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Classification and Geological Significance of Biostromes

Stephen Kershaw, London

KEYWORDS: REEFS – BIOSTROMES – BIOHERMS – AUTOBIOSTROME, PARABIOSTROME, AUTOPARABIOSTROME, ALLOBIOSTROME – BIOSTROME CLASSIFICATION

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SUMMARY

Biostrome and bioherm were described as terms by CUMINGS (1932), and bioherm has become synonymous with reef because of the discrete mound or lens shape in vertical section. The phrase "reefs and biostromes" is common in the literature and emphasises that biostromes are normally regarded explicitly as not reefal structures, because of the lack of topographic relief and common absence of a framework. However, the position adopted here is that bioherm and biostrome are most usefully applied to simply describe the outline shape of an organic accumulation, and not to denote any particular inherent internal structural organisation. Furthermore, the view here is that biostromes are most usefully considered as single organic layers (i.e. beds). Observations of biostromes of numerous ages and settings indicate that a considerable variety of internal structure exists within the outline which defines biostrome. Often, the structure comprises frameworks and dense clusters of in-place organisms and is just as much "reefal" as similar constructions with a biohermal shape. In other cases biostromes consist of beds of skeletal debris consistent with the concept of biostrome used by

many workers. These differences demonstrate that classification of biostromes is needed in order to allow comprehensive palaeoenvironmental analysis, and highlight the long-standing problem of using 'reef' to describe organic buildups. For biostromes, *autobiostrome*, *autoparabiostrome*, and *parabiostrome* are introduced to describe a continuum from structures where the constructing organisms are mostly in place (autobiostromes), to mostly debris of the structure (parabiostromes), with autoparabiostrome as intermediate. *Allobiostrome*, describes biostromes formed of material derived from allochthonous sources, for example skeletal plankton sedimented onto the sea bed. Most biostromes are of calcareous construction and their composition is most adequately described by existing limestone classification terminology.

Other descriptive terms include: a) for biostrome geometry - *ribbon* and *sheet*; b) for internal layering - *internally unbedded* and *internally bedded*, because some biostromes show lateral facies changes resulting in single layers becoming internally divided by bedding; c) for internal packing variation of constructors, using terminology introduced by R. Riding - *dense* (where constructors are closer together than one unit distance), and *sparse* (where constructors are more distantly spaced). Biostromes are further categorised to account for thickness variations. Adaptation of terminology used for bed thickness descriptions is applied; standard bed thickness categories are not appropriate to biostromes, which are often thicker than 1m. Instead: *Very thin biostromes* - up to 0.1m, *thin biostromes* - 0.1-0.5m, *medium biostromes* - 0.5-2.0m, *thick biostromes* - 2.0-5.0m, *very thick biostromes* - >5.0m. Autobiostromes which form significant features in sedimentary successions may be regarded as the peak of in place benthic organic skeletal buildup (= reef *sensu lato*) development, and their recognition is required to permit full palaeoenvironmental analysis of facies containing them. Particular emphasis may be placed on their role in identifying sea level change in shallow water carbonate sequences, and thence their utility in models to explain such change.

1 INTRODUCTION

The term bioherm was introduced in a footnote by CUMINGS & SHROCK (1928: 599) and later, CUMINGS (1932) fully defined bioherm, and introduced biostrome to describe bedded organic accumulations which do not have a lens or mound morphology, therefore distinct from bioherms (Fig. 1). CUMINGS (1932: 334) emphasised that '*biostrome* means literally an *organic layer*' (his italics). As a result of the detailed discussion by CUMINGS (1932), which focused on problems of reef terminology, a generally agreed synonymy between bioherm and reef as terms has since developed, which usually excludes biostrome from anything reefal in the minds of most workers. Biostrome has become chiefly a description of debris beds of skeletons; see examples in the reef review of FAGERSTROM (1987).

CUMINGS (1932: 347) primarily regarded biostromes as comprising sedentary organisms, and included features such as crinoidal debris beds, shell beds and even coal seams, but extended the term to encompass layered accumulations of pelagic microfossils. Unfortunately, the definition provided by Cumings is so broad that it is possible to include all layered organic deposits under this term, so that it is therefore open to interpretation. For example, JAMES (1983: 379), in contrast to the use of biostrome by other authors to denote debris bands, illustrates a stromatolite biostrome, composed principally of *in situ* sheets and domes of stromatolites. Furthermore, in JAMES' (1983: 372, Fig. 57) illustration of the concept of bioherm and biostrome, biostromes are described as made of 'generally in-place carbonate skeletons'. Thus, the conclusion that can be drawn is that biostrome has been applied both to structures with in-place skeletal growth, and with debris. However, this broadness allows an opportunity to classify and highlight the potential importance of some biostromes in palaeoenvironmental analysis. Thus some biostromes are composed of largely *in situ* organisms as a sheet-like buildup, sometimes with a frame. Examples are: Proterozoic stromatolite biostromes illustrated by JAMES (1983), Silurian biostromes of Gotland (e.g. halysitids-NIELD 1981, stromatoporoids and algae- RIDING & WATTS 1991), Carboniferous biostromes of Britain and America (e.g. chaetetids- JOHNSON 1958, CONNOLLY et al. 1989, VOEGELI 1992), and Cretaceous biostromes (e.g. rudist bivalves- KAUFMAN & SOHL, 1979, SKELTON 1979). Other biostromes are clearly debris (e.g. phylloid algae, TOOMEY 1976), while still others are a mixture of in place and broken skeletal

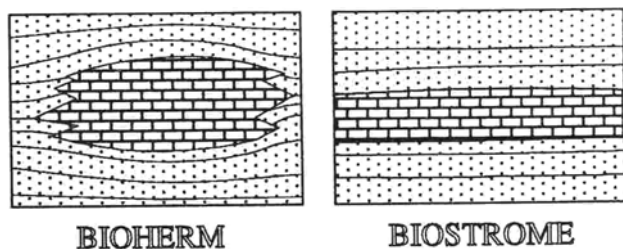


Fig. 1. Stylised vertical sections of outline shapes of bioherm and biostrome, following CUMINGS' (1932) definition. Note the general conformity of biostrome form with subjacent and superjacent sediment, in contrast to the bioherm.

material (e.g. stromatoporoids, KANO 1990, KERSHAW 1990), see Pl. 9. Thus, biosromes composed of *in situ* skeletons could be regarded as reefal, but the purpose of this paper is not to re-examine the problem of defining reef as a term in relation to biostromes (see FLÜGEL & FLÜGEL-KAHLER 1992 for database of the great variety of 'reefs' through time, in which biostromes are included, also BRAITHWAITE 1967, HECKEL 1974). Instead, the aim is to appraise Cumings' definition of biostrome as a descriptive term, and discuss its utility, a topic which has received little attention in the literature. A classification of biostromes is presented, for international discussion, to sharpen the practical value of the term biostrome, and to aid interpretation of biostromes in facies analyses. Several terms which emphasise various attributes of biostromes are introduced to highlight crucial variations. The geological importance of biostromes is emphasised; this paper contends that some biostromes played a significant role in shallow water facies development, and may be of value in formulation of models of even global magnitude where they occur at critical stratigraphic levels. For example, the potential relevance of biostromes to a recent model of oceanographic processes applied to the Silurian is highlighted. The overall conclusion is that exclusion of some biostromes from such models may lead to incomplete analysis.

Although biostromes are common features in modern environments in that shell beds are commonplace, modern reefs with a biostrome shape are not recognised so easily, probably partly due to the paucity of vertical sections of modern reefs. The result is that there are no satisfactory analogues amongst Recent reefs and reef-associated deposits for fossil biostromes, the interpretations of which therefore rely on sedimentological study.

2 BIOSTROME vs BIOHERM

CUMINGS (1932: 333) used bioherm to describe '... reeflike, moundlike, lenslike or otherwise circumscribed structures of strictly *organic origin*, embedded in rocks of different lithology, and biostromes as organic features which are '... purely bedded structures. . . . not swelling into moundlike or lenslike forms' (CUMINGS 1932: 334), a point noted by other authors, e.g. JOHNSON (1958). In situations where the structures developed by *in situ* organic growth across a surface, it is the way in which the surface aggrades in relation to various environmental controls, which leads to either form. Cumings did not provide detailed criteria for the morphological boundary between bioherm and biostrome, but in a review, FAGERSTROM (1987: 15) emphasised that biostromes have essentially flat and parallel upper and lower surfaces. There is a problem of scale here, because biostromes rarely have flat surfaces when seen in detail, and the upper and lower surfaces may be parallel (in strict geometric sense) in only certain parts of the structure. When viewed from a sufficient distance, however, biostromes normally have approximately flat basal and top surfaces, which are usually approximately parallel, and usually interbedded with other rocks. Therefore most biostromes are conformable with beds above and below, do not display sediment

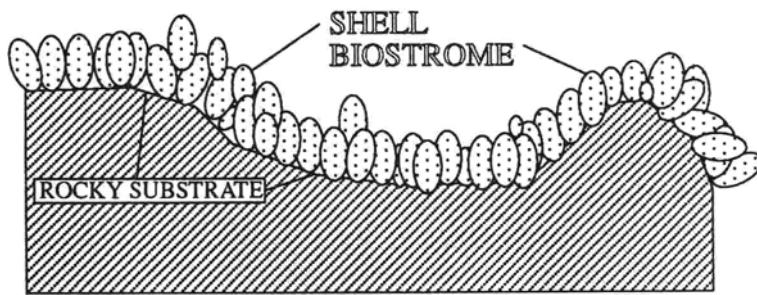


Fig. 2. Stylised vertical section of a mytilid bivalve shell layer developed on an uneven substrate, modelled on a modern rocky shore, Rhossili Bay, South Wales. The shells are in place, and form a layer one or two shells thick which is effectively a biostrome. This example demonstrates that biostromes are not necessarily flat.

drapes with significant original dips, nor do they overstep, or are overstepped by, other rocks unlike bioherms (Fig. 1). Such overstepping relationships would, however, be expected to exist at biostrome margins and in surface depressions, and biostromes can therefore be considered geometrically as extremely laterally extended bioherms. Thus, applying Cumings' definition, organic banks, which have low topographic relief, would be considered as biohermal, and there is obviously an area of uncertainty whereby very low topographic relief could allow a bank to be called either a bioherm or a biostrome. Applying thickness/width ratios and examining the shape of the biostrome upper and lower surfaces are potential discriminants, as noted by HECKEL (1974: 92), but because biostromes are not usually seen entire due to outcrop constraints, such measurements are unrealistic to obtain. In the majority of cases, bioherms are discrete objects, clearly distinguishable in vertical rock sections; instead, biostromes are usually interbedded with other sediments, with the margins normally not visible because of discontinuous outcrop, and there is virtually no problem of overlap between these two terms. It is not compulsory for biostromes to have flat and parallel bases and tops. Some modern shell accumulations, such as mytilid and barnacle colonizations of intertidal rocky shores, may drape irregular rocky surfaces, developing a dense cover on the substrate over substantial areas (Fig. 2). These form thin sheets and are consequently biostromal in form, despite conforming to an undulating substrate.

Cumings did not provide clear guidelines for describing the internal arrangement of the composing elements of bioherms or biostromes. Although he described biostromes as having 'strictly bedded or layered form' (CUMINGS 1932: 347), he also described biostrome as 'an organic layer' (CUMINGS 1932: 334). Thus it is not clear whether internal stratification was intended as a character of biostromes; a stratified biostrome should consist of several organic layers. The view presented here is that defining biostromes as single beds is a more useful approach. In logical consequence, every biogenic bed on Earth is a biostrome, but because CUMINGS (1932) included shell beds, crinoid beds and even coal seams as biostromes, then it seems that this view is not new! Bioherm and biostrome thus refer most usefully to the overall geometric outline shape of the structure in vertical section. Existing terminology of limestone classification (e.g. FOLK, 1962, DUNHAM, 1962) may be applied to carbonate biostromes, and describes the internal arrangements of the components, including the extensions (EMBRY & KLOVAN,

1971) of frame, baffle, bind, float and rud, and the distributional terms of RIDING (1990a, b) of which dense and sparse clusters apply commonly to biostromes.

In the same way that the size and shape limits of bioherms were not defined by Cumings, so too were biostromes. Therefore a shell bed made of a single layer of shells, one shell thick, is as much a biostrome as a structure several metres thick. In the horizontal dimension a biostrome seen in vertical section may be a medial section through an extensive sheet, or a fortuitous section through a thin organic ribbon, so the three-dimensional geometry is important to consider.

Bioherms and biostromes are not mutually exclusive structures. WATTS (1988) and RIDING & WATTS (1991) demonstrated lower Wenlock bioherms in Gotland, Sweden, to have developed into biostromes, with a skeletal frame in their upper parts; they referred to these features as biohermal and biostromal phases of patch reef growth. In the view that biostromes are debris beds, then the idea of these phases is nonsense. From a geometric viewpoint, ignoring internal organisation, consideration of such phases provides, at least qualitative, data on reef growth rates, and possibly even sea level change (KERSHAW 1993). CROWLEY (1973) related stromatoporoid biostromes to shallow waters at the top of a Middle Silurian reef sequence in New York State.

3 CLASSIFICATION OF BIOSTROMES

The foregoing discussion demonstrates complexity involved in the term biostrome. The resulting classification, given below, is presented to international reef workers as a basis for discussion. Quantitative limits are applied, based on field observations of a variety of biostromes; see Fig. 3.

Definition. CUMINGS' (1932) loosely written definition, is constrained: a biostrome is an organic layer '..... not swelling into moundlike or lenslike forms' (CUMINGS 1932: 334), and the term refers only to the external geometry. These points are actually implicit in Cumings' paper.

Types: see Fig. 3a. Biostromes are here broadly divided into *autobiostrome* and *allobiostrome* as end-members of a continuum, with *parabiostrome*, and *autoparabiostrome* as intermediate terms. Biostromes with predominantly in-place fossils are autobiostromes although of course there is much variation of shapes and sizes of constructor skeletons. For example, a hypothetical biostrome may be composed of a laminar frame where the constructing organisms form an in-place framestone, and occupy 50% of area of rock, the

TYPES

A



AUTOBIOSTROME



AUTOPARABIOSTROME (heterogeneous)



AUTOPARABIOSTROME (homogeneous)



PARABIOSTROME



ALLOBIOSTROME (allochthonous)

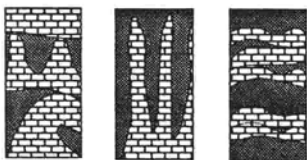
COMPOSITION

B

AUTOBIOSTROME CHARACTERS

PARA/ALLOBIOSTROME CHARACTERS

FRAME BAFFLE BIND

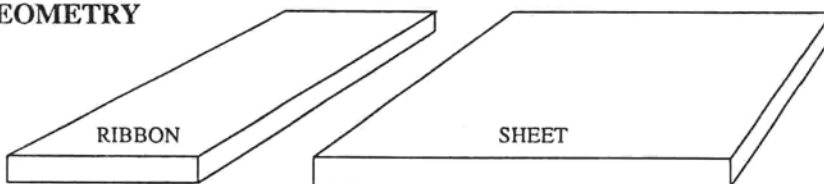


FLOAT
RUD
GRAIN
PACK
WACKE
MUD

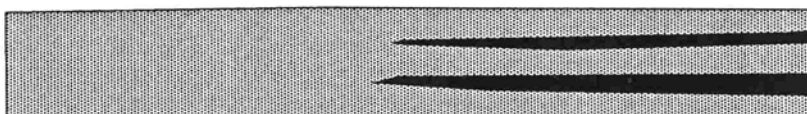
THICKNESS

Very thin	up to 0.1m	thin	0.1 to 0.5m
medium	0.5 to 2.0m	thick	2.0 to 5.0m
very thick	> 5.0m		

GEOMETRY



INTERNAL BEDDING



INTERNALLY UNBEDDED

INTERNALLY BEDDED

Fig. 3. A proposed classification of biostromes, based on a revised definition of CUMINGS' (1932) work. Biostromes are here considered to be single organic layers, and the term biostrome refers only to the external geometry.

A. Stylised vertical sections through biostromes to illustrate the variety of types and terminology applied to them. Symbols used suggest reef-building clonal organisms although the skeletons could be shells instead. Biostrome constituents form a continuum from 100% in-place to 100% allochthonous. They may be divided into auto-, para-, autopara- and allo- subtypes, to reflect the provenance of their components. Autobiostromes contain skeletons predominantly in place (60% and more in place); autoparabiostromes are autobiostromes sufficiently storm-influenced to disrupt their components, but still retain an impression of having previously been autobiostromes (20-60% in place); parabiostromes comprise a large amount of debris of autobiostrome constructors and may represent a biostrome which has been mostly destroyed, or may be a storm deposit lateral to an autobiostrome (<20% in place); allobiostromes comprise totally allochthonous skeletal material (0% in place).

B. Attributes of biostromes. COMPOSITION: because biostromes are mostly limestones, standard textural groups are directly applicable in most cases. THICKNESS: biostrome thickness limits are more appropriately served by the given figures than by standard bed thickness terminology, because they are normally thicker. GEOMETRY: biostromes may be narrow ribbons, or sheets in three dimensions. INTERNAL BEDDING: A stylised vertical section through part of a biostrome; left hand portion shows no stratification (uniform grey symbol), right hand portion shows vertical facies variation (a second lithology in black).

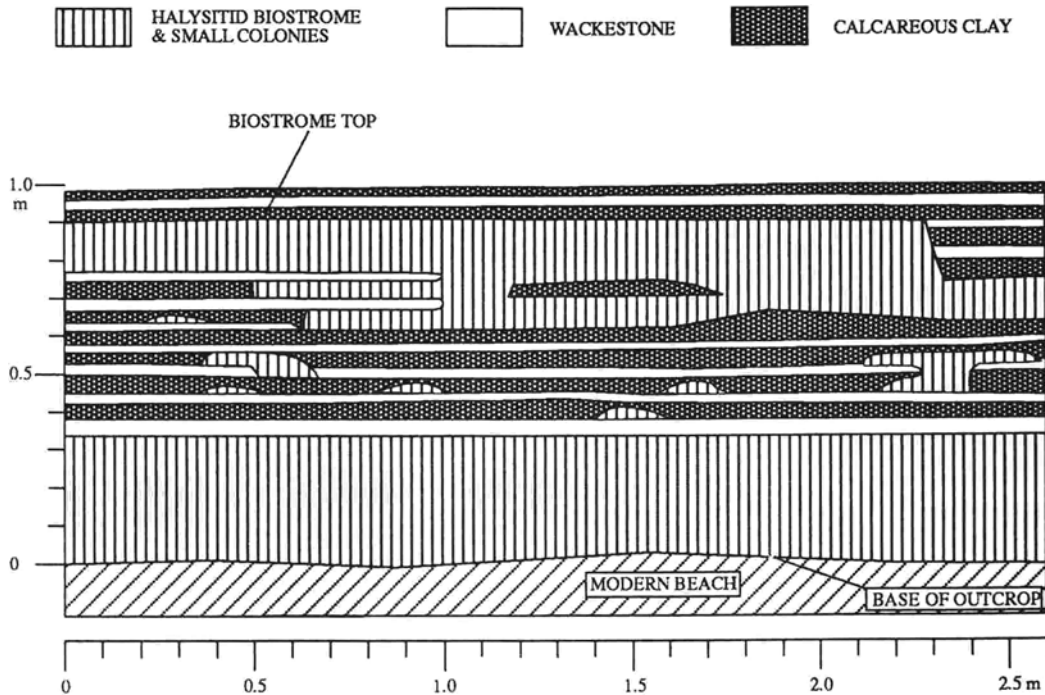


Fig. 4. Mapped vertical section of a small part of a halysitid biostrome stack, Lower Wenlock, Ireviken 3, Gotland. The biostromes are exposed in a cliff for several hundred metres at beach level, and are not visible on photographs. In the map, the stack comprises two halysitid autobiotromes formed in a short geological interval, and indicates a time when the sea bed received little sediment, permitting the biostromes to grow.

remainder infilled with debris. In another potential case, the constructors may be very large *in situ* individuals (e.g. big corals), but few in number, occupying a large percentage of the rock. Therefore an autobiotrome may be defined as a biostrome in which the constructor organisms are predominantly in place, but needs not specify that these be either very numerous or occupy a large percentage of the rock. Autobiotromes which have been disrupted by storm action, such that their original character is still recognisable despite heavy damage, are autoparabiotromes. Parabiotromes are composed of fossil skeletons of the constructors, predominantly not in place, usually as debris, derived from the buildup. The prefix *para-* reflects the relatively local redistribution of skeletal material within the buildup. Examples of auto-, *para-* and autoparabiotromes are given in Pl. 9. Allobiotrome describes biostromes composed of organic debris which has been transported far from its source, for example resedimented shell debris downslope from a reef front, turbidite-related skeletal material, and skeletal plankton settled to the sea bed in layers. Potential overlap may occur between *para-* and allobiotrome as concepts, because of variable distances of transport of material, and an autobiotrome may contain an allochthonous component.

Adjectives applied to autoparabiotrome can describe variations in relative distribution of auto- and *para-* elements. In homogeneous autoparabiotromes, the debris is evenly distributed amongst *in situ* constructors, whereas in heterogeneous autoparabiotromes debris is concentrated in some parts, while other parts appear autobiotromal.

Because of the great variation of morphology of constructors, the application of rigid percentage discrimination between auto-, autopara-, *para-* and allo-biotromes is diffi-

cult. Broadly, from examples studied, if 60% or more is *in situ*, then the structure gives the visual impression of being largely in place, and is considered autobiotrome; between 20 - 60% *in situ* for autoparabiotrome; 20% and less for parabiotrome; and 0% *in situ* for allobiotrome.

Composition: see Fig. 3b. Biostrome constituents vary, of course, so broad groups can be identified: a) large clonal metazoa, such as corals, bryozoans and calcareous sponges, major constructors in 'reefal' biostromes; b) small acclonal metazoa, such as small shells and crinoids. Standard limestone classification schemes apply directly to describe the internal organisation of the components. Broadly, frame, bind and baffle are autobiotrome features, while float-, rud-, grain-, pack-, wacke- and mudstone are *para-/allobiotrome* features.

Geometry: see Fig. 3b. Biostromes are normally viewed in vertical section only, and therefore the three-dimensional shape is not seen. Arguably, biostromes could be widespread sheets, or narrow ribbons, depending on local depositional conditions, and *sheet biostrome* and *ribbon biostrome* are introduced to describe such variation.

Scale: see Fig. 3b. Biostromes vary in thickness, and an adaptation of terminology applied to sedimentary beds provides appropriate subdivisions which match the known range of biostrome thicknesses. In practice, the standard terminology applied to bed thickness (e.g. TUCKER, 1982) does not quite match biostrome thickness ranges, and the following categories have been found to be more appropriate: *very thin:* up to 0.1 m; *thin:* 0.1-0.5 m; *medium:* 0.5 - 2.0 m; *thick:* 2.0-5.0 m; *very thick:* >5.0 m.

BIOSTROMES IN KOPPARSVIK QUARRY, GOTLAND

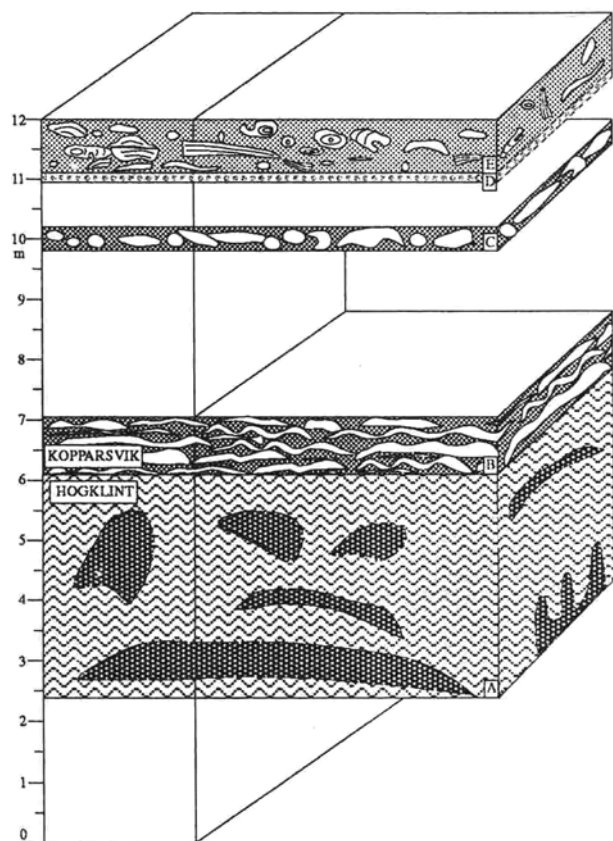


Fig. 5. Stylised log of the Kopparsvik Quarry, Visby, Gotland, with a variety of biostromes highlighted; blank portions contain bedded limestones and shales not illustrated.

A. Högklint Fm biostromal phase of patch reef, comprising large stromatoporoids (dark) and sediment-filled algal frame, thick autoparabiostrome; B. Kopparsvik Fm laminar frame stromatoporoid thin autobiostrome; C & E. stromatoporoid debris, thin parabiostromes; D oncolite bed, very thin parabiostrome.

Internal bedding: Fig. 3b. Because biostromes are considered here as single organic layers, they may display lateral changes so that the structure becomes partially or completely internally stratified, reflecting facies variations which demonstrate environmental variations laterally across the biostrome. The term *internal bedding* is applied to empha-

size these features, so that biostromes may be *internally bedded* or *internally unbedded*.

4 BIOSTROME EXAMPLES

By assigning size criteria to biostromes of various types, the opportunity to identify and highlight biostromes of significance to palaeoenvironmental models of local and possible global nature, is available. The utility of the scheme is best shown by example, in this case from Gotland, England and Kansas. The following examples are chosen to demonstrate the variety of types of biostromes, and the usefulness of the terminology, but are not exhaustive.

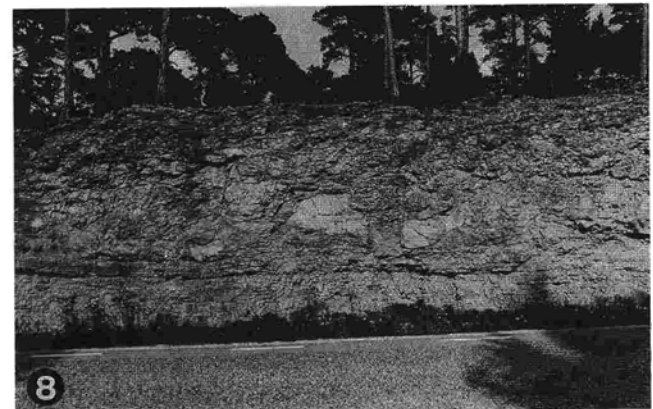
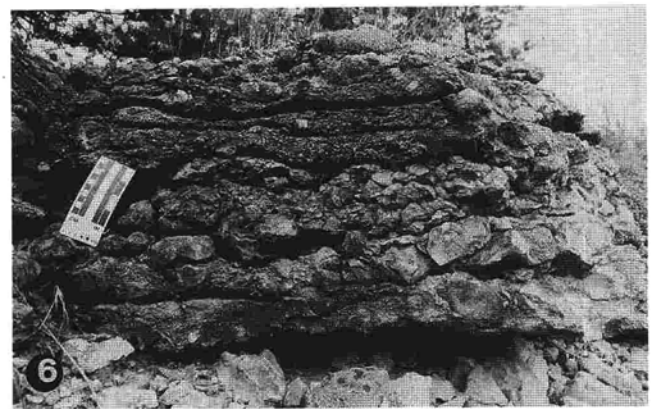
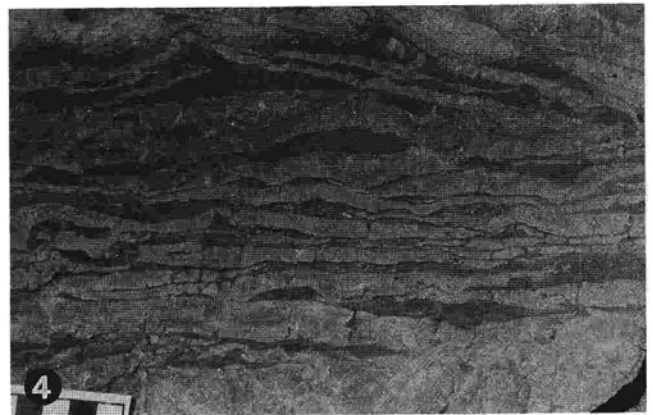
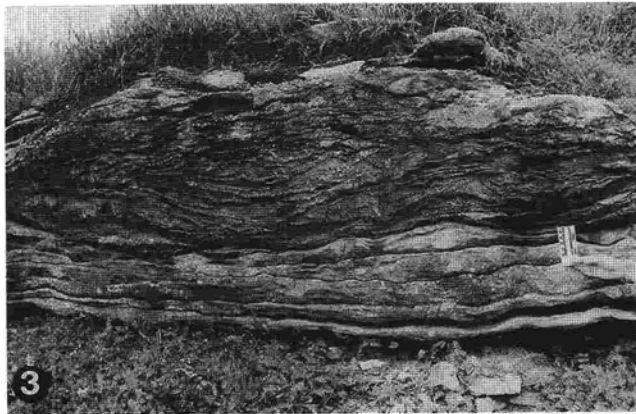
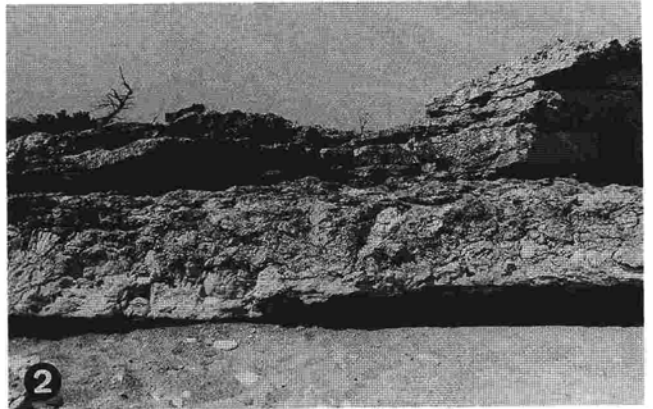
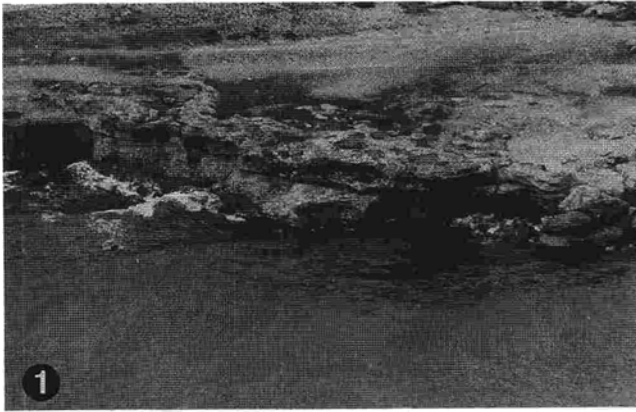
4.1 The Hemse Group Ludlow biostromes of Gotland

The magnificent stromatoporoid biostromes in the upper Hemse Group of middle Ludlow age in southeast Gotland provided the inspiration for this study (Pl. 9/1, 2, 5). Documented by KANO (1990), KERSHAW (1990, 1993), KERSHAW & KEELING (1994) and RIDING (1981), the outcrops display different types of stacked biostromes. Present are thin to very thick stromatoporoid autobiostromes, autoparabiostromes (Pl. 9/5), rudstone parabiostromes (composed chiefly of stromatoporoids, Pl. 9/2), some internally bedded, and interbedded with thin to medium crinoid-dominated para/allobiostromes (Pl. 9/2). KERSHAW (1993) and KERSHAW & KEELING (1994) have demonstrated that the thick autoparabiostromes, composed of dense clusters of stromatoporoids, form significant build-ups (up to 1 km in diameter) under conditions of stable sea level, starved clastic supply, over a large enough area of suitable substrate to perpetuate the structures laterally. The biostromes occur in a portion of the Silurian record examined by JEPSSON (1990) in his proposal of a two-state oceanic model for the Silurian, with alternating states between warmer and cooler states referred to respectively as Secundo (S) and Primo (P), based on conodont extinction patterns. The implications of Jeppsson's work for some of the Hemse Group stromatoporoid biostromes are profound, because evidence collected so far demonstrates that at Kuppen, biostromes grew during S-state conditions when the climate was warmer (KERSHAW & KEELING 1994).

Plate 9

Examples of biostromes from the Silurian of Gotland, and the Pennsylvanian of Kansas.

- Fig. 1. Oblique aerial view of medium to very thick stacked biostromes at Kuppen 2 (Laufeld 1974), Ludlow Hemse Group, Gotland. Cliff height 6m.
- Fig. 2. Thin (0.5m) stromatoporoid-dominated parabiostrome, overlain by crinoidal debris as para/allobiostrome, at Sjauster, Ludlow Hemse Group, Gotland.
- Fig. 3. Medium thickness autobiostrome of laminar frame chaetetids, Highway 69, Fort Scott, Kansas, Pennsylvanian.
- Fig. 4. Enlargement of another part of the autobiostrome in C.
- Fig. 5. Enlargement of A, showing autoallobiostrome character.
- Fig. 6. Interbedded thin stromatoporoid/coral rudstone and thin crinoid grainstone/packstone allobiostromes, Lilla Snögrinde 2, Wenlock Klinteberg Group, Gotland.
- Fig. 7. Small bioherm of densely packed chaetetids (by hammer) in autobiostrome at Stine Spur, Kansas, Pennsylvanian. This is an enlargement of biostrome in Fig. 6.
- Fig. 8. Thick, presumed autoallobiostrome, top eroded in Recent times, highly heterogenous, above thinly bedded limestone. Small bioherms are discernable. Bofride 1, Wenlock Klinteberg Group, Gotland.



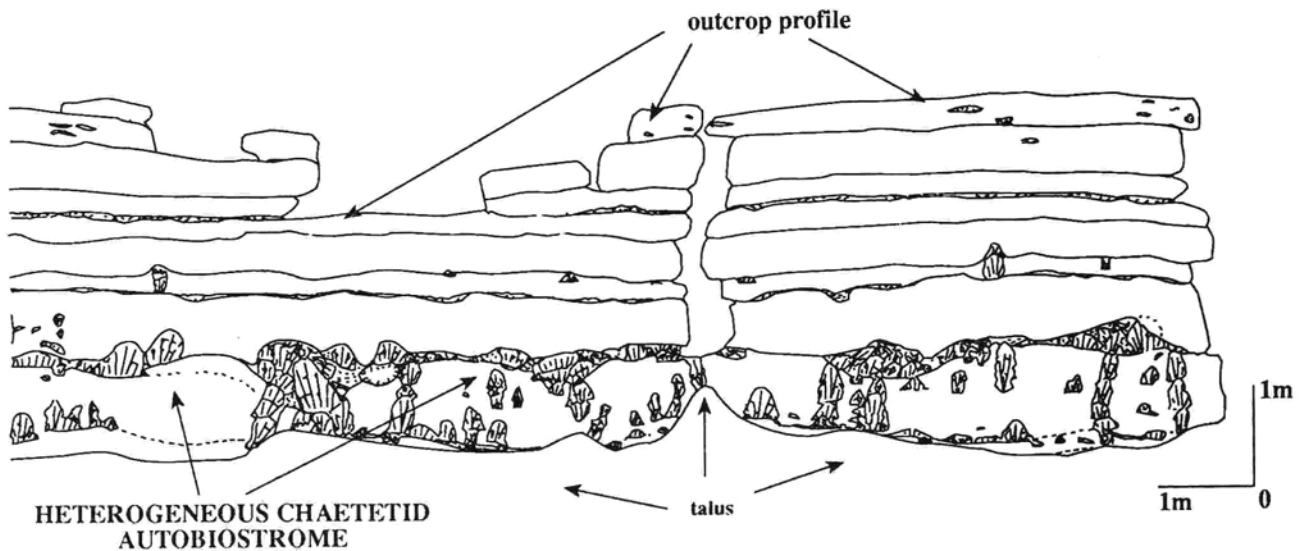


Fig. 6. Vertical section of part of a chaetetid biostrome from Pennsylvanian of Kansas overlain by other bedded sedimentary rocks (from VOEGELI 1992: Fig. 21). Note 1) the heterogeneous distribution of chaetetids varying from dense to sparse, forming small bioherms within a biostrome; 2) dashed lines denoting intermittent internal bedding in this part of the biostrome. Voegeli recognised five units in the biostrome, which is therefore internally bedded. The top portion commonly contains chaetetids which are disturbed from growth position. Note that the visual impression given by the diagram is that because chaetetids are largely in place, the structure could be called an autobioströme; however, chaetetids clearly occupy less than 60% of the exposed area, the remainder composed of algal and other skeletal fragments of apparently allochthonous origin. Its classification should reflect both components and may be called a medium auto-allobioströme.

4.2 Halysitid biostromes, Lower Wenlock of Gotland

A series of stacked very thin and thin halysitid biostromes (NIELD, 1981) at locality Ireviken 3 (LAUFELD, 1974) crop out at beach level (Fig. 4). They extend for several hundred metres in a 1-metre thick unit and represent a period of low sedimentation in the Visby Fm sedimentary unit. The stack developed in quiet water (fine, clay-rich sediment) at greater depth than other reef units on Gotland, with the halysitids reflecting the ease with which sediment can be shed. The biostromes have numerous accessory organisms, principally colonial and solitary rugose corals, making use of the stable substrate provided by the halysitids. The biostrome stack has not been affected by storm disruption, so that each biostrome is fully autobioströmal and framestone. Thus, in Fig. 4, all the halysitids are in growth position.

4.3 Stromatoporoid-coral biostromes of Lower Wenlock of Gotland

Kopparsvik Quarry, Visby, Gotland, exposes an excellent vertical section of lower Wenlock carbonates in shallow water environments and is the type locality of the Kopparsvik Fm of RIDING & WATTS (1991), a revision of the Tofta Fm and parts of related Fms of Hede (1960). The lowest beds reveal a biostromal phase of Högklint patch reefs of the Högklint Fm, overlain by biostromes of the Kopparsvik Fm. The Högklint biostromal phase is a large heterogeneous structure consisting of parts of continuous autoparabioströme passing laterally into parabioströme in places, in which are small bioherms equivalent in composition to the autobioströme parts. Fig. 5 shows the variations of biostromes in the

Kopparsvik Quarry, in which details are drawn from field sketches, and Fig. 7B schematically demonstrates the larger scale relations, modelled on the Kopparsvik exposure. The Kopparsvik biostromes vary from framestone autobioströmes (Fig. 5B) to thin and very thin parabioströmes, one of which is oncoidal (Fig. 5D).

4.4 Carboniferous chaetetid biostromes

Chaetetids built well-developed biostromes in marine Lower Carboniferous limestones. A well-exposed Pennsylvanian biostrome at Stine Spur, near Coffeyville, southeast Kansas, displays several characteristics of the biostrome classification presented above. Fig. 6 shows a mapped section of the autobioströme (from VOEGELI 1992), where its heterogeneous nature is clear. Although overall it forms a separate unit from beds above and below, internally the chaetetids do not form a frame, and cluster in places to form small subsidiary bioherms within the biostrome. The matrix is wacke/packstone. Thus the structure is a medium thickness, heterogeneous autoallobioströme. This biostrome is a small scale feature, but demonstrates that a sufficiently long marine phase was available to grow large chaetetid skeletons.

The chaetetid-coral band (the Potts Beck Limestone, GEORGE et al. 1976: 10) at Little Asby Scar, Cumbria, England, (not illustrated) in contrast to the Kansas example, contains dome-shaped chaetetids which are mostly out of growth position, and sprawling masses of branching rugose corals which are largely in place. Distribution of these elements fluctuates laterally, with corals concentrated in some areas, and chaetetids in others. This autoparabioströme is heterogeneous, with a variation from dense to sparse

distribution of corals and chaetetids from place to place along its outcrop.

5 DISCUSSION

5.1 Heterogeneity of biostrome composition

The terminology introduced above is, in effect, a larger scale extension of the limestone textural concepts of DUNHAM (1962) and EMBRY & KLOVAN (1971), and although the terms permit subdivision of biostromes, the percentage limits between the various categories are given as guidelines, and it may prove necessary to adjust these. However, the consequence of regarding biostromes as single organic layers, so that all biogenic layers are biostromes, means that all layer-form limestone deposits can be described under this scheme along a continuum from fully in-place to fully allochthonous. Thus, most limestone beds are allo- to parabiostromes, and biostromal reefal deposits fall largely into auto- and autoparabiostrome categories. Identification of a particular deposit as one or other of these types, is similar to the use of the Dunham scheme. In the latter, any limestone bed may contain differential distribution of shell content, so that in one place, packstone applies; a few cm away, the rock may be wackestone, a few cm more it is mudstone, and for this to be useful in facies studies, averages are used. The same is true for the present scheme, which is most useful when applied in a broad sense to biostromes, although precise limits can be applied where appropriate.

Heterogeneity of the packing distribution of the component constructors is therefore important in the classification. The proportion of in-place reef builders can vary from place to place in a biostrome, so that one part may be autobiostrume with most fossils in place, whereas other parts of the same structure may be parabiostrome, giving the whole biostrome an autoparabiostrome classification. Alternatively, for example, if in-place and disturbed components are intermixed, then autoparabiostrome designation for the whole biostrome may give the same percentage in-place, but the distribution is different. It is unrealistic in this context to develop firm divisions between these categories. These problems are further compounded by consideration of the percentage of large constructor organisms of the total volume of rock such that some biostromes have densely packed large clonal skeletons, while others, or parts of the same, biostrome, have a less dense accumulation, the remainder being para-/allochthonous matrix and shell/crinoidal hash, for example. RIDING (1990a, b) addressed this problem introducing the concept of dense and sparse clusters of organisms in reefs where such percentages vary. This approach is adopted here, where it is clear that a continuum exists from high to low percentage of large skeletal metazoa. Variation within a single biostrome may demonstrate a transition from densely packed large skeletons, giving a 'reefal' appearance, which grades into a sparsely distributed, level-bottom, community organisation (Robert Riding pers. comm.), within a single biostrome, see Fig. 7. However, the concept of density also applies to all the constructing elements, and does not have to be restricted to large clonal metazoa.

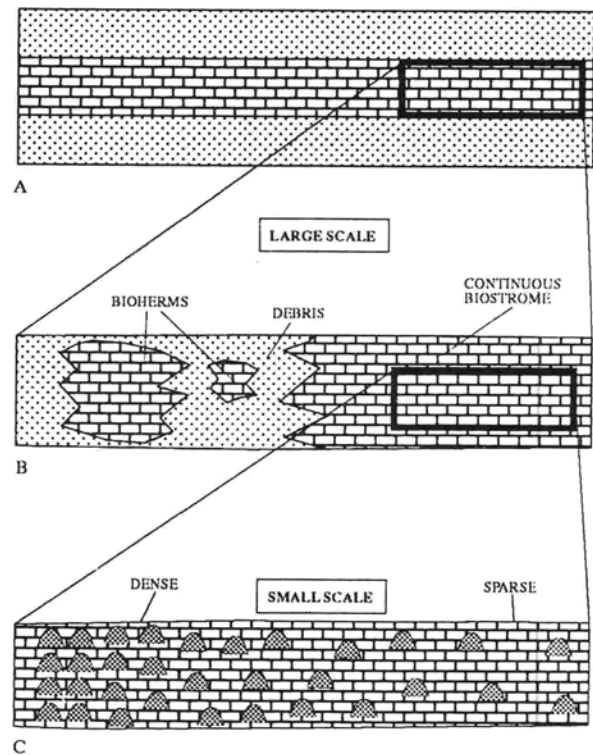


Fig. 7. Stylised vertical sections through biostromes at different scales. A. largest scale, where a biostrome is a substantial organic limestone unit, in brickwall symbol. B. Variation from continuous biostrome to small bioherms within the confines of the larger scale unit. Vertical thickness of biostrome for A and B is c. 5 m. C. Distributional variation of large constructor skeletons at small scale (biostrome thickness 2m), using terminology of RIDING (1990a,b); for *dense*, skeletons are closer than one unit distance, for *sparse*, skeletons are further apart.

Parabiostromes include virtually all structures internally composed of disturbed and transported material. They may be derived from the destruction of autobiostrumes or bioherms by storm action, with reef debris being scattered as sheets or ribbons on level substrates. The categories described by CUMINGS (1932) as crinoid beds and shell debris beds are largely parabiostromes, or possibly allobiostrumes, but in-place accumulations of shells and, arguably, coal seams, would be autobiostrumes. If field relationships allow, parabiostromes may be demonstrably lateral equivalents of autobiostrumes or may be genetically linked to particular autobiostrumes or bioherms. Allobiostrumes are included in the scheme to provide for cases of allochthonous origin, and the foraminifera beds mentioned by CUMINGS (1932), would be an example, providing they are planktonic forms.

5.2 Biostrome size

When viewed from a sufficiently large distance a biostrome is a clearly definable structure containing inhomogeneities of internal structure and composition. Taking this observation to its extreme, limestones deposited in episodes of geological time when carbonate build-ups formed in a substantial stratigraphic interval, such as the Much Wenlock

Limestone Fm (Wenlock) in Britain, up to 30 m thick, could qualify as very large scale, highly heterogeneous, biostromes; directly above and below this particular lithostratigraphic unit, the facies are shale-dominated and no reefs occur. Such a view, that the entire Much Wenlock Limestone Fm. is a single biostrome, is of limited practical classification use, but emphasises this episode of British Silurian geological history when organic build-ups formed, and demonstrates the effects of varying scale on the classification. It is important to remember that there is no defined lower or upper size limit for bioherms, and biostromes, nor should there be.

Thus the spacing of large metazoans in biostromes, and the clustering of bioherms to form biostromes, are simply different scales of the same problem.

5.3 Modification of biostrome form

Syn- and post-formational depositional and erosive processes will modify the outline morphology and internal organisation of biostromes. As noted above, a shell bed may consist of *in situ* shells, followed by biostratinomic disruption and local redeposition, retaining a layer form.

More problematic is the post-lithification erosion of the top and edges of the structure, e.g. one of the biostromes in the Hemse Group example, at Kuppen, Gotland (RIDING 1981), and biostromal phases of Högklint reefs (WATTS 1988), where tops of biostromes are erosion surfaces. The resultant modified geometry potentially creates classification problems of biostrome form and thickness and therefore influences palaeoenvironmental interpretation in individual cases, but the presence of thick to very thick autobiotromes, as in parts of the Gotland sequences where such biostromes are common, indicates their importance. In any case it may be expected that biostromes built by large skeletal metazoans would be often eroded because of their shallow water setting.

6 THE GEOLOGICAL IMPORTANCE OF CLASSIFYING BIOTROMES

Biostromes are significant geological features in some shallow water carbonate-dominated environments. Reefs are typically regarded as being important elements in discussions of controls on carbonate-bearing sequences, such that acknowledgement of the presence of reefs takes on almost a magical quality, while biostromes are not given such prominence.

Thus models of palaeoenvironmental analysis of carbonate build-ups would be deficient if buildups containing such dense accumulations of large 'reef-building clonal skeletal metazoa as stromatoporoids, bryozoans and corals were excluded simply because they were classed as biostromes rather than bioherms. Recognition of the significance of some biostromes is therefore an essential part of facies analysis of such environments. On Gotland, for example, the most reef-fossil rich units are biostromes, especially auto-parabiostromes, and if these are not given due prominence, then application of such models may not reach their full potential. By attempting to classify biostromes, there is an

opportunity to realise this potential and build on such pertinent reef studies as those by COPPER & BRUNTON (1991), and BRUNTON & COPPER (in press) where global problems of Silurian reef development are addressed.

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Following the completion of this paper, the work of NELSON et al. (1962) was brought to my attention. They provided a comprehensive review of reef terminology and discussed CUMMINGS' (1932) use of bioherm and biostrome; they noted that Cumings was not always consistent in his view of the composition of biostromes. Their approach was that the term biostrome should be restricted to apply to organic structures composed of in-place skeletons.

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