = 1cm

B-C Fractured section of colony showing fascicles and horizontal platforms.
B : Scale bar = 1cm
C : Scale bar = 5mm

D Scanning electron micrograph of colony surface. Zooids between fascicles are covered by terminal diaphragms.
Scale bar = 1mm

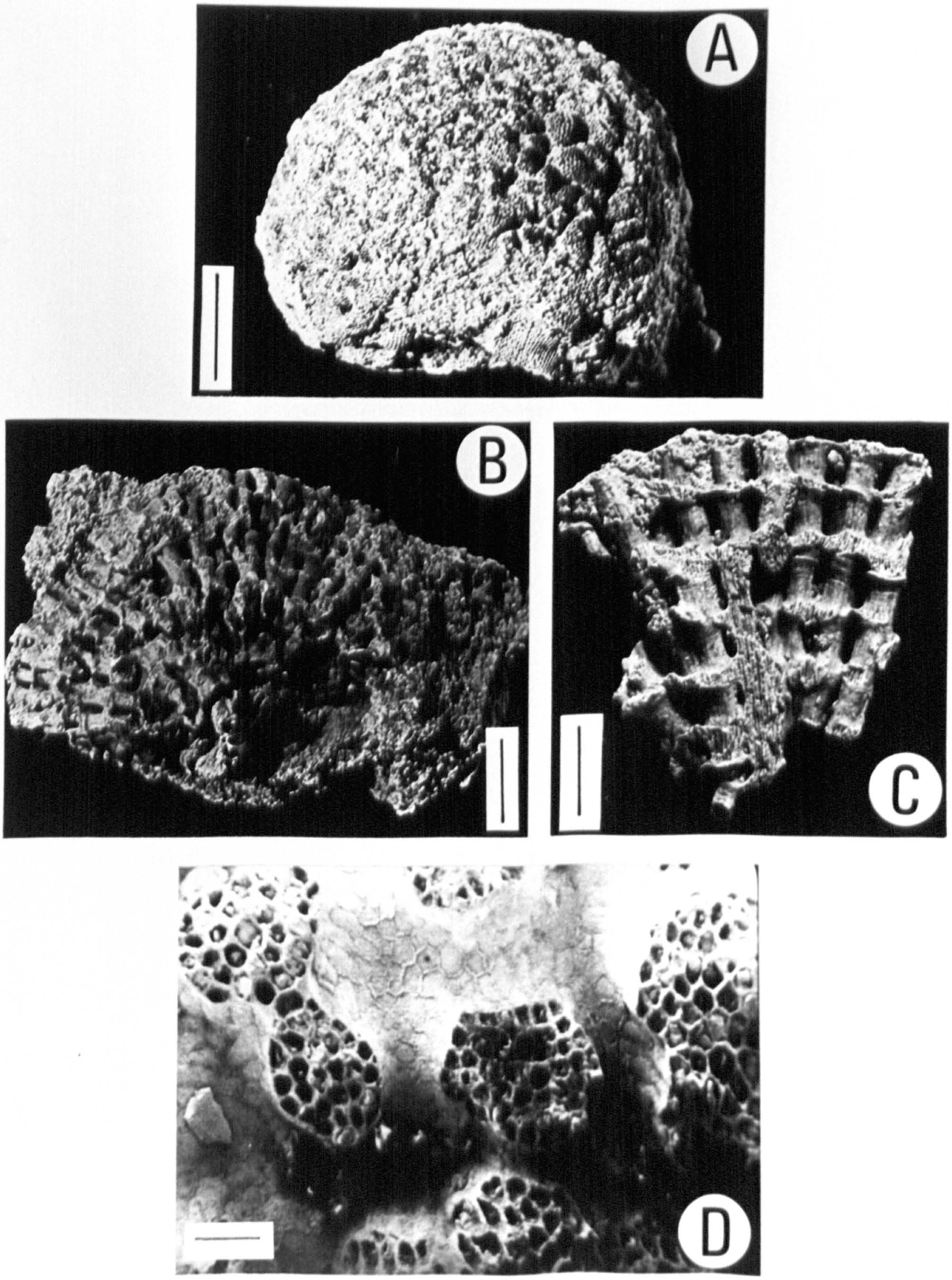
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Plate 21

Blumenbachium globosum Koenig, 1825

A Spheroidal colony. Aldeburgh Hall (locality 32).
Scale bar = 1cm

B Section through spheroidal colony. Substrate was an aragonitic bivalve shell (subsequently removed by solution) with an encrusting celleporiform Cheilostome. Note layered nature of colony growth. Aldeburgh Hall (locality 32).
Scale bar = 1cm

C-E Views of colony surface showing various stages of colony development. Crag Pit Nursery (locality 38).
Scale bars = 5mm

F Scanning electron micrograph of colony surface.
Aldeburgh Hall (locality 32).
Scale bar = 1mm

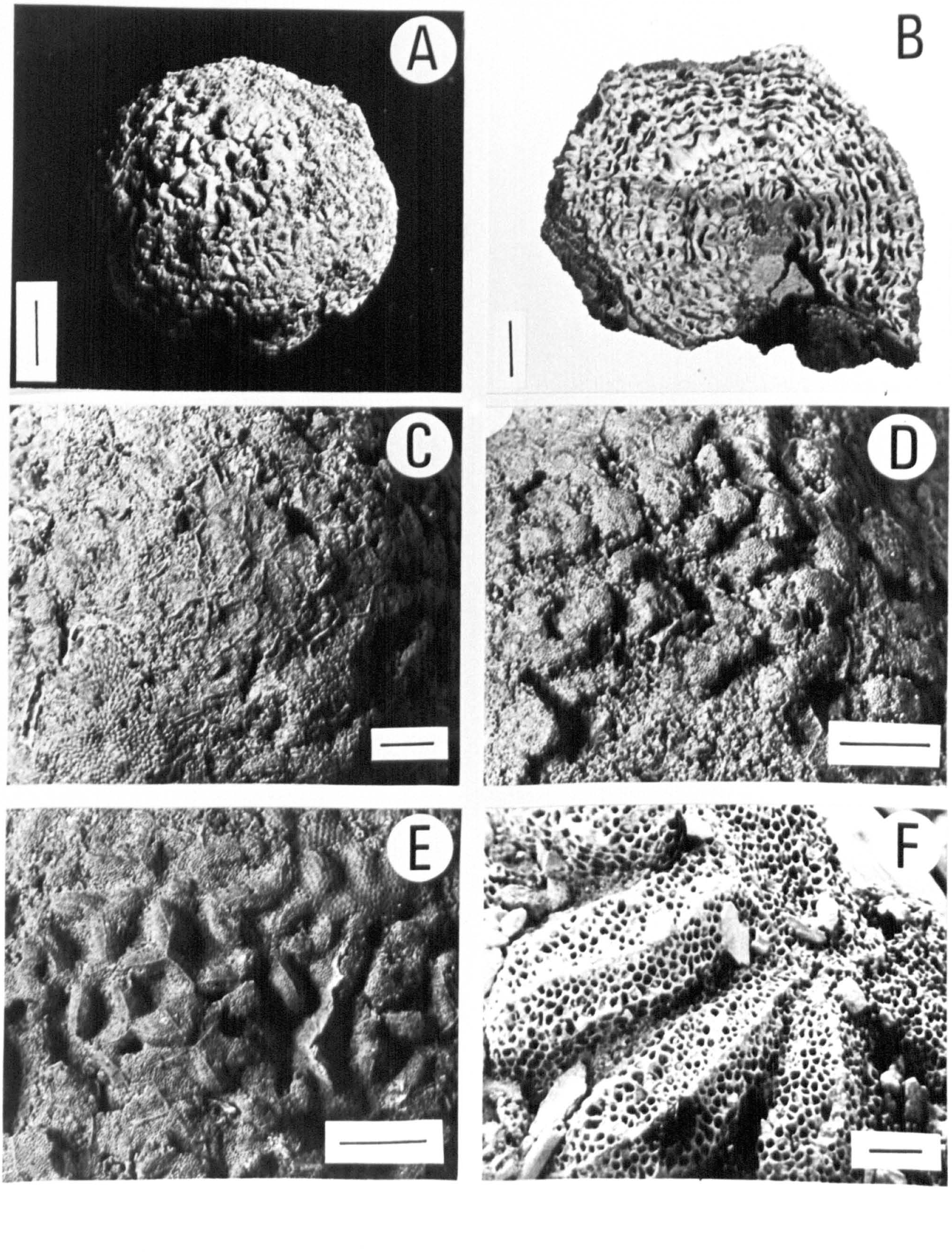
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Plate 22

?Multifascigera sp nov. All specimens from Ramsholt Cliff (locality 3)

A Colony surface showing mamelons formed by individual subcolonies.
Scale bar = 5mm

B Fractured colony showing layered nature of colony growth in transverse view.
Scale bar = 1cm

C Fractured colony showing detail of layered colony growth-form. The subcolonies of each generation were initially separate and bounded by exoskeletal walls but during upward growth some expanded outwards, contacted adjacent expanding subcolonies and overarched the remaining subcolonies. This gave rise to a continuous platform of zooecia. A new generation of subcolonies then formed on top of the platform.
Scale bar = 5mm

D Scanning electron micrograph showing interzooidal pores on exoskeletal walls (arrowed).
Scale bar = 500μm

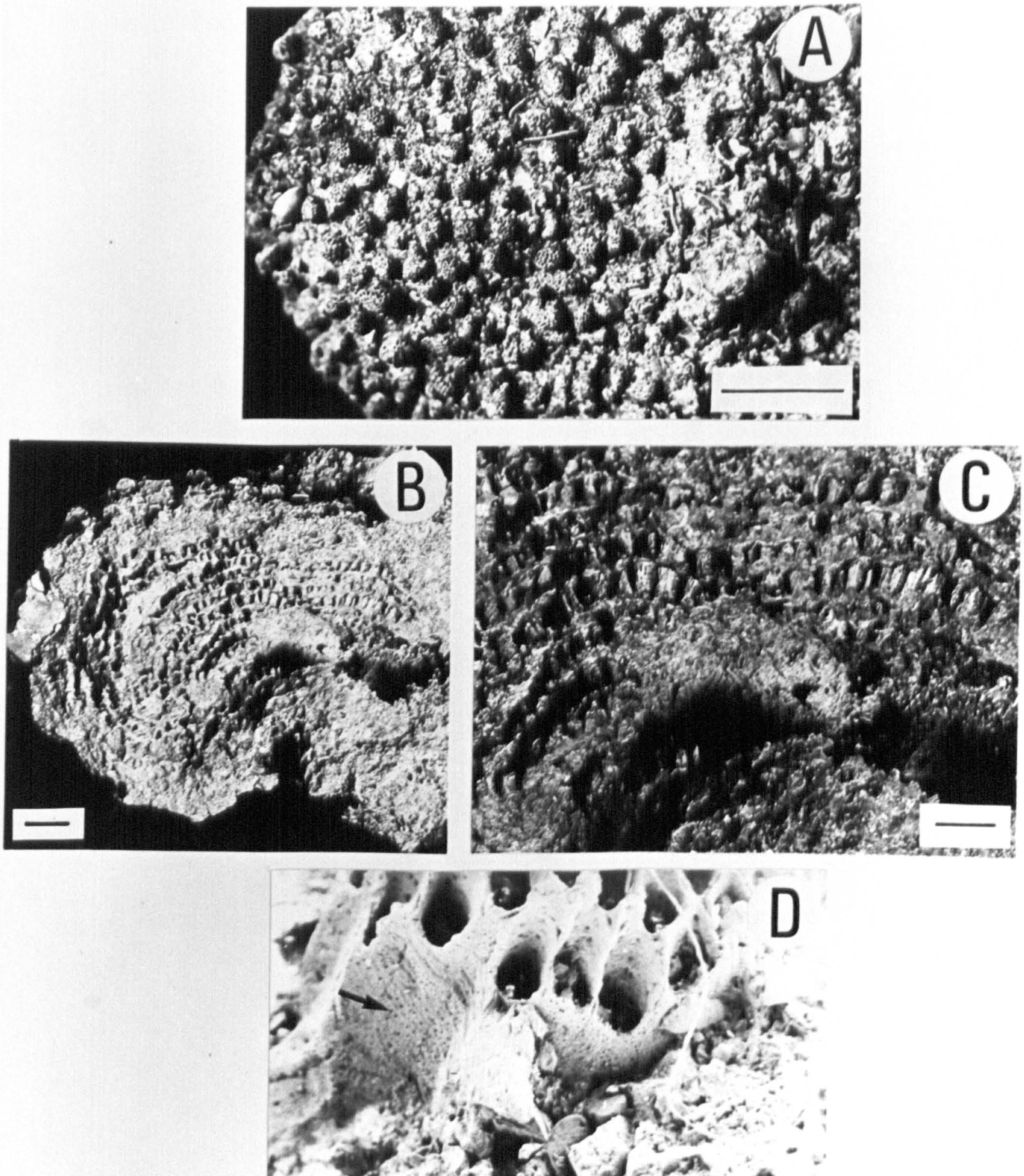
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Plate 23

Circumrotatory and non-circumrotatory growth in large Cyclostomes.

A *Blumenbachium globosum*, Aldeburgh Hall (locality 32)
Colony showing non-circumrotatory growth. Substrate was probably a bivalve shell.
Scale bar = 1cm

B *Meandropora aurantium*, Suffolk (locality unknown)
BMNH B4306, Bowerbank Collection
Colony showing non-circumrotatory growth. Substrate was a bivalve shell.
Scale bar = 1cm

C *B. globosum* Red House Farm Reservoir (locality 28)
Spheroidal non-circumrotatory colony. Colony was supported above the sediment surface by an elongate organic substrate allowing spheroidal growth. The substrate is not preserved but is recorded as a narrow cylindrical cast which opens onto the surface of the colony as a small aperture (arrowed).
Scale bar = 5mm

D *M. aurantium* (locality unknown) Sedgwick Museum C51085
Spheroidal non-circumrotatory colony. Colony was supported above the sediment surface allowing spheroidal growth.
Scale bar = 1cm

E *B. globosum* (Suffolk, locality unknown) BMNH D51070 Mantell Collection. Circumrotatory colony enclosing a celleporiform Cheilostome substrate.
Scale bar = 1cm

F *M. aurantium* Aldeburgh Hall (locality 32)
Circumrotatory colony which enclosed an aragonitic bivalve shell substrate. Shell has been subsequently removed by solution.
Scale bar = 1cm

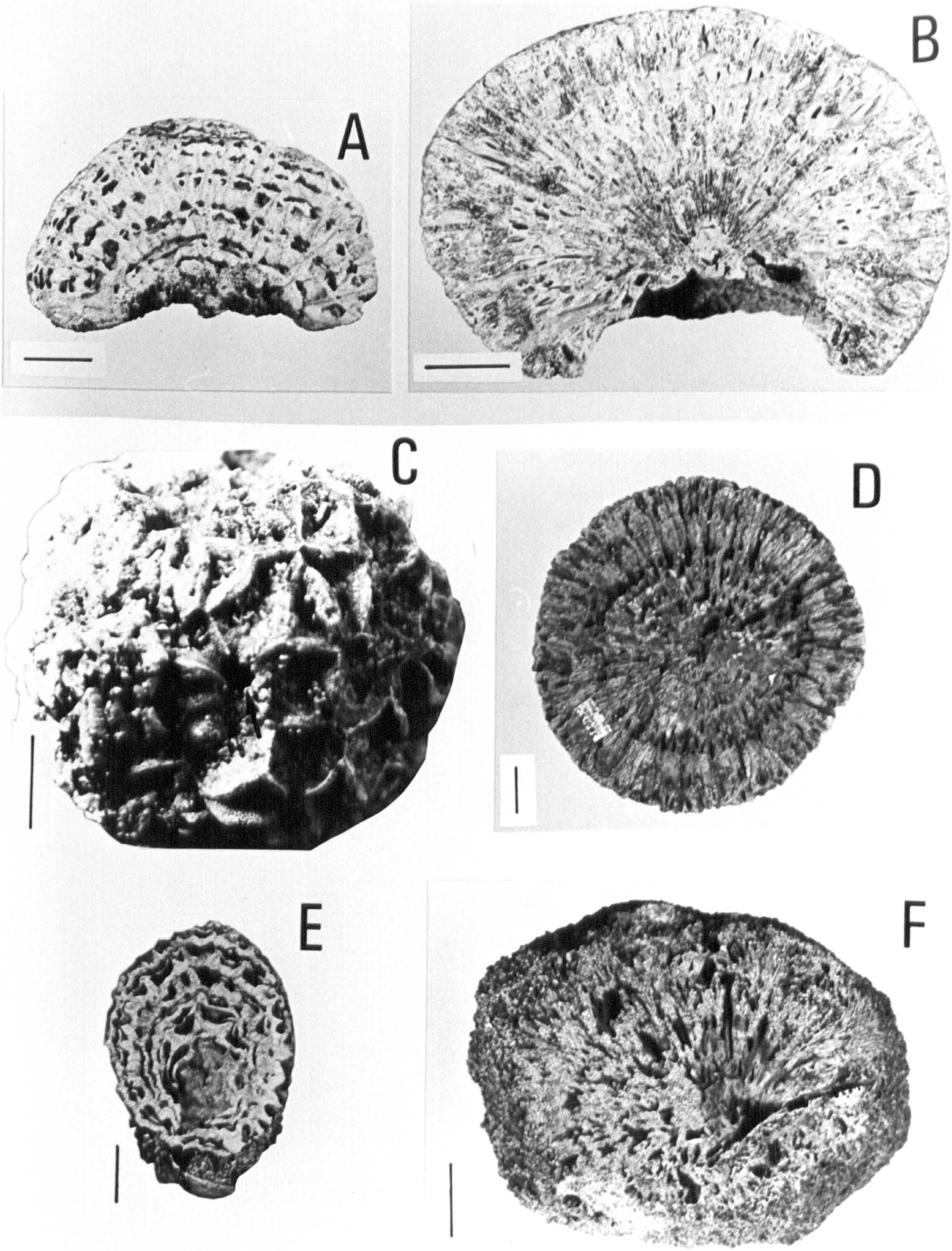
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Plate 24 (continued)

G *M. aurantium* Aldeburgh Hall (locality 32)
Colony encrusted eschariform cheilostome colony.
Scale bar = 1cm

H-I *M. aurantium* Broom pit, Gedgrave Sedgwick Museum C51082
Large colony showing basal excavation made by benthic organisms.
Scale bar = 1cm

Plate 24

Large Cyclostome Substrates

A Meandropora aurantium Aldeburgh Hall (locality 32)
Circumrotatory colony which enclosed an aragonitic bivalve shell. The shell, which has been subsequently removed by solution, had an earlier encrusting celleporiform Cheilostome which was also overgrown by the Cyclostome.
Scale bar = 1cm

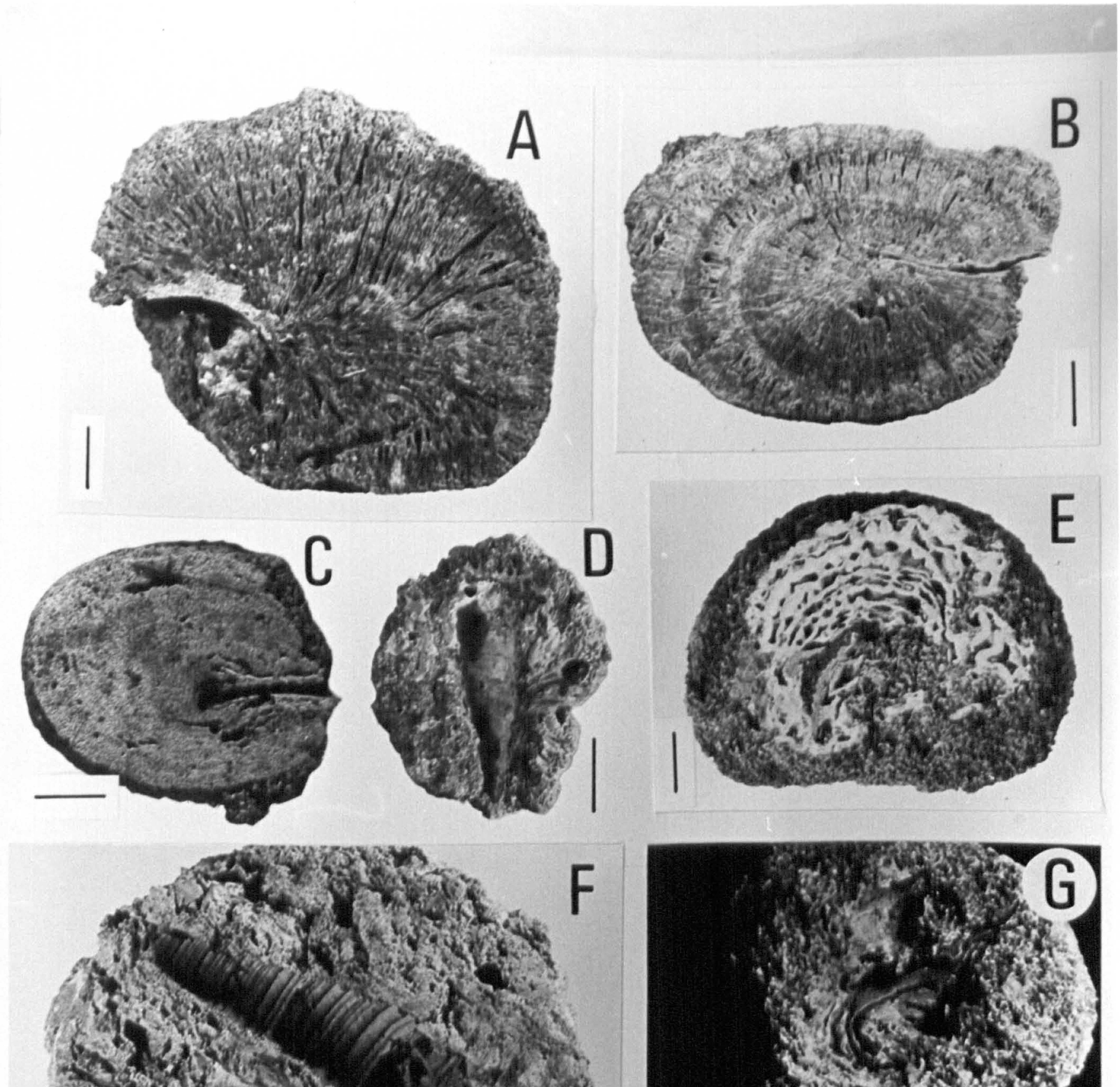
B M. aurantium Aldeburgh Hall (locality 32)
Circumrotatory colony which enclosed an aragonitic bivalve shell. The shell has been subsequently removed by solution. The colony shows cyclical growth banding.
Scale bar = 1cm

C Turbicellepora sp. Aldeburgh Hall (locality 32)
Circumrotatory celleporiform cheilostome which enclosed an aragonitic bivalve shell. Compare with the growth form of the cyclostomes in A and B.
Scale bar = 1cm

D M. aurantium Orford (locality unknown) BMNH B3749
Colony encrusted a turritellid gastropod shell which has been removed by later solution.
Scale bar = 1cm

E Blumenbachium globosum Aldeburgh Hall (locality 32)
Circumrotatory colony which enclosed a calcitic bivalve shell.
Scale bar = 1cm

F M. tubipora Sudbourne (locality unknown) BMNH B1667
Searles Wood Collection
Colony encrusted a turritellid gastropod shell which has been removed by later solution.
Scale bar = 1cm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Appendix 1 Geochemistry of the Crag phosphorite mineral

A1.1 Phosphorite terminology

A1.2 X-ray diffraction analysis (XRD)

A1.3 Electron microprobe analysis

A1.4 X-ray fluorescence analysis (XRF)

A1.5 CO_2 content

A1.6 Fluorine content

A1.7 Conclusions

Appendix 1 Geochemistry of the Crag phosphorite mineral

A1.1 Phosphorite Terminology

'A mineral name has never been more appropriately selected than that of apatite, which is from ἀπατάω (I deceive)' (McConnell, 1938). Apatite is the mineral group to which belong the various types of sedimentary phosphorite minerals. The proliferation of mineral names for these members of the apatite group has resulted in much confusion in the literature. McConnell (1973) defined a phosphorite as "....a sedimentary rock of which the essential mineral component is ordinarily a carbonate fluorapatite". Carbonate fluorapatite, or francolite, is further defined as a carbonate apatite with a fluorine content of greater than 1%. Carbonate apatite with a fluorine content of less than 1% is referred to as carbonate hydroxyapatite or dahllite. These two minerals make up the bulk of all sedimentary and biological apatites.

Dahllite is the material of which vertebrate teeth and bones are made (Beevers and McIntyre, 1946). It does, however, have an affinity for fluorine and "probably is ultimately converted to francolite when an adequate supply of fluorine is available, given sufficient time" (McConnell, 1973). The rate of this uptake of fluorine can be used to date bones of sub-Recent age. The most notable application of fluorine uptake was used in the dating which resulted in the exposure of the Piltdown Man hoax (Oakley and Hoskins, 1950).

Many authors have referred to carbonate apatite with a high fluorine content simply as "fluorapatite", which has led to confusion with the significantly different fluorapatite of igneous and metamorphic sources.

The term collophane or collophanite is also frequently found in phosphorite literature to describe an amorphous apatite. McConnell (1950, 1958) disliked this term and stated that no truly amorphous apatite substance had been discovered. He used the term collophane "to denote a natural microcrystalline, phosphatic material that produces an X-ray pattern similar to apatite if it has not been investigated with sufficient thoroughness or if it is too impure to justify a specific name, such as dahllite, dehrnite or francolite". More recently he defined it as "a cryptocrystalline carbonate apatite for which the fluorine content is not known" (McConnell, 1973; p 10).

In order to identify the apatite mineral present in the Crag phosphorite material a series of analyses were made. The apatite mineral was identified as francolite and therefore the use of the term collophane is not necessary in this study.

A1.2 X-ray diffraction analysis (XRD)

X-ray diffraction studies were made on a Philips (PW 1010) goniometer using CuKα radiation. Each sample was crushed together with a small amount of pure quartz powder which was added as an internal standard. Each sample was scanned from 25 to 54^{o} 2θ. The positions of the main diffraction peaks are listed in Table 21 and characteristic traces are shown in figure 45.

In each sample analysed the positions of the peaks correspond closely with those of francolite (carbonate fluorapatite). There is a significant difference between the peak spacings

hkl	X-ray diffraction data (°2θ)							
	1	2	3	4	5	6	Francolite*	Dahllite*
002	25.86	25.80	25.82	25.90	25.80	25.80	25.88	25.88
210	29.30	29.22	29.62	29.16	29.24	29.17	-	28.77
211	32.10	32.06	32.08	32.03	32.05	32.05	32.055	31.82
112	32.23	32.23	32.26	32.13	-	-	32.29	
300	33.30	33.25	33.16	33.18	33.20	33.25	33.15	32.775
202	34.18	34.16	34.15	34.17	34.13	34.17	-	-
310	40.30	40.29	40.30	40.14	40.12	40.30	-	39.67
311	-	-	-	-	-	-	-	-
222	47.07	47.04	47.07	46.90	46.93	47.03	47.04	46.53
213	49.61	49.62	49.72	49.60	49.54	49.63	49.695	-
231	51.05	50.96	50.98	-	50.96	51.05	50.975	-
410	51.99	51.89	51.85	-	51.74	51.92	51.59	-
402	52.55	52.50	52.53	-	52.44	52.56	52.55	-
004	53.18	53.12	53.10	53.26	53.13	53.10	53.205	-

Table 21 Positions of main diffraction peaks (XRD) for Crag phosphorite components

1. Crag phosphorite nodule, Red House Farm Reservoir (locality 28). 2. Crag phosphorite nodule, Rockhall Wood (locality 5). 3. 'Boxstone' matrix, Bawdsey. 4. Phosphatised shark tooth, Crag, Ramsholt (locality 3). 5. Phosphatised cetacean bone, Crag, Bawdsey. 6. London Clay phosphorite concretion, IGS Crystal Palace borehole. *Data from McConnell (1973)

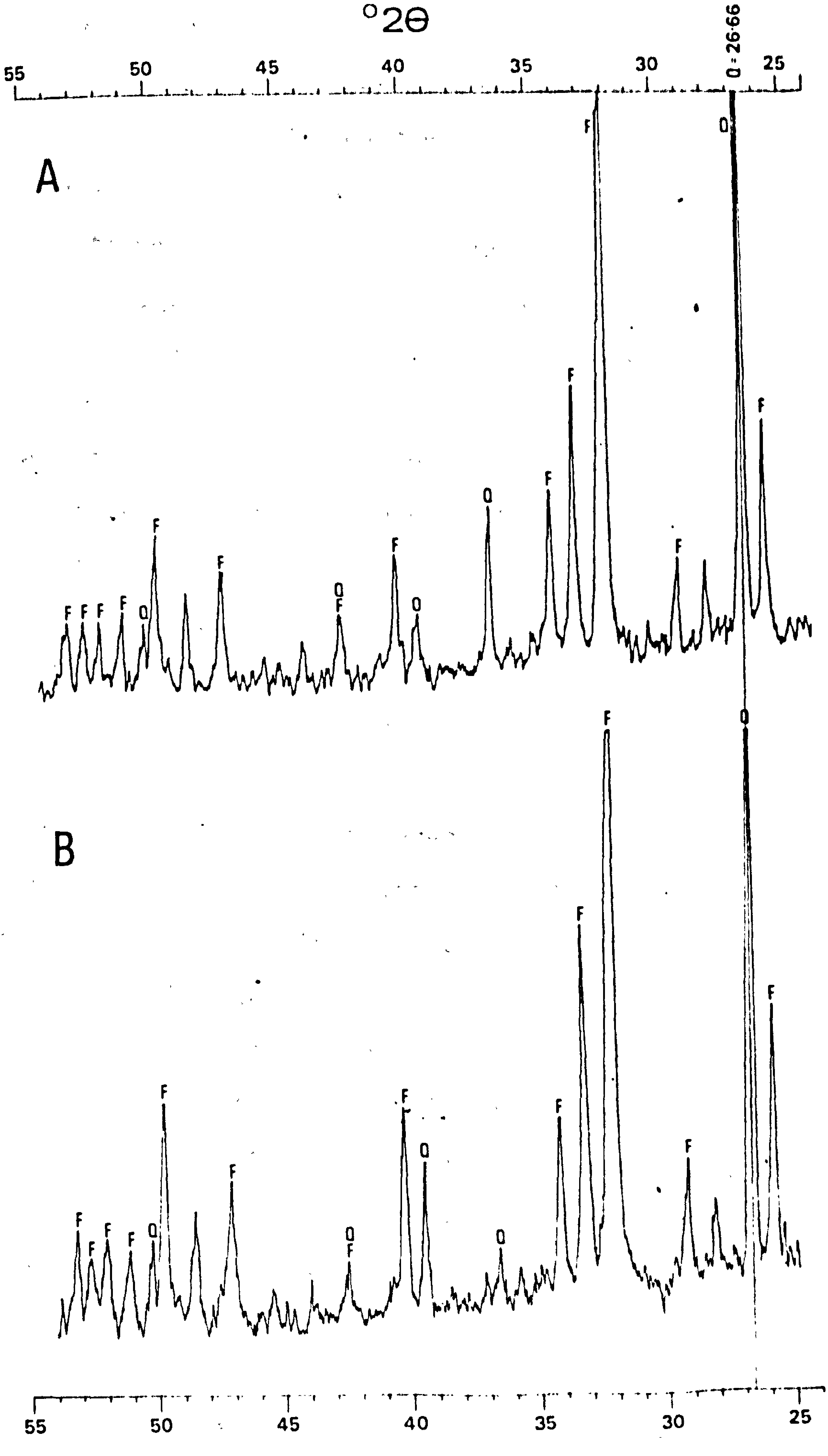

Figure 45 Characteristic X-ray diffraction traces for phosphorites. A. Crag phosphorite nodule (Rockhall Wood, locality 5). B. London Clay phosphorite concretion (IGS Crystal Palace borehole).
F - Francolite peaks Q - Quartz peaks used as standard.

of the shark tooth and cetacean bone samples from the spacings expected for dahllite. This shows that the original dahllite has been altered to francolite by fluorine uptake. The X-ray traces for all the concretionary apatites show sharp, well defined peaks (see figure 45) which Birch (1979) thought suggested that the apatite was well crystallised. The traces of the tooth and bone apatite have more ragged, diffuse peaks (see figure 46). This may be due to a number of factors including smaller crystallite size, greater range of crystallite sizes or distortion in the crystallite symmetry due to CO_3 groups in the structure (McConnell, 1973).

A1.3 Electron microprobe analysis

Electron microprobe analyses were made using the energy dispersive electron probe microanalyser EDS system in the Department of Mineralogy and Petrology, University of Cambridge. This equipment uses a Si(Li) detector and Harwell Highspec pulse processor system 3073 interfaced to Data General Nova 1220 minicomputer. The peaks are processed and measured by iterative peak stripping.

Microprobe analysis is concentrated on only a small spot on a polished rock section and therefore gives a better indication of the composition of a given mineral, in this case, francolite. As francolite is cryptocrystalline, however, the analysis may include components derived from the admixture of other minerals, especially quartz and clay minerals.

Average analyses are given in table 22 where the results are compared with analyses of phosphorite from other deposits

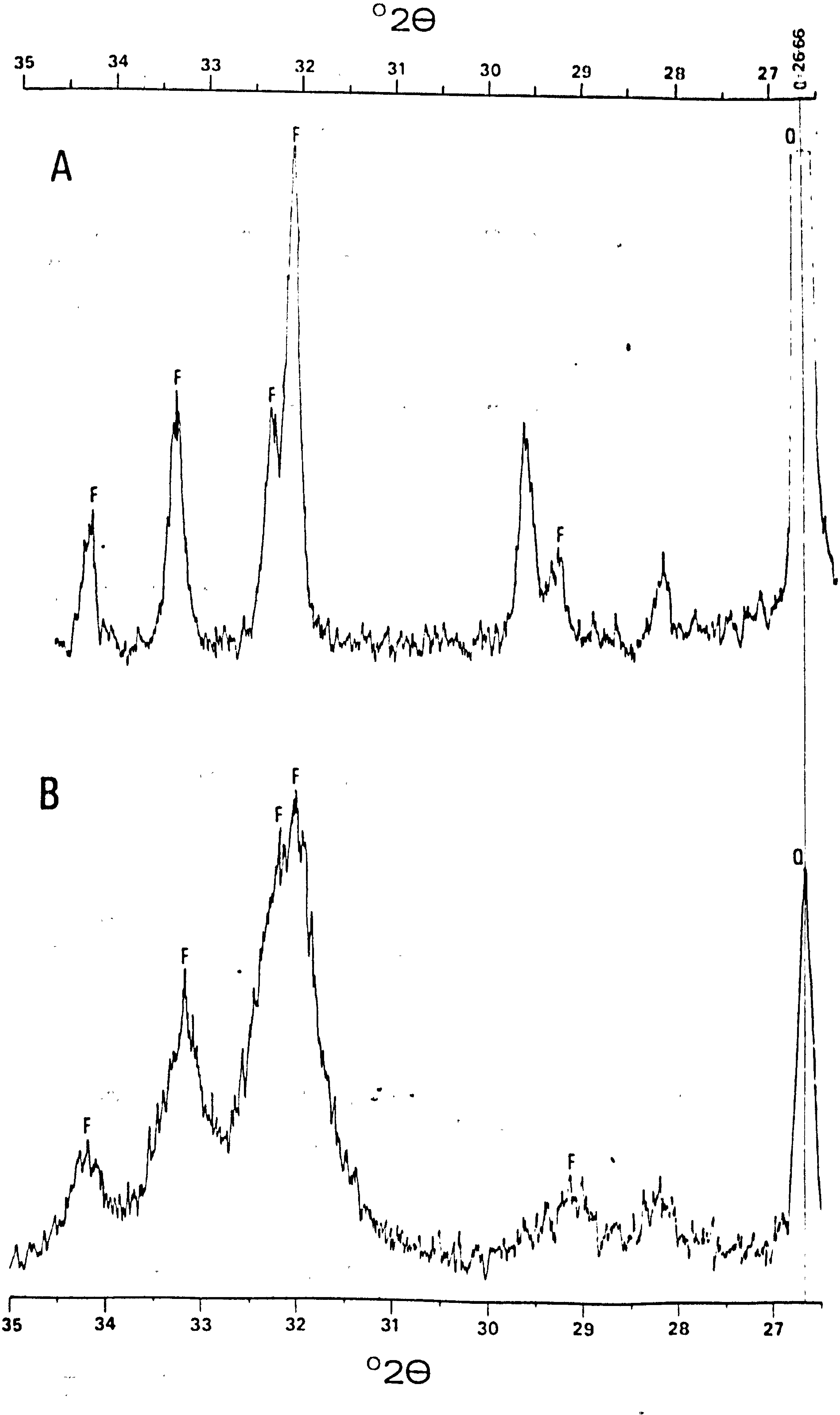

Figure 46 X-ray diffraction traces showing major apatite peaks. A. 'Boxstone' matrix (Bawdsey). B. phosphatised shark tooth (Ramsholt, locality 3). F - Francolite peaks Q - Quartz peak used as standard.

	London Clay phosphorite	Crag phosphorite	'Boxstone' matrix	Peru-Chile*	Phosphoria* Formation	Agulhas* Bank	Crag shark tooth	Crag cetacean bone
No. of analyses	3	7	8	15	60	21	1	1
Na_2O	0.38	0.65	0.63	0.85	0.6	0.67	0.43	0.66
MgO	0.48	0.22	0.33	1.07	0.3	1.35	0	0
Al_2O_3	2.38	2.00	1.27	5.15	1.7	1.85	0	0
SiO_2	8.02	5.88	3.98	22.13	11.9	12.84	0.17	0
P_2O_5	29.03	30.98	30.89	22.61	30.5	16.18	36.66	34.96
K_2O	0.43	0.23	0.22	1.30	0.5	1.29	0	0
CaO	45.31	46.49	48.15	33.93	44.0	37.29	50.82	50.53
Fe_2O_3	1.58	2.72	2.08	2.85	1.1	8.24	0.75	2.61
total oxides	87.61	89.17	87.55	89.89	90.6	79.71	88.83	88.76
CaO/P_2O_5	1.56	1.50	1.56	1.50	1.44	2.30	1.39	1.44

Table 22 Partial analyses (energy dispersive electron microprobe) of various phosphorite concretions, phosphatised teeth and phosphatised bone expressed as weight percent of oxides. *Data from Burnett (1977)

taken from the literature. It will be noticed that organically precipitated apatite e.g. apatite of teeth and bones, is deficient in some components notably MgO, Al_2O_3, SiO_2 and K_2O which are probably contributed by clay minerals in inorganic concretionary apatite.

Comparisons can be made between these analyses and the wet chemical analyses of Crag phosphorite nodules by Herapath (1851; pp.97-98) and Voelcker (1860; pp.359-360) and of phosphatised bones by Herapath (1851; pp.100-101). It was not possible to analyse for fluorine on the Cambridge equipment so samples of a London Clay phosphorite concretion and a Crag phosphorite nodule were analysed at the Open University using a Cambridge Instruments Microscan 9 wavelength dispersive electron probe microanalyser. It should be noted, however, that due to the lightness of the fluorine atom (Atomic weight = 19), results obtained by electron microprobe cannot be regarded as accurate. A correction procedure is also required to recalculate the fluorine percentages obtained on this equipment such that:

%F true = %F apparent - 0.2044.wt %P as an element.

The results obtained for the Crag phosphorite nodule (Ramsholt) was 3.71%F (mean of 3 analyses) and for the London Clay phosphorite concretion (Crystal Palace borehole) was 3.50%F (mean of 2 analyses). These results are of the same order as those of other authors in other phosphorite samples and which are summarised in table 23.

These results, however, are markedly higher than the values obtained by the wet chemical analysis used in section A1.6. Differences may in part be due to the difference in

		% Fluorine	No of analyses
Voelcker (1860)	Crag phosphorite nodule*	3.66	2
Gulbrandsen (1966)	Phosphoria Formation	3.1	60
Burnett (1977)	Peru - Chile	2.22	15
Baturin & Bezrukov (1979)+	S.W. Africa Shelf	3.02	--
Baturin & Bezrukov (1979)+	Chile Shelf	2.55	--

* wet chemical analysis

\+ hard nodules

Table 23

% Fluorine content of various phosphorites fluorine content of the apatite mineral and the rock matrix.

A1.4 X-ray fluorescence analysis (XRF)

In order to quantitatively examine the whole rock composition of the phosphorite components, X-ray fluorescence analysis (XRF) was used. Analyses were performed on a Philips PW 1212 X-ray spectrometer at the Department of Geology, University of London, Bedford College. For major element analysis measured amounts of powdered sample together with lithium tetraborate flux were made into fusion pellets. The use of fusion pellets eliminates any effects of grain size. For trace element analysis pressed powder pellets were used. These were made by mixing measured amounts of powdered sample with powdered bakelite which was then compressed into pellets.

XRF analysis techniques use rock powders and results therefore represent the bulk compositional properties of the rock in contrast to microprobe techniques which analyse only a very small area of a polished rock section.

The results of the XRF analyses are given in Table 24 and are also discussed in Chapter 4. It will be noted that phosphatised bone has a lower SiO_2 content and is deficient in Th, Nb, Y, Rb and Zr when compared with apatite of phosphorite concretions and nodules. This is probably due to the lack of admixed clay minerals with the apatite. Perhaps not surprisingly the bone also has a higher P_2O_5 content. The concretionary apatites are broadly similar in composition but the Crag phosphorite nodule has a slightly higher P_2O_5 content.

	London Clay phosphorite	Crag phosphorite	Crag Cetacean bone
P	21.67	26.07	31.31
Ca	37.37	43.47	49.58
Fe	3.10	3.81	1.65
Na	0.85	1.27	1.30
K	0.86	0.49	0.05
Mg	2.74	0.31	0.32
Al	1.44	2.83	0.15
Si	13.82	6.71	0.00
Mn	0.10	0.00	0.00
Ti	0.27	0.20	0.03

	London Clay phosphorite	Crag phosphorite	Crag Cetacean bone
Th	1	0	1
Nb	28	28	11
Y	416	363	1
Sr	1118	2161	1314
Rb	46	26	-
Zr	83	83	51

Table 24

Partial analyses (X-ray fluorescence) of phosphorite concretions and phosphatised bone.

Above : major elements (weight percent)

Below: trace elements (parts per million)

A1.5 CO_2 content

The X-ray peak pair method of Gulbrandsen (1970) was used to determine the carbonate content of the apatite of the Crag phosphorite deposit. The pair of peaks 002 and 300 were used as both these peaks are of strong intensity and are easily definable on the XRD traces.

According to Gulbrandsen (p.B11) the method is as follows:-

$$y = 185.0 + 25.5740x$$

where

$y = CO_2$ weight percent and

$x = \Delta 2\theta^{\circ}_{(300)-(002)}$

However, as x is a positive quantity, the right hand side of the equation is therefore equal to several hundred %. It is believed that the published equation is an error and should read:-

$$y = 185.0 - 25.5740\,x$$

The results obtained using this equation are shown in Table 25. The values for the concretionary apatites (analyses 1-7) fall between 4.7 and 6.3 weight % CO_2. A lower value of 3.15 was found for cetacean bone (analysis 8) but difficulties arose due to the diffuseness of the peaks making the exact $\Delta 2\theta^{\circ}$ difficult to measure. The proportion of CO_2 present is thus appreciable and sufficient to qualify the phosphorite mineral as a carbonate apatite.

A1.6 Fluorine content

In addition to determination of fluorine content by microprobe techniques (Section A1.3) use was also made of the wet chemical technique employed by Hall and Walsh (1969). This involves comparison of a solution of a fused sample

	Sample				CO_2 weight %
1	Phosphorite nodule	Coralline Crag,	Ramsholt (locality 3)	exterior	5.9508
2	" "	" "	"	interior	5.8034
3	" "	" "	"	whole rock	4.4772
4	" "	" "	Red House Farm Reservoir (locality 28)		6.0982
5	" "	" "	Rockhall Wood (locality 5)		5.5087
6	" "	London Clay	IGS Crystal Palace borehole		6.2455
7	'Boxstone' matrix		Bawdsey		5.2140
8	Phosphatised Cetacean bone		Bawdsey		3.1509

Table 25

Weight % CO_2 in phosphorite concretions and phosphatised bone determined by the X-ray peak pair method of Gulbrandsen (1970).

of phosphate mineral with a known solution of sodium fluoride using alizarin fluorine blue reagent. The reagent is a reddish-purple colour, which becomes bluish-purple in the presence of large amounts of fluorine. Analysis was obtained by comparison of the optical densities of the solutions using a Unicam SP500 spectrophotometer. The % fluorine in the unknown rock sample is given by:-

$$\%\text{F in unknown} = 0.015^{*} \text{ X } \frac{\text{Optical density of unknown}}{\text{Optical density of NaF standard}} \text{ X } \frac{\text{ideal weight of unknown used in preparation of solution } (= 0.1\text{g})}{\text{weight of unknown used in preparation of solution.}}$$

* µg of fluoride in standard

The results are given in Table 27.

The accuracy of the analyses was checked by determining the fluorine content of a USGS reference sample granodiorite (GSP) in the same batch of analyses. The quoted value of 0.38%F (Flanagan, 1967) is tolerably close to the value of 0.32% obtained in this study. From Table 26 it can be seen that the fluorine content of the phosphatic components is variable but generally lies between 1.2 and 1.8%. The low value for the 'boxstone' matrix is probably due to the large amounts of admixed quartz in the sample. The samples analysed were all crushed material which probably contained some proportion of quartz, clay minerals, glauconite and other minerals which will all have affected the overall fluorine percentage.

Table 26 % Fluorine content of various phosphatic samples.

				%F	300 peak $^{o}2\theta$
Coralline Crag					
1	Phosphorite nodule	(exterior)	Ramsholt Cliff (locality 3)	1.4920	33.25
2	"	(interior)	" "	1.6251	33.26
3	"	(whole)	" "	1.6072	33.26
4	"	(whole)	Red House Farm reservoir (locality 28)	1.7792	33.30
5	"	(whole)	Rockhall Wood (locality 5)	1.5094	33.25
Coralline / Red Crag					
6	Phosphatised Cetacean bone, Bawdsey			1.2652	33.20
7	"		Ramsholt Cliff (locality 3)	1.3460	-----
London Clay					
8	Shark tooth,		Ramsholt Cliff (locality 3)	1.3389	
9	Phosphorite concretion,		Sheppey, Kent	1.4787	-----
10	"	(exterior)	IGS Crystal Palace borehole	1.2488	-----
11	"	whole	"	1.5188	-----
'Trimley Formation'					
12	'Boxstone'	(matrix only)	Bawdsey	0.8916	-----
Standard					
13	USGS GSP			0.3187	-----

When fluorine content was plotted against the position of the 300 peak obtained by X-ray diffraction an interesting relationship is seen (Fig. 47). The position of this peak clearly changes with increasing F%. The substitution of ions in the apatite lattice by other ions is well documented (e.g. McConnell, 1938). Smith and Lehr (1966) wrote, "....excess fluorine appears to enter the apatite lattice with consequent change of the unit-cell dimensions". The variety of different possible substitutions has resulted in the proliferation of mineral names for isomorphous varieties of several complex series between the end members of the apatite group.

A1.7 Conclusions

1. The term francolite or carbonate fluorapatite should be used to describe sedimentary apatites occurring in phosphorite deposits where the carbonate and fluorine content of the apatite are each greater than 1%.
2. Inorganically precipitated concretionary francolites yield sharper diffraction peaks than organically formed apatite like that found in teeth and bones.
3. Electron microprobe analyses show the Crag phosphorite nodules to have a similar composition to phosphorite concretions of the London Clay and to the matrix of Suffolk 'boxstones'.
4. The CaO/P_2O_5 ratios for phosphorite concretions and the matrix of 'boxstones' are similar possibly indicating a similar mode of formation which was not by replacement of carbonate.
5. XRF analysis shows London Clay phosphorite concretions to have a lower P_2O_5 content than Crag phosphorite nodules.

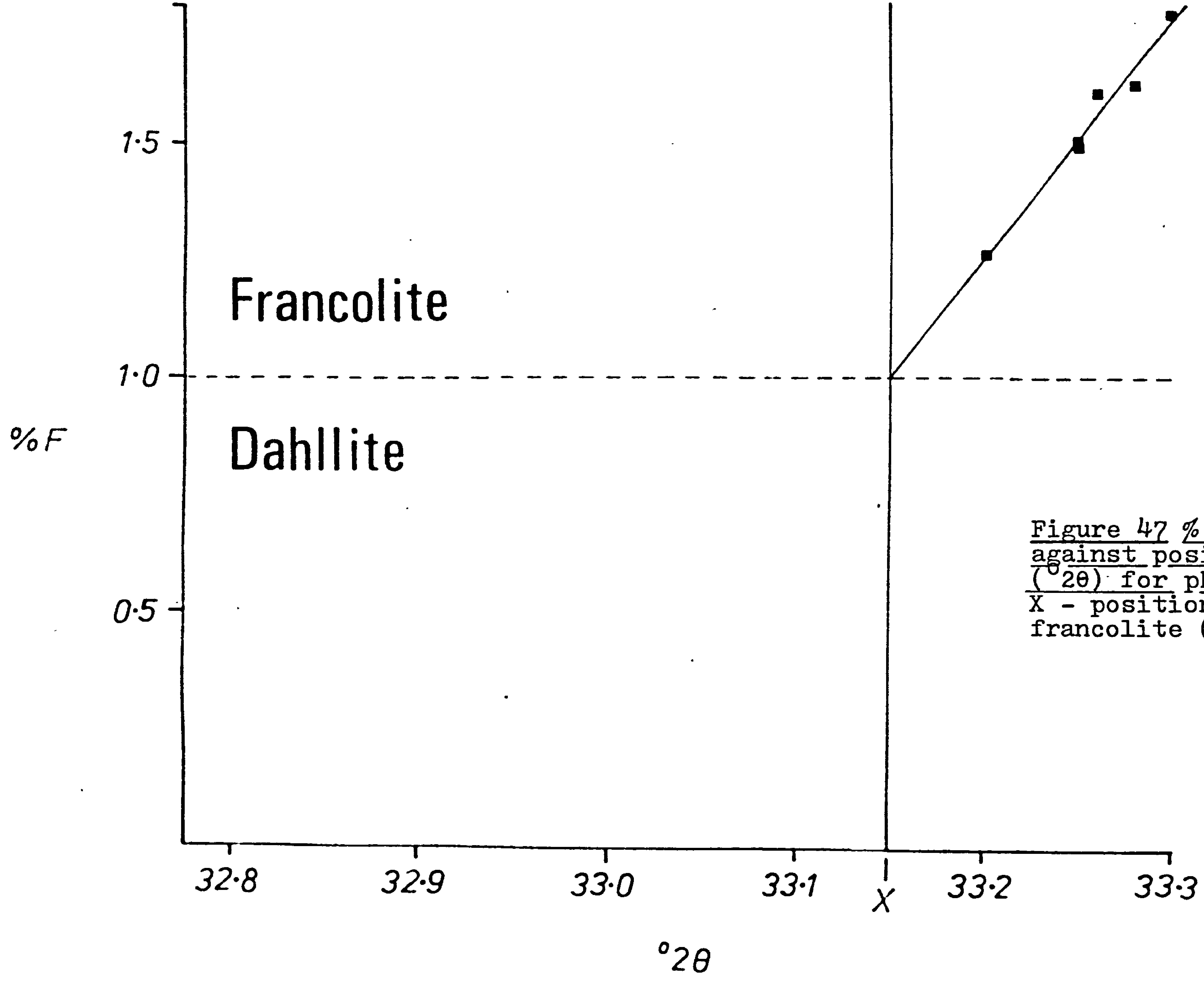

Figure 47 % Fluorine plotted against position of 300 peak (°2θ) for phosphate samples
X - position of 300 peak for francolite (McConnell, 1973)

This may be due to secondary enrichment with respect to P_2O_5 during the Miocene (see Chapter 4).

6. CO_2 content for Crag phosphorite concretions and the matrix of 'boxstones' is between 5.2 and 6.3% which is sufficient to merit the term carbonate apatite.
7. The fluorine content of the Crag phosphorite nodules is between 1.2 and 1.8%. This value is likely to be an underestimate due to admixture of other materials, particularly clay minerals, in the samples. The fluorine content is thus probably well above the 1% necessary for the designation 'francolite'.

Appendix 2

The "Trimley Formation".

The 'Suffolk boxstones' are nodules of arenaceous phosphorite which appear to have developed as concretions around sites of organic decay at shallow depths in a Miocene deposit of muddy sands (Balson, 1980). The nodules are commonly between 5 and 20 cm in diameter and are found in association with other phosphatic material incorporated into the conglomeratic beds, collectively termed the Crag phosphorite deposits (= Suffolk Bone-Beds or coprolite bed of authors), which are found intermingled with the basal sediments of the Coralline and Red Crags.

The term 'boxstone' was first applied to these nodules by Lankester (1870). Elsewhere, this term has been widely applied to hollow concretions from many formations of different ages and it therefore has no stratigraphic significance. Furthermore, most of the so-called 'boxstones' from Suffolk are not hollow at all and therefore the term is not strictly warranted.

The 'boxstones', as found today, clearly represent erosional remnants of a once more extensive deposit. Any new stratigraphical term should thus relate to the geological formation of which the 'boxstones' are the only known remaining evidence and not to the lag deposit in which the remnants are now incorporated.

'Boxstones' have been formerly recorded from many localities but they appear to be most abundant in the easternmost parts of the Crag outcrop. 'Boxstones' are abundant in the shingle of the spit at the mouth of the River Deben (GR: TM 332 375).

These have been derived from the Red Crag phosphorite deposit which is intermittently exposed in the cliff at Bawdsey a short distance to the north (GR: TM 345 385). Bawdsey Cliff is one of the only localities where "_in situ_", 'boxstones' have been seen in recent years (Ovey and Pitcher, 1948) where they are found resting on the irregular, erosional surface of the London Clay. "_In situ_" 'boxstones' have also been found in the Coralline Crag phosphorite deposit at Ramsholt Cliff (GR: TM 297 427) (this study).

At both of the above localities the 'boxstones' are typically irregularly round cobbles. Lankester (1870; p. 500) wrote "with one exception all the masses of sandstone ['boxstones'] I have seen.... have been spherical, oblong or irregular masses about the size of the fist, on an average, or sometimes of an elongated cylindrical form. The exception was in a pit at Trimley, near Ipswich, where I found four blocks of a flagstone shape about a foot and a half [45 cm] square, which contained casts of shells, and seemed to be identical in origin with the box-stones". Tabular blocks of this sandstone were also noted from Trimley and Bucklesham by Taylor (1874: in Bell 1917). Clearly, blocks of this size are unlikely to have been readily transported and must therefore represent a more or less _in situ_ occurrence of this Miocene formation.

The formation from which the 'boxstones' are derived can perhaps be usefully termed the "Trimley Formation", after its former exposure in the Trimley area and the ambiguous term 'boxstone' can therefore be discontinued. In the absence of any exposure at Trimley in recent years the locality at Bawdsey is proposed as the type locality for the present day manifestation of this formation.

Thus the "Trimley Formation" was a deposit of mud-rich sands in which phosphates became concentrated and were precipitated as carbonate fluorapatite (francolite) around centres of organic decay. This cementation of the sand by phosphorite formed the 'boxstones' of previous authors. These concretions were left behind as a lag deposit when the uncemented sands were subsequently winnowed away. The petrology of the 'boxstones' was described by Boswell (1915) as comprising between 20 and 80% matrix, the balance being mainly quartz. The molluscan fauna of these concretions has been studied in detail by Wood (1859) and Bell (1911, 1915, 1917, 1918) and generally indicate a shallow marine environment. Abraded fragments of phosphatised cetacean bones and teeth,and teeth of Procarcharodon megalodon,believed to be contemporaneous with the molluscan fauna,are occasionally found with adherent arenaceous phosphorite.

The age of the 'Trimley Formation', and thus of the associated phosphogenic episode, is difficult to determine. By comparison with the more complete sequences of Neogene deposits in Belgium the fauna is believed to be Anversien (Upper Middle Miocene) in age.

Appendix 3 Statistical grade parameters used in this study

i) Median Md (Inman, 1952)

$$\phi \text{Md} = \phi 50$$

The median diameter is the 50 percentile diameter of a cumulative frequency curve. Half the sample is finer and half is coarser than the median. There have been many discussions on the relative merits of the median and the mean in environmental interpretation of grain size frequency curves (see Koldijk, 1968, p.58). In symmetrical distributions the mean and the median will be the same. The median will be less affected than the mean by extreme values of kurtosis. Folk and Ward (1957) pointed out that the median can be very misleading as a measure of average size since it is based on only one point of the cumulative curve; "For example, a sediment consisting of 40% pebbles and 60% fine sand may have the same median as one with 60% fine sand and 40% clay". In practice in the Coralline Crag the values for the median and the mean are generally similar (see tables 5 - 9).

ii) Graphic Mean Mz (Folk and Ward, 1957)

$$\phi \text{Mz} = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Mz is an approximation to the logarithmic mean, the arithmetic mean of sizes on a log scale. The logarithmic mean is at the centre of gravity of the logarithmic curve. "Because the mean grain size takes into account the physical effects of the magnitude of the particle diameter, it is preferable to the arbitrarily chosen median grain size" (Koldijk, 1968, p.58).

iii) Inclusive graphic standard deviation σ_i (Folk and Ward, 1957)

$$\phi\sigma_i = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

The 16th and 84th percentiles on a normal frequency curve represent diameters 1 standard deviation either side of the mean. As $\phi 5$ and $\phi 95$ are also considered, σ_i reflects dispersion or sorting over 90% of the cumulative curve i.e. 3.3 standard deviations. As a measure of the standard deviation, σ_i becomes less accurate for highly skewed distributions. The value for σ_i is also seriously affected by bimodal distributions. Fortunately bimodal distributions in the Coralline Crag sediments are very rare.

Sorting $\phi\sigma_i$ (from Folk and Ward, 1957)

<0.35	very well sorted
0.35 - 0.50	well sorted
0.50 - 1.00	moderately sorted
1.00 - 2.00	poorly sorted
2.00 - 4.00	very poorly sorted
>4.00	extremely poorly sorted

iv) Inclusive graphic skewness Sk_i (Folk and Ward, 1957)

$$Sk_i = \frac{\phi 16 + \phi 84 - (2 \times \phi 50)}{2 (\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - (2 \times \phi 50}{2 (\phi 95 - \phi 5)}$$

Skewness compares a measured grade distribution to the normal distribution. The departure of the mean from the median of a non-symmetrical distribution is a measure of skewness. This departure is divided by the standard deviation in order to provide that skewness is independent of dispersion. Sk_i is a pure number with mathematical limits of - 1.00 to + 1.00. Positive values indicate a tail of 'fines', negative values indicate a tail of coarse material in the grain-size distribution. This method of calculating skewness has one drawback in that it cannot be calculated when the weight percentage of either the finest or the coarsest grain-size class exceeds 5%.

Skewness Sk_i (from Folk & Ward, 1957)

$- 1.00 - {}^{-}0.30$	very negative
$- 0.30 - {}^{-}0.10$	negative
$- 0.10 - {}^{+}0.10$	nearly symmetrical
$+ 0.10 - {}^{+}0.30$	positive
$+ 0.30 - {}^{+}1.00$	very positive.

Appendix 4 Locations of Coralline Crag exposures used in this study

Facies	Thesis locality no.		N.G.R.
A1	1	Lemon's Hill Bridge, Tattingstone	TM 139 375 *
A1	2	Tattingstone Hall Farm	TM 143 374 *
A2	3	Ramsholt Cliff	TM 298 428 ‡
A3/A2	4	Rockhall Wood	TM 304 440
A2	5	Rockhall Wood	TM 306 440 ‡
A3/A2	6	Rockhall Wood	TM 305 441
B/A2	7	The Cliff, Gedgrave	TM 397 486
A2	8		TM 399 488 ‡
B	9	Gedgrave Hall	TM 405 486
A2	10	Gedgrave Hall	TM 406 485 ‡
B	11	Richmond Farm	TM 412 492
B	12	Orford Castle	TM 418 498
B	13	Daphne Road, Orford	TM 425 501
B	14	Lodge Farm	TM 425 513
B	15	Orford Belt	TM 415 515 ‡
A2	16	Sudbourne Park	TM 407 513 ‡
B	17	Sudbourne Park	TM 411 515 ‡
B	18	White Lodge	TM 415 518
B	19	Sudbourne Church	TM 420 519
B	20	Crag Farm	TM 428 523
B	21	Crag Farm	TM 430 524
B	22	High House Farm	TM 433 526 ‡
B	23	Valley Farm	TM 436 531
B	24		TM 426 531
B	25	Crag Pit Cottage	TM 427 532 ‡
C	26	The 'Firs' reservoir	TM 432 534 *

C	27	Red House Farm	TM 435 547 *
C	28	Red House Farm Reservoir A	TM 439 548 *
C	29	Red House Farm Reservoir B	TM 440 549 *
B	30	Poplar Farm	TM 434 555
C	31	Stanny Farm	TM 437 562 ‡
C	32	Aldeburgh Hall	TM 453 566
C	33	Aldeburgh Brickworks	TM 452 571 †
C	34		TM 448 570 ‡
C	35		TM 444 573 ‡
C	36	Round Hill, Aldeburgh	TM 444 573
C	37	Aldeburgh Golf Course	TM 445 577
C	38	Crag Pit Nursery	TM 458 580

* reservoir sites now under water (1981)

† site expected to be infilled by refuse tipping in near future.

‡ exposure very small or temporary only.

Locations of Coralline Crag exposures listed above are indicated on figures 2 and 3.

The origin and evolution of Tertiary phosphorites from eastern England

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The origin and evolution of Tertiary phosphorites from eastern England

P. S. Balson

SUMMARY: Remanié deposits of nodular phosphorite are found at the base of the Coralline Crag (Pliocene) and the Red Crag (Plio-Pleistocene) of Suffolk and Essex. The phosphatic components include phosphorite concretions (nodules), phosphatized vertebrate teeth and bones, and cobbles of sandstone cemented by a phosphatic matrix ('boxstones'). The phosphorite mineral is carbonate fluorapatite (francolite). The source of the phosphorite concretions was the London Clay (Eocene). They formed in unlithified anoxic sediment around sites of organic decay. The source of the 'boxstones' was a Miocene mud-rich sand formation tentatively correlated with the Belgian Anversian. They were formed by concretionary growth in anoxic sediment around sites of organic decay by a similar mechanism to that producing the London Clay concretions. Miocene teeth and bones with a low organic content were phosphatized by an apatite replacement process. This replacement process also enriched the phosphate content of derived phosphatic fossils and phosphorite concretions from the London Clay. Phosphorite formation in eastern England was linked with periods of transgression, while periods of regression were important in concentrating dense phosphatic material as a remanié deposit.

At the base of the Coralline Crag (Pliocene) and Red Crag (Plio-Pleistocene) of Suffolk and Essex lies a nodular phosphorite remanié deposit resting unconformably on an eroded surface of London Clay (Eocene) (and also lower London Tertiaries and Chalk in the case of the Red Crag). This deposit contains a variety of phosphatic components:

1. *Phosphatic concretions* (nodules).

Variously shaped, commonly spheroid or ellipsoid, concretions dominantly composed of fine-grained carbonate fluorapatite (francolite). Their size varies between 1 and 10 cm long with an average of *c.* 3 cm, though the size distribution may vary locally. The exterior of the concretions is dark brown, smooth and polished, sometimes with small depressions 0.3–1.0 cm in diameter resulting from the action of marine boring organisms. Most concretions have no easily discernible nucleus in section. Some have developed within the carapaces of decapod crustacea. Other organic nuclei include the roots of sharks' teeth and crustacean burrow fills. These phosphorite concretions were originally thought to be coprolitic in origin (Henslow 1843) which led to the term 'coprolite bed' being widely used to describe the Crag phosphorite deposits.

2. *Phosphatized fossils.*

In addition to those fossils which acted as a nucleus for concretionary growth of carbonate apatite described above, a wide variety of other phosphatized fossils occurs and fall into 3 groups:
(*a*) *Derived Mesozoic forms*: These include phosphatized casts of ammonite chambers.
(*b*) *Derived London Clay forms*: Most common of these are the teeth of *Striatolamia* (=*Odontaspis*), '*Lamna*' and *Myliobatis*. Phosphatized wood of Eocene age is also found.
(*c*) *Derived Miocene forms*: These include teeth of *Procarcharodon megalodon* (Agassiz), and the bones of various cetacea.

3. *Phosphatic sandstone* ('Boxstones').

Rounded cobbles of quartz sandstone cemented with a matrix composed dominantly of francolite but with a high proportion of limonite cement. Size is again variable, most cobbles having a long axis dimension of 8–25 cm. These sandstone cobbles were first recorded and described by Clarke (1851) and given the name 'boxstones' by Lankester (1870), referring to the fact that on being broken the cobbles often reveal a mould of a large bivalve or gastropod. Occasionally they enclose cetacean teeth or pieces of cetacean bone.

As well as these phosphatic components there are a variety of non-phosphatic components:
(*a*) *Non-phosphatized fossils.* These include silicified belemnite rostra where calcite has been replaced by beekite. Unmineralized teeth and bones of terrestrial vertebrates of Pliocene age are recorded.
(*b*) *Miscellaneous rock fragments.* The commonest rock types are rounded fragments of London Clay carbonate septaria and large flints. Other rock types recorded include quartzite, granite, porphyry, mica-schist and Liassic marlstone (Bell 1915).

During the 19th century the Crag phosphorite deposits were a large, easily accessible and commercially exploitable source of phosphate. Commercial production reached a peak during 1854 when *c.* 12 000 tons of phosphate were extracted (Reid 1890). During this time many pits were opened and large collections of fossil material were made. Poor descriptions in the available literature and poorly localized material in museum collections, together with the present day lack of good

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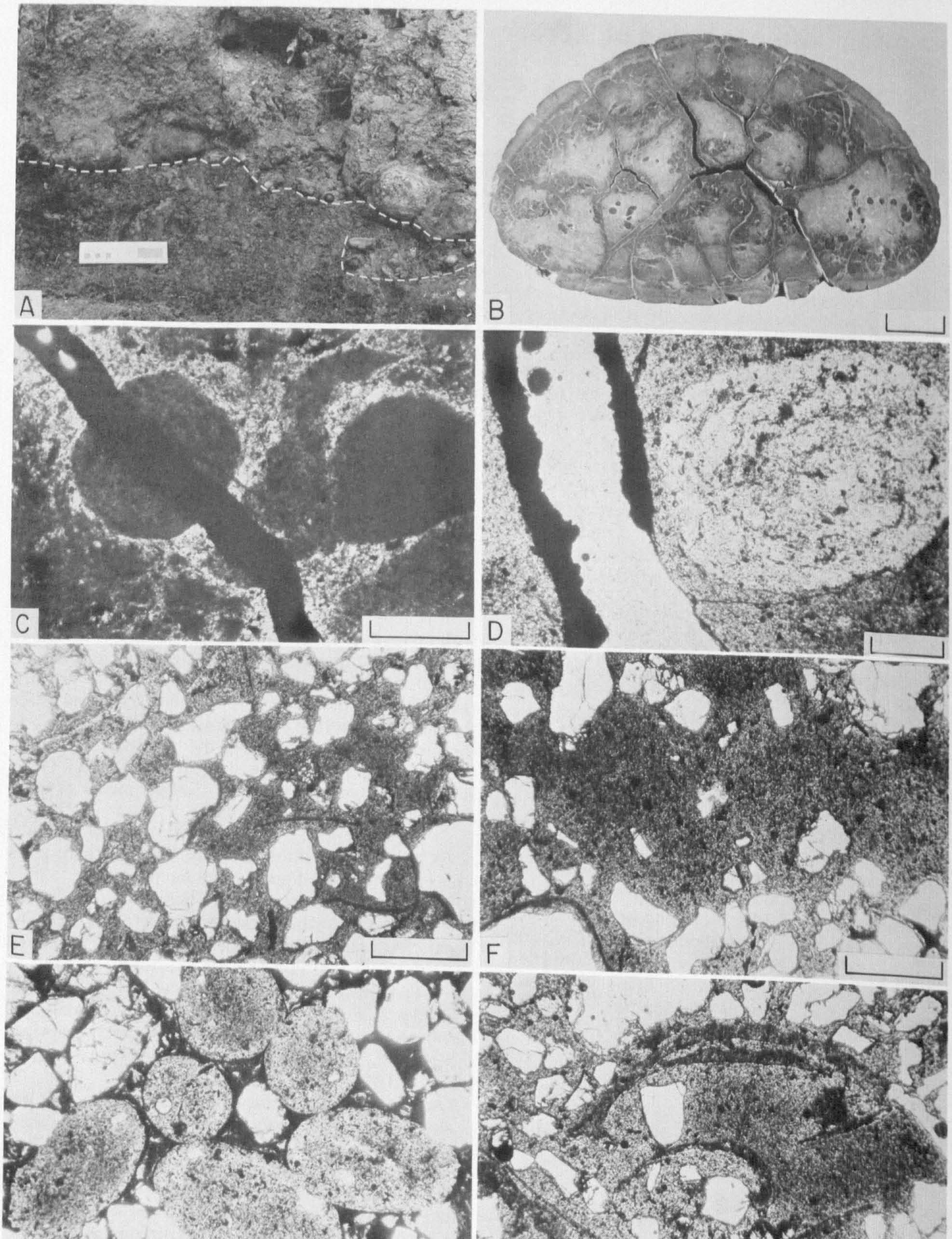

FIG. 1.

exposures, has led to confusion regarding the Crag phosphorite deposits. The presence of a phosphorite deposit beneath both the Coralline and Red Crag was noted by Lankester (1868), who termed the two deposits collectively as the 'Suffolk Bone-Bed'. The presence of a phosphorite deposit beneath both the Red and Coralline Crag, although doubted by Cambridge (1977), is here confirmed. The Crag phosphorite deposits show evidence of a complex history of formation. This paper proposes a model for the evolution of the deposits involving periods of reworking during transgressive/regressive cycles and two phosphogenic episodes during the Tertiary in the E of England.

Eocene events

Phosphatic concretions are abundant in the London Clay (Eocene) of Eastern England. X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses show these concretions to be dominantly composed of francolite. Most of the concretions are spheroid to ellipsoid in shape, with a buff-coloured exterior and a harder dark brown interior. They formed as early diagenetic concretions of primary carbonate apatite at a shallow depth within the anoxic sediment. Pyrite, which is also precipitated at shallow depths (Curtis 1978), can often be found in septarian veins sometimes cutting existing structures within the concretions (Fig. 1C). Pyrite formation must, in part at least, therefore post-date the precipitation of carbonate apatite. Concretions often contain structureless pellets of amorphous carbonate apatite, 0.5–2.0 mm in diameter. The abundance of these pellets in some concretions could indicate that the concretions frequently developed around burrows. Some concretions formed as a response to an organic nucleus, particularly crustacean carapaces, the roots of sharks' teeth and other skeletal remains of fish. These nuclei all have a high primary phosphate content. However, many phosphate-rich skeletal remains from the London Clay show no associated concretion growth, e.g. the majority of sharks' teeth. Concretions of calcium carbonate or pyrite are often found around material which was originally calcite or aragonite.

For apatite to be precipitated, the dissolved phosphate content must be raised high enough so that the calcium ion is being controlled by apatite rather than by carbonate equilibria (Burnett 1977). Organic phosphorus from decaying organisms is a primary source of phosphorus in interstitial pore waters. This provides a 'patchy structure of the microenvironment' which Baturin & Bezrukov (1979) believed to be the probable reason why phosphate is being precipitated irrespective of the mineral nature of the nucleation centre. Organic decay seems to be the most important factor in concretion growth in the London Clay, although apatite precipitation does show a degree of substrate specificity.

Sharks' teeth probably had only a small organic content when they were incorporated into the anoxic sediment. Where organic material was still present, this would be expected to be dominantly concentrated in the porous roots of the tooth and indeed this is the site where concretion growth occasionally occurs. Concretion growth has not been found around tooth enamel, which has a comparatively insignificant organic content (McConnell 1973).

The phosphatic concretions are associated with the magnesium-rich clay mineral montmorillonite and fine-grained dolomite in the London Clay. Association between apatite precipitation, magnesium-rich clays and dolomite is well known (Bushinskii 1966; Riggs 1979), although the significance of this relationship is not fully understood. Scattered grains of glauconite are also found in the concretions.

A period of regression followed the London Clay period in eastern England. During this time large amounts of London Clay were probably eroded. Phosphorite concretions formed at shallow depths in unconsolidated sediments; thus large numbers would be derived from even superficial erosion. The concretions have a high specific gravity (2.77) and would thus be readily concentrated as a lag deposit on the erosional surface.

FIG. 1.

A. Phosphorite deposit at base of Coralline Crag shown resting on erosional surface of London Clay. Large cobbles are fragments of London Clay carbonate concretions. Pebbles are derived London Clay phosphorite concretions. Scale bar 15 cm.

B. Polished section of Crag phosphorite nodule which originated as a London Clay concretion. Septarian veins, originally pyrite, now partially infilled with limonite. Scale bar 1 cm.

C. Thin section showing pellet of amorphous apatite in London Clay phosphorite concretion cut by later diagenetic pyrite vein. Scale bar 0.5 mm.

D. Thin section showing pellet in Crag phosphorite nodule. Vein, originally pyrite, now partially infilled with limonite. Scale bar 0.25 mm.

E. Thin section of 'boxstone'. Matrix typically forming *c.* 50% of sediment. Scale bar 0.5 mm.

F. Thin section of 'boxstone' showing matrix support of quartz grains. Scale bar 0.5 mm.

G. Thin section of 'boxstone' with ? faecal pellets of amorphous apatite. Scale bar 0.25 mm.

H. Thin section of boxstone showing pseudomorphism of ostracod valves by high ferroan carbonate. Scale bar 0.5 mm.

During the initial stages of regression boring bivalves could penetrate the softer outer portion of the concretions, their crypts terminating against the harder core. In the absence of any associated bivalve body fossils it is safest to refer the borings to the *Ichno* genus, *Teredolites* (Leymerie), this name referring to flask-shaped structures with constricted apertures which are normal but not necessarily attributable to bivalve activity in lithified substrates (S. R. A. Kelly, pers. comm.). The concretions are often bored on all surfaces, indicating that they were not enclosed in the sediment and were periodically overturned. Abrasion removed the softer exterior, leaving a polished surface pitted with small depressions representing the distal extremities of the crypts. During the regressive phase oxidation of pyrite led to the break-up of concretions with septarian veins of that mineral. This resulted in the formation of fragments of phosphorite with a rather triangular cross-section. Such fragments are commonly found in the Crag phosphorite deposit. Occasionally the concretion did not break-up (Fig. 1B) and the vein cavities have become partly filled with limonite, although some small crystals of pyrite remain. Carbonate concretions were undoubtedly exhumed during this period, but were probably removed by weathering. This period of exposure and concentration was followed by a renewed transgression in the Neogene, probably during the Miocene.

Miocene events

The Miocene transgression resulted in the deposition of a formation of mud-rich quartz sands. The remnants of this Miocene formation, the 'boxstones', are found as a component of the Crag phosphorite deposit in a small area of Suffolk. The percentage of matrix in the sand varies between 20 and 80% (Boswell 1915), but is commonly found to comprise *c.* 50% in thin section point counts (Fig. 1E,F). The matrix was found by XRD and electron microprobe analyses to be dominantly a mixture of francolite and limonite. The limonite cement may have been derived from the breakdown of glauconite grains, which are rare in studied thin sections of 'boxstones'. This would have been a later, post-lithification process, probably occurring in conjunction with the solution of calcareous mollusc shells, since small amounts of limonite are often found precipitated in the cavities formed by the removal of these shells. Limonite was therefore not the primary cement in the formation of 'boxstones'. These moulds of gastropods and articulated bivalves are generally found at the centre of the sandstone cobbles. The 'boxstones' clearly originated as concretions around these calcareous nuclei, as first noted by Clarke (1851). Growth is only rarely found around vertebrate, i.e. phosphatic, material. This is the converse of most London Clay phosphatic concretions. This apparent difference may be due to a difference in the diagenetic sequence in which apatite was not the primary cement. The possibility that the 'boxstones' matrix was originally calcium carbonate which was later replaced by apatite was investigated.

Electron microprobe analysis was used by Parker (1971) to obtain a CaO/P_2O_5 ratio of 2.30 for replaced limestones from Agulhas Bank, SW Africa. The CaO/P_2O_5 ratio for the 'boxstone' matrix is 1.56 (Table 1). This figure accords more closely with the value of 1.50 quoted by Burnett (1977) for phosphorite nodules from the Peru–Chile shelf. As this figure is only slightly higher than that expected for a pure carbonate fluorapatite, Burnett used this result as an indication that there were no 'unreplaced residuals' that might have been present if apatite had formed by replacement of calcite.

TABLE 1. *Partial analyses (electron microprobe) of phosphorite concretions expressed as weight % of oxides.* 1, *London Clay phosphorite concretion*; 2, *Crag phosphorite nodule*; 3, *'Boxstone' matrix*

	1	2	3
Na_2O	0.38	0.65	0.63
MgO	0.48	0.22	0.33
Al_2O_3	2.38	2.00	1.27
SiO_2	8.02	5.88	3.98
P_2O_5	29.03	30.98	30.89
K_2O	0.43	0.23	0.22
CaO	45.31	46.49	48.15
Fe_2O_3	1.58	2.72	2.08
Total oxides	87.61	89.17	87.55
CaO/P_2O_5	1.56	1.50	1.56

However, in the case of the 'boxstones' the molluscan shell moulds are evidence of the removal of calcite and aragonite after lithification. A late-diagenetic carbonate cement is often found infilling small spaces between the early diagenetic apatite rim cement of quartz grains. The carbonate has a high ferroan content, and a lowest refractive index equal to or greater than balsam. Rims of apatite around mineral grains are another criterion used by Burnett as indicating primary precipitation of apatite. Parker & Siesser (1972) observed a decrease in P_2O_5 content from the surface to the centre of replaced limestone blocks. Electron microprobe traverses from the surface to the centre of 'boxstones' revealed no significant variations in the P_2O_5 content of the matrix. Additionally no pseudomorphism of calcareous shells and microfossils by apatite has been observed, although this may be due to a preference for finer-grained carbonate by the replacement process. Although phosphate replacement cannot be entirely ruled out as a mechanism for the formation of the 'boxstones', it is considered more likely that apatite was precipitated directly from solution as a primary cement.

In common with the London Clay phosphatic concretions, apatite precipitation was in response to organic decay. Some 'boxstones' with no body fossil nuclei consist of extensively bioturbated sediment. Pellets of francolite 0.5–1 mm in length are fairly common (Fig. 1G). These pellets are not concentrically layered and are probably the faecal pellets of burrowing organisms. Precipitation of apatite is often quoted as being a response to local fluctuations of pH in the microenvironment (Burnett 1977; Baturin & Bezrukov 1979). Increases in pH may result from the liberation of NH_4^+ into the interstitial porewaters around decaying animals. Phosphatized wood derived from the London Clay is also present in the Crag phosphorite deposit. Xylem decomposes giving acid conditions (Bushinskii 1966), thus pH may not be such an important factor. As in the London Clay, supersaturation of porewaters with respect to phosphate is probably the most important single factor in concretion growth. Where large amounts of organic phosphate are liberated in the surrounding porewaters due to the decay of animal tissue, supersaturation with respect to phosphate will occur and apatite will be precipitated. This is the mechanism for concretion formation around calcareous molluscs and burrows with faecal pellet concentrations. As in the London Clay, teeth may have a small organic content in rare cases, and a concretion may form around the root.

The abundant teeth and bones of sharks and marine mammals derived from this deposit are characteristically phosphatized. They show evidence of marine boring and extensive abrasion. This is probably an indication of the prolonged transport subsequent to the death of the animal in the deeper waters of the basin until they were incorporated into the muddy sands at the basin margin. Above the sediment/water interface the organic content of the teeth and bones would be greatly reduced by scavengers and bacteria. In this case where organic phosphate is not liberated by decay within the anoxic sediment, apatite may be precipitated within existing structures as a replacement process. This is the mechanism by which the dahllite of teeth and bones were phosphatized in this deposit. Derived teeth of London Clay sharks and rays were also phosphatized in this way during the Miocene. This second type of process occurs in the phosphatization of wood (xylem) in the London Clay.

XRF analysis shows that phosphatic concretions from the Crag phosphorite have a slightly higher content of P_2O_5 than London Clay concretions (Table 2). This is probably enrichment due to further apatite precipitation during the Miocene in a similar replacement process to that which phosphatized the teeth and bones.

TABLE 2. *Partial analyses (XRF) of phosphorite concretions expressed as weight % of oxides. 1, London Clay phosphorite concretion; 2, Crag phosphorite nodule*

	1	2
Na_2O	0.84	1.27
MgO	2.74	0.31
Al_2O_3	1.44	2.83
SiO_2	13.82	6.71
P_2O_5	21.67	26.07
K_2O	0.85	0.49
CaO	37.37	43.47
Fe_2O_3	3.10	3.80
Total oxides	81.83	84.95

Deposition of this Miocene unit was followed by another regression. This resulted in the winnowing of the unconsolidated sand. Freshly exhumed concretions with marine bivalve borings, often on all sides, indicate exposure on the sediment surface and periodic overturning. Finally all the unlithified sediment was winnowed away leaving the 'boxstones' behind on the London Clay erosional surface. Due to the large size of the 'boxstones' and their limited distribution within the Crag phosphorite deposit, it is not believed that they were transported any appreciable distance. Lankester (1870) observed some large flag-like slabs of this phosphatic sandstone near Trimley, Suffolk. These probably represent nearly *in situ* material lowered by the action of erosion onto the surface of the London Clay.

Plio-Pleistocene events

The various components of the phosphorite deposit were then covered by bioclastic sands during a further transgression during the Pliocene when the Coralline Crag was deposited. During the transgression, pieces of London Clay carbonate septaria were incorporated into the deposit. After a further brief regression, the Red Crag transgression overstepped the Coralline Crag onto the London Clay, Lower London Tertiaries and Upper Chalk further inland.

It is difficult to state with confidence at which stage in the evolution of the Crag phosphorite deposit the Mesozoic components and other miscellaneous rock types were incorporated. It is not known if only some or all of these components were present before the deposition of the Coralline Crag, or whether it was not until the more extensive Red Crag transgression that they were incorporated. Certainly Chalk flints are very common in the Red Crag but not in the Coralline Crag (which overlies only Tertiary strata). The various phosphatized Mesozoic fossils were probably mineralized before the Tertiary and were derived directly into the Crags.

Terrestrial vertebrate remains younger than Miocene are also found in the Red Crag phosphorite deposit. These are largely unmineralized and are probably contemporary with the Plio-Pleistocene marine deposits. There is at present no evidence of a further phosphogenic episode since the Miocene.

Age of 'boxstones'

There seems no doubt that the poorly preserved molluscan fauna found in the 'boxstones' and most of the phosphatized abraded, indeterminate vertebrate remains, which only rarely show adherent phosphatic sandstone, are contemporary. Most of the identified molluscs have long time ranges and broad ecological tolerances. The 'boxstones' have been traditionally regarded as derived from a Miocene deposit (Cambridge 1977). Lankester (1865) pointed out the strong similarity of the 'boxstone' fauna to the fauna of the 'Middle Crag of Antwerp'. This deposit contains teeth of *Procarcharodon megalodon* and abundant cetacean bones. It is therefore suggested that the 'boxstones' and thus the Miocene phosphogenic episode should be correlated with the 'Middle Crag of Antwerp' which forms part of the Anversian (Curry *et al.* 1978) and is of Lower to Middle Miocene age.

Sources of phosphorus

Although oceanic upwellings are an important process in supplying phosphorus in the marine environment, they are not the sole mechanism necessary to produce a phosphorite deposit (Riggs 1979). Transport of phosphorus by river waters from humid highlands, and also volcanic processes, have been considered to be important in producing a phosphogenic system (Bushinskii 1966).

The E of England is unlikely to have been directly affected by oceanic upwellings during Tertiary times. Knox & Ellison (1979) described ash bands in the London Clay. The ashes have mostly undergone total alteration to montmorillorite, which is an abundant clay mineral often associated with phosphorite formation. Therefore a volcanic source of phosphorus in the London Clay seems a possibility.

Miocene phosphorite deposits have a worldwide distribution. Carter (1978) interpreted this distribution as being due to an increase in the concentration of dissolved phosphorus during a global eustatic regression. However, phosphorite formation in the Tertiary of eastern England appears to be related to transgressive episodes, while regressive episodes are only seen to be important in the concentration of phosphatic material in a remanié deposit.

Conclusions

1. In the Eocene of E England, phosphorite concretions were formed by the precipitation of carbonate fluorapatite in microenvironments of organic decay. The dominant mechanism involved precipitation from interstitial porewaters supersaturated with respect to phosphate. The preferred nucleation centres were rich in organic material and usually also rich in inorganic phosphates, e.g. crustacean carapaces. Material with a high inorganic phosphate content but only a low organic content, e.g. teeth, rarely acted as nucleation centres.

2. During a Miocene transgression, muddy quartz sands were deposited over a small area of E Suffolk. Apatite was similarly precipitated as a concretionary growth in interstitial porewaters surrounding centres of organic decay. However, these centres were generally associated with molluscs or patches of bioturbated sediment. Concretion formation was rare around centres primarily rich in inorganic phosphate, but with a low organic content. These centres formed sites for the precipitation of apatite by replacement.

3. Although these differences exist between phosphorite formation in the Eocene and Miocene of E England the major factor influencing the formation of a phosphorite concretion was the availability of high local concentrations of organic phosphate in interstitial porewaters. The mineral nature of the nucleation centre seems less important.

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