

Conceptual Framework for the Analysis and Classification of Fossil Concentrations

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PALAIOS, 1986, V. 1, p. 228–238

Densely fossiliferous deposits are receiving increasing attention for their yield of paleobiologic data and their usefulness in sedimentology and stratigraphy. This trend has created a pressing need for standardized descriptive terminology and a genetic classification based on a coherent conceptual framework. The descriptive procedure outlined here for skeletal concentrations stresses four features—taxonomic composition, bioclastic fabric, geometry, and internal structure—that can be described readily in the field by nonspecialists. The genetic classification scheme is based on three end members, representing biologic, sedimentologic, and diagenetic factors in skeletal concentration. Concentrations created through the simultaneous or sequential action of two or more factors are classified as mixed types. As a conceptual framework for comparative biostratigraphic analysis, the broad categories of this ternary classification scheme should facilitate recognition of large-scale temporal and spatial patterns in skeletal accumulation. The usefulness of this approach is suggested by the good agreement between biostratigraphic patterns observed in ancient onshore-offshore facies tracts and those predicted across paleobathymetric transects based on modern processes of skeletal concentration.

INTRODUCTION

Concentrations of biologic hardparts are common and conspicuous features of the stratigraphic record. They have come under increasing scrutiny in recent years, both by paleontologists concerned with post-mortem bias of fossil assemblages and by geologists concerned with the determination of paleohydraulic regimes, facies analysis, and marker-bed correlation (e.g., Baird and Brett, 1983; Kreisa, 1981; Fürsich, 1978, 1982; Futterer, 1982; Hagdorn, 1982; Kidwell and Jablonski, 1983; Aigner, 1985; Kidwell, 1985; Seilacher, 1985). None-

theless, densely fossiliferous horizons are often not fully exploited for the information they record, and there have been few attempts to relate them to one another in terms of genetic classifications or models.

Schäfer (1962, transl. in 1972) provided one of the earliest biostratigraphic classifications, subdividing all marine biofacies—hardpart-rich and hardpart-poor—into five types based on water oxygenation and energy. This scheme was broadened and recast by Rhoads (1975), who used trace and body fossil abundances to classify facies. The “Fossil-Lagerstätten” scheme of Seilacher and Westphal (1971; Seilacher et al., 1985) focused on deposits which are unusually rich in paleontologic information, irrespective of whether the deposit is densely or sparsely fossiliferous. Such beds are classified according to process of concentration (condensation, placer, passive fissure trap) or mode of preservation (stagnation, rapid burial, conservation trap).

To facilitate biostratigraphic analysis and comparison, this paper summarizes our joint efforts 1) to standardize nomenclature for the field description of skeletal concentrations, using both new and existing terms, and 2) to devise a conceptual framework or genetic classification scheme for skeletal concentrations. These range from localized fecal pods and channel lags to reefs and shelf-wide bioclastic sands, so a major challenge is to identify significant similarities among the many possible kinds of concentrations rather than to differentiate further among them. We have aimed for a system that is simple and yet as inclusive and general as possible.

Our descriptive and genetic schemes for fossil concentrations address only a subset of all fossil assemblages, of course, since fossils are not always found in great abundance. The schemes are thus intended to supplement rather than to replace more general models for the formation of fossil assemblages (e.g., Fagerstrom, 1964; Johnson, 1960), which stress the biasing effects of hardpart destruction, transport, and time-averaging on paleoecological data.

Fossil Concentrations and Fossil Assemblages

We define a skeletal (or fossil) concentration as *any relatively dense accumulation of biologic hardparts, irrespective of taxo-*

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nomie composition, state of preservation, or degree of post-mortem modification. Concentrations of steinkerns are included in this category. Although macroinvertebrate and vertebrate hardparts are more conspicuous, ostracods and algae can constitute concentrations as do even smaller elements such as sponge spicules, radiolarians, and coccoliths. Concentrations are not necessarily restricted in physical scale, and they can reflect fossil accumulation over very brief or very prolonged periods of time.

Fagerstrom (1964) has defined a fossil assemblage as “any group of fossils from a suitably restricted stratigraphic interval and geographic locality” (his italics). Most authors discriminate among types of assemblages by the extent and nature of preburial alteration of the remains of the original living community (Boucot, 1953; Johnson, 1960; Craig and Hallam, 1963; Fagerstrom, 1964; Hallam, 1967; Lawrence, 1968). Scott (1970) employed a comparative procedure based on a series of questions. Are the fossils in their life positions or disturbed? If disturbed, do they occur in the original or in some foreign substratum; that is, were they transported out of the original life habitat or not? Is the assemblage ecologically homogeneous or heterogeneous, and, if heterogeneous, were specimens mixed by biological or physical processes? In such an analysis, the abundance of fossils in the stratigraphic interval is not a factor. A fossil assemblage may occur in a bed containing abundant and densely packed fossils or in one where only widely dispersed specimens are present (Johnson, 1960).

A skeletal concentration may consist of a single, homogeneous assemblage, or it may be heterogeneous, consisting of several subsidiary fossil assemblages. We characterize these assemblages in conventional European terms that have come into common use in North America and are broadly synonymous with categories established by Scott (1970).

Autochthonous assemblages are composed of specimens derived from the local community and preserved in life positions. This category is largely synonymous with Scott’s “in-place assemblage,” Johnson’s (1960) Model I assemblage, and Fagerstrom’s (1964) end-member “fossil community.” Many autochthonous assemblages are ecologically homogeneous and are undisturbed records of mass kills. Autochthonous assemblages can, however, be ecologically heterogeneous owing to time-averaging (Peterson 1977) or faunal condensation (Fürsich 1978) of successive, ecologically dissimilar species, which colonize the substratum in response to fluctuations in water salinity or oxygenation, progressive change in substratum mass properties (dewatering of mud, accumulation of bioclastic debris), or autogenic, biotically-driven succession.

Parautochthonous assemblages are composed of autochthonous specimens that have been reworked to some degree but not transported out of the original life habitat. Specimens can be reoriented, disarticulated, and concentrated by biologic agents (bioturbators, predators, scavengers) and by physical processes. This category is thus synonymous with Scott’s (1970) “disturbed-neighborhood assemblage” and includes Johnson’s (1960) Model II assemblage and Fagerstrom’s (1964) “residual fossil assemblage,” in that some original elements of the life assemblage can be missing due to selective destruction or transport out of the habitat.

Allochthonous assemblages, composed of specimens trans-

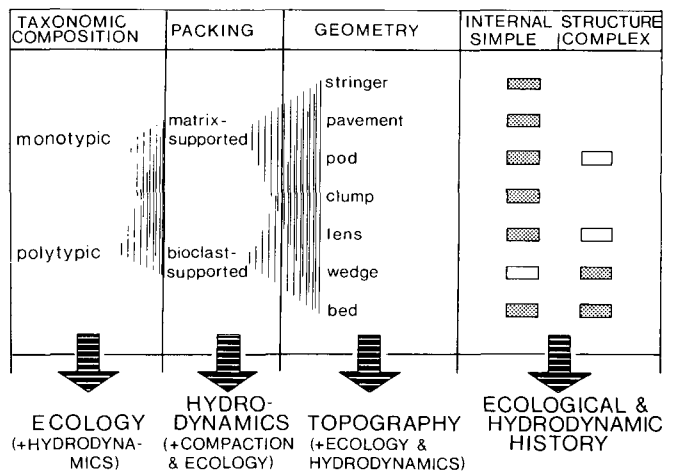


FIGURE 1—Procedure for description of skeletal concentrations, with standardized terms for major features and their genetic significance. Not all combinations of features are likely. For example, stringers and pavements are almost always simple in internal structure (shaded box), whereas among the thicker beds, both simple and complex internal structures are common.

ported out of their life habitats and occurring in a foreign substratum, are equivalent to the “transported assemblages” of Johnson (1960: Model III), Fagerstrom (1964), and Scott (1970). Assemblages composed of specimens of different origins are referred to as *mixed autochthonous-parautochthonous*, *parautochthonous-allochthonous*, or *autochthonous-allochthonous*. These types subdivide the “mixed assemblage” category of Fagerstrom (1964) and Scott (1970).

All of these terms refer to skeletal material that is roughly contemporaneous in age with the embedding sediment. Following Craig and Hallam (1963), we use *remanie* to refer to significantly older material that is reworked into the assemblages, and we use *leaked* to indicate younger material piped down into the assemblage through burrows or fissures.

We emphasize that there is no necessary one-to-one correspondence or synonymy between types of fossil assemblage and types of fossil concentration. Fossil concentrations are formed by sedimentologic as well as biologic processes, so their analysis and classification complements paleoecological terminology and the relation of fossil assemblages to the once-living communities from which they have been derived.

DESCRIPTIVE NOMENCLATURE FOR SKELETAL CONCENTRATIONS

Of the many possible field observations of skeletal concentrations (Ager, 1963), our descriptive scheme stresses only four: 1) taxonomic composition, 2) bioclastic fabric (specifically close-packing), 3) geometry, and 4) internal structure of the deposit (Fig. 1). Most of these characters show a continuous range of states, so our terminology incorporates arbitrary subdivisions. The descriptive categories could be quantified, but here we stress visual definitions in order to maximize practicality for field studies.

Although reefs and other biologic buildups are certainly

skeletal concentrations, they are not included in this discussion. Nomenclature for the description of boundstones is quite distinctive and usually inappropriate for level-bottom marine and terrestrial fossil concentrations (Heckel, 1974; James and MacIntyre, 1985).

Taxonomic Composition

This criterion depends upon the biologic structure of living communities of skeletonized organisms—the source of hardparts—and also upon the hydrodynamics of their accumulation, since differential fragmentation and transport of skeletal elements affect the final taxonomic composition of the deposit (Hollmann, 1968; Force, 1969; Cadée, 1968; Aigner and Reineck, 1982). Taxonomic composition is also a function of differential preservation of skeletal elements in consequence of post-mortem exposure on the sea floor and early diagenesis (Driscoll, 1970; Peterson, 1976), reworking or stratigraphic leakage of hardparts, and time-averaging or faunal condensation of successive ecologic associations (Fürsich, 1978; Peterson, 1977; Kidwell and Aigner, 1985).

Concentrations are characterized as *monotypic* or *polytypic* by whether they are composed of a single or several types of skeletons. We broaden Fagerstrom's (1964) original definition of monotypy to apply to any taxonomic level appropriate to the study, not to species alone. A monotypic accumulation can be composed solely of pelecypods, of ostreids, or of *Crassostrea virginica*. The lower the taxonomic level, of course, the greater the ecological or hydrodynamic significance of monotypy. Monospecific and polyspecific are useful variants, and the term paucispecific is valuable for reference to an assemblage of only a few species, especially if it is strongly dominated by one species.

Biofabric

Biofabric refers to the three-dimensional arrangement of skeletal elements in the matrix. It includes skeletal orientation, close-packing, and sorting by size and shape. The biofabric depends primarily on the hydrodynamics of hardpart concentration, but it may also reflect rotation and disarticulation of elements during compaction; preferential destruction of the matrix by pressure solution; the ecology and necrology of the organisms, including their life positions; and the ecology of other organisms that modified the skeletal remains (predators, scavengers, bioturbators).

In the plane of bedding surfaces, orientation is usually described by rose diagrams (Figure 2). It has been used by many workers as a paleocurrent indicator (review, Potter and Pettijohn, 1963; Nagle, 1967; Brenner, 1976; Futterer, 1982). In assemblages comprising more than one modal size or multiple shapes, it is commonly necessary to evaluate the orientation of each mode or shape separately in order to detect the unimodal or bimodal alignment of elongate elements (Urlichs, 1971).

For orientations observed in cross section, no consistent terminology has been proposed. We suggest *concordant* to describe the parallel to subparallel alignment with bedding of long axes of hardparts or flat surfaces of platy elements; *perpendicular* to describe elements arranged largely at right angles to bedding; and *oblique* for elements exhibiting interme-

diat positions (Fig. 2). We recommend *concordant* as a less ambiguous term than parallel or subparallel, which can equally well refer to the orientation of hardparts relative to one another. Special terms are reserved for fabrics that are characteristically ordered in cross section; these include *imbrication*, *edgewise*, *stacking*, and *nesting*. *Telescoping* is an unusual but highly diagnostic fabric in which conical elements interpenetrate. It has been recognized in nautiloid concentrations, where the apex of one shell pierces the septa of another (Tasch, 1955), and in scaphopod and hololithid concentrations (Spath, 1936; Yochelson and Fraser, 1973; James and Klappa, 1983).

Close-packing in fossiliferous deposits ranges from highly dispersed fabrics to densely packed concentrations containing 70% or more hardparts by volume. Because the visual estimation of close-packing (e.g., charts of Schäfer, 1969) is a function of the shape and orientation of hardparts as well as their volumetric abundance, we adapt Dunham's (1962) petrographic fabric terms to describe skeletal accumulations. *Matrix-supported* refers to concentrations in which the hardparts "float" in the matrix, and *bioclast-supported* indicates that hardparts are in physical contact with each other, supporting the bed structurally or as a house-of-cards. These biostratigraphic categories are roughly comparable to Dunham's mudstone/wackestone and packstone/grainstone categories.

The hydrodynamic and ecological significance of hardpart size-frequency distributions is poorly understood owing to the effects of shape and density on hydraulic equivalence (Maiklem, 1968; Braithwaite, 1973) and the complexities of population dynamics, ecology, compaction, and differential preservation potential according to size (Shimoyama, 1985; Green et al., 1984; Mancini, 1978; Price, 1982). We describe the size ranges of species that predominate in numbers of individuals or skeletal volume and record whether the distribution is unimodal or polymodal, well sorted or poorly sorted. The frequency distribution of hardpart shapes is difficult to quantify, but it is implied by taxonomic composition and by the extent of fragmentation and disarticulation, which are described as aspects of shape and size sorting.

Geometry

The geometry of a fossil concentration depends upon a number of biologic and physical factors. These include 1) the inherited topography of the depositional surface (e.g., crevice and burrow fills); 2) the mode of life of the hardpart producer (e.g., epibenthic clumps of gregarious taxa such as oysters and mussels); 3) activities of other living organisms (e.g., fecal pellets, gastric residues, shell-lined burrows, and shell lags produced through selective deposit feeding); and 4) physical processes of hardpart concentration that produce syngenetic topography (e.g., lags produced by migrating ripples, channels, and shoals).

Innumerable terms have been used to describe the geometries of fossil concentrations. Some of the most common ones are illustrated in Figure 3. Thin, virtually two-dimensional bedding-plane concentrations are referred to as *pavements* and *stringers*, depending on whether the concentration is laterally continuous or only patchily developed at the scale of a single outcrop. A stringer indicates a very localized and usually elongate concentration. Where thickness exceeds that of one shell

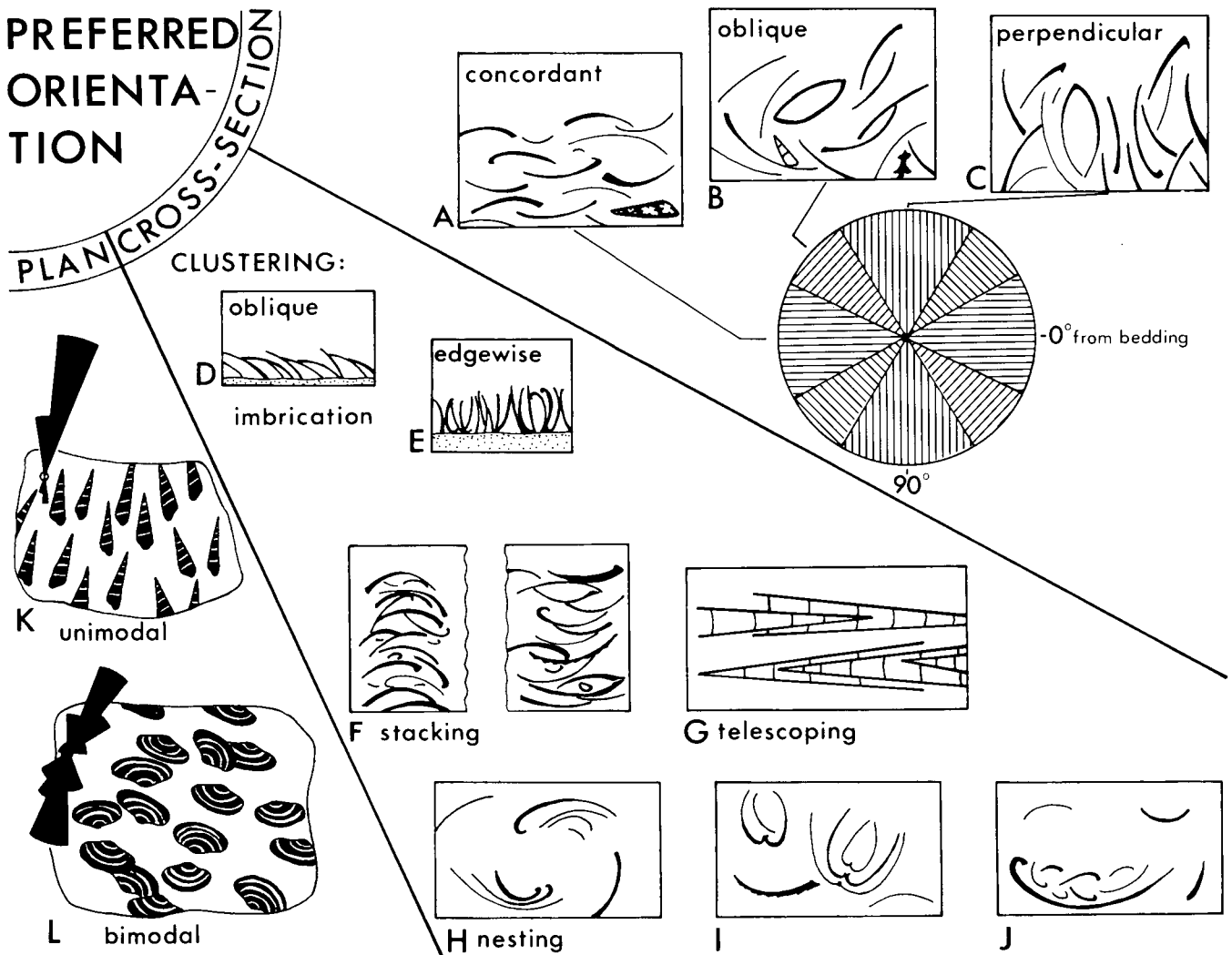


FIGURE 2—Terminology for hardpart orientation on bedding planes and in cross section of bed.

or other skeletal element, the terms *clump*, *pod*, *lens*, *wedge*, and *bed* are applied. A pod denotes a small-scale, irregular concentration with well-defined edges (e.g., isolated burrow fill, some fecal masses), and a clump denotes a concentration with poorly defined margins (e.g., clusters of shells in life position, or small concentrations that have been disturbed by sediment bioturbation). Small or large lenses have a more regular geometry with tapered lateral terminations (pinched out or erosively beveled). They include ray-pit fills, channel and scour fills, isolated shoals, and biohermal structures. Wedges taper laterally in a more complex manner, in only one direction, whereas beds are continuous tabular or sheet-like accumulations. Beds can exhibit considerable variation in thickness depending on the topography of their upper and lower boundaries, and are distinguished from horizons of physically discrete lenses or pods.

Internal Structure

Lateral and vertical variation in the taxonomic composition,

biofabric, and matrix of fossil deposits provides important evidence of complex histories of hardpart accumulation.

Simple skeletal concentrations are internally homogeneous (invariable) or exhibit at most some monotonic trend in features, such as lateral or upward fining in the grain size of matrix or bioclasts. Shelly turbidites and offshore tempestites (Aigner, 1982) are examples of skeletal concentrations showing simple internal variation.

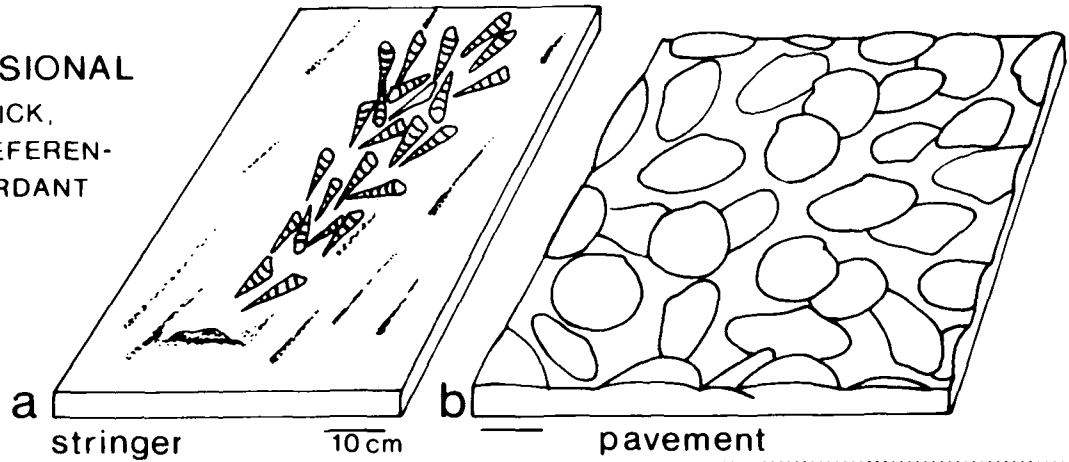
Complex concentrations exhibit more complicated patterns of variation in one or more features, such as alternating horizons of articulated and disarticulated, reoriented hardparts. Concentrations produced through lateral or vertical amalgamation of smaller-scale concentrations (Aigner, 1982; Fürsich and Oschmann, in press; Kidwell and Aigner, 1985) are examples of complex internal structures.

Simple and complex are used here in a strictly descriptive sense: they do not necessarily indicate simple or complex origins for the concentration, nor do they translate directly into the single- and multiple-event genetic categories of Aigner et

GEOMETRY OF SKELETAL ACCUMULATIONS

TWO-DIMENSIONAL

1-2 VALVES THICK,
LONG AXIS PREFEREN-
TIALY CONCORDANT
WITH BEDDING



THREE-DIMENSIONAL

≥ 2 VALVES THICK,
ANY ORIENTATION

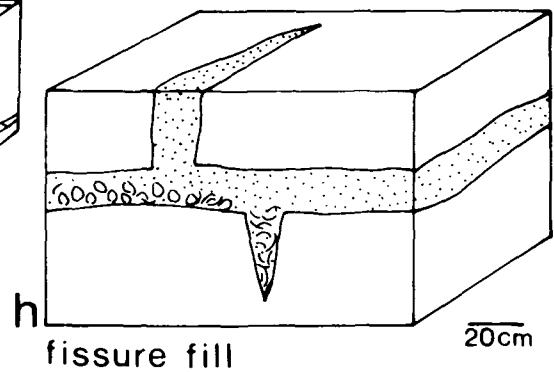
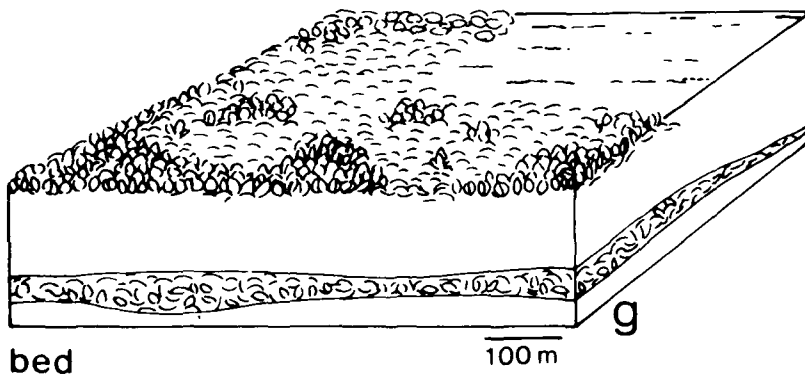
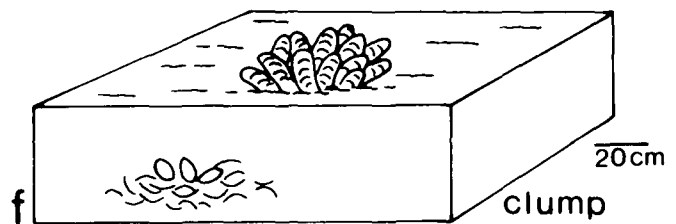
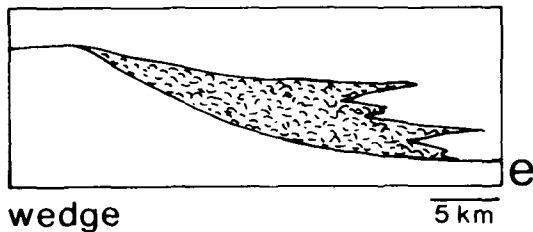
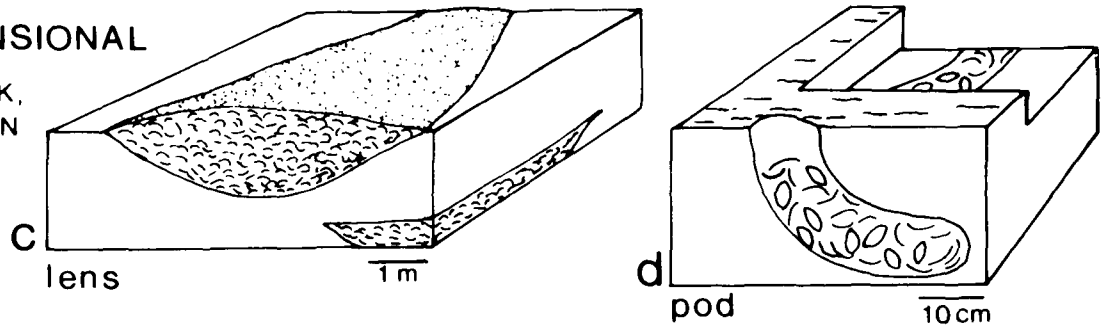


FIGURE 3—Terminology for the geometry of skeletal concentrations.

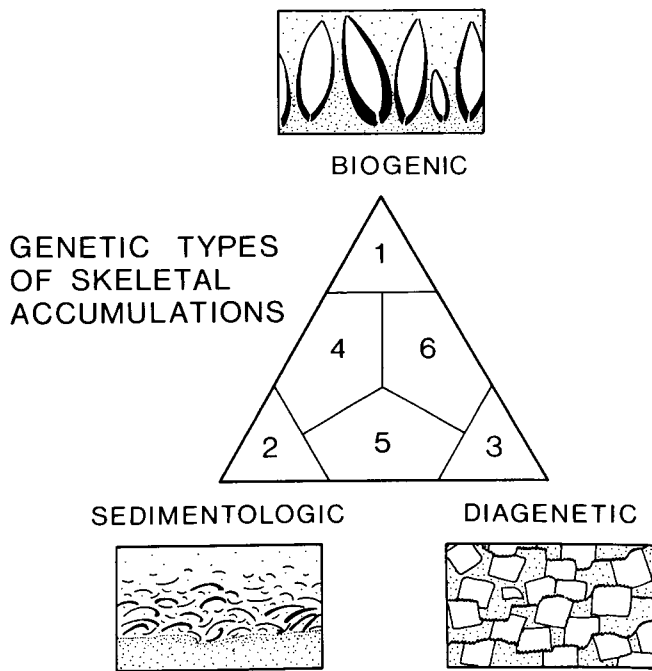


FIGURE 4—Conceptual framework for genesis of skeletal concentrations based on three end-member sets of concentrating processes. Biogenic concentrations (area 1) are produced by the gregarious behavior of skeletonized organisms (*intrinsic* biogenic) or by the actions of other organisms (*extrinsic* biogenic). Sedimentologic concentrations (area 2) form through hydraulic reworking of hardparts as particles and/or through nondeposition or selective removal of sedimentary matrix. Diagenetic concentrations (area 3) include residues of concentrated skeletal material along pressure solution seams and compaction-enhanced fossil horizons. Mixed origin concentrations (areas 4–6) reflect the strong influence of two or more different kinds of processes, for example, hydraulic overprinting of a biogenic precursor concentration. End-member concentrations (areas 1–3) can record single or multiple events of skeletal concentration; beds of mixed origin will most commonly reflect more than one episode of skeletal concentration. Concentrations of any of the six types can form rapidly (a few hours) or very slowly (hundreds to thousands of years); long-term concentrations will typically be mixed in origin.

al. (1978). Many internally simple concentrations probably originate in single events that bring hardparts together, but concentrations with complicated, multiple-event histories may be simple in structure because of thorough admixing of earlier and later skeletal concentrations. Moreover, a laterally complex concentration can be produced by a single event if it affects a geomorphically or bathymetrically variable area.

BIOSTRATINOMIC CLASSIFICATION OF SKELETAL CONCENTRATIONS

In our genetic classification, skeletal concentrations are grouped according to the inferred relative importance of biologic, physical sedimentologic, and diagenetic processes (or agents) of concentration (Figure 4). Fossil assemblages of the three end-member and three mixed concentration types recognized here can be autochthonous, parautochthonous, or allochthonous in origin.

Biogenic Concentrations

Although individual hardparts are produced by biologic processes, not every fossil concentration owes its high density to biologic processes alone. Those that do are categorized here as biogenic, including the ecologic shell beds of Aigner et al. (1978) and the biologic concentrations of Kidwell (1982a).

Biogenic concentrations can be divided into two subtypes. *Intrinsic biogenic* concentrations are created by the organisms that produce the hardparts: concentration results from intrinsic gregarious behavior—in life or death—of the skeletonized organisms themselves. The component fossil assemblages are typically autochthonous or parautochthonous. Intrinsic biogenic concentrations can record 1) preferential colonization by larvae of sites with abundant adults, as seen among vermetid gastropods, oysters, and some scallops; 2) single colonization events of opportunistic species characterized by large population sizes (Levinton, 1970); and 3) dense ephemeral aggregations of skeletonized organisms associated with feeding, spawning, or moulting (Waage, 1964; Speyer and Brett, 1985).

Extrinsic biogenic concentrations are produced by other organisms that interact with skeletonized organisms or their discarded hardparts. Component fossil assemblages are typically parautochthonous or allochthonous. Examples include hardpart-rich fecal masses (Mellett, 1974; Korth, 1979; Freeman, 1979), subsurface lags produced by “conveyor belt” deposit feeders (Rhoads and Stanley, 1965; van Straaten, 1952; Cadée, 1976; Trewin and Welsh, 1976), shell-filled pits produced by bottom-feeding predators and scavengers (Gregory et al., 1979), accumulations produced by shell-transporting birds (Teichert and Serventy, 1947; Lindberg and Kellogg, 1982), and burrows that have been selectively lined or back-filled with shells (e.g., *Diopatra*; Schäfer, 1972; Kern, 1978).

Sedimentologic Concentrations

Sedimentologic concentrations result from physical, usually hydraulic, processes of concentration, in which hardparts behave as sedimentary particles and nonbioclastic matrix is either reworked or fails to accumulate. Common histories of sedimentologic concentration include the following: 1) Concentration of initially dispersed, locally produced hardparts either by hydraulic sorting of the hardparts and enclosing sediment, or by preferential removal of fine sediment, leaving a lag of immobile hardparts; such a fossil assemblage is parautochthonous, a Model II assemblage of Johnson (1960). 2) Gradual accumulation of locally produced hardparts during a period of low net sedimentation; this yields a concentration of autochthonous-parautochthonous hardparts, also a Model II assemblage. 3) Hydraulic transport and selective redeposition of allochthonous elements, which can be mixed with autochthonous-parautochthonous elements at the accumulation site, yielding an assemblage comparable to Johnson’s (1960) Model III.

Examples of sedimentologic concentrations include shelly storm lags (Kreisa, 1981; Aigner, 1982), aeolian beach pavements (Carter, 1976), channel lags in fluvial, intertidal, and subtidal environments (van Straaten, 1952; Schäfer, 1972), and shell-paved turbidites (Tucker, 1969).

Diagenetic Concentrations

These are skeletal concentrations created or significantly enhanced by physical and chemical processes acting after burial. Most fossil assemblages are altered in some way by diagenesis, but only where fossil density is significantly *increased* are these classified as diagenetic concentrations. The most important diagenetic processes of hardpart concentration are probably 1) compaction, which can increase the close-packing of shells, particularly in a fine-grained matrix (Fürsich and Kauffman, 1984), and 2) selective pressure solution of matrix in bioclastic limestones, which leaves enriched fossil horizons along stylolitic seams (Wanless, 1979; Eller, 1981). Relative concentrations of hardparts can also result from the diagenetic destruction of hardparts in adjacent beds (Fürsich, 1982; Haszeldine, 1984).

Concentrations of Mixed Origin

Concentrations inferred to have formed by the interplay of two or more kinds of processes, or by the strong overprinting of a precursor concentration of one type by later processes of a different kind, are mixed in origin and plot in one of the intermediate fields of our ternary diagram (areas 4–6, Fig. 4). Biostromes built up by alternating gregarious settlement and hydraulic reworking are common examples of deposits of mixed origin, formed by multiple events of hardpart concentration.

The mixed biogenic-sedimentologic category of Figure 4 (area 4) includes skeletal accumulations with two common types of history. One is the enrichment of an initial biogenic concentration through a later episode or episodes of physical reworking, which yields a largely parautochthonous fossil assemblage. Examples from the Maryland Miocene include localized pavements of flat-lying, articulated *Pinna* which have been eroded out of their upright, semi-infaunal life positions; beds of disarticulated, convex-up valves of the gregarious infaunal bivalve *Glossus*; and pavements of wave-oriented shells of the gregarious infaunal gastropod *Turritella* (Kidwell, 1982a). Because hydraulic reworking can obscure or even erase evidence of the original biogenic nature of a concentration, many concentrations classified as purely sedimentologic in origin may in fact be strongly overprinted biogenic deposits. Such overprinting can usually be inferred for small-scale pavements and lenses of hydraulically-oriented specimens whose taxonomic composition is similar to that of biogenic concentrations in the same or adjacent facies. An interpretation of mixed origin is strengthened by other evidence for gregarious behavior, as where closely related or homomorphic living taxa create intrinsically biogenic concentrations. If reworked skeletal elements are judged to be allochthonous, the concentration is classed as sedimentologic rather than overprinted biogenic.

Sedimentologic concentrations that have been recolonized by bottom-dwelling organisms represent a second major mode of formation of mixed biogenic-sedimentologic concentrations. Because the sedimentologic concentration of hardparts provides a hard or coarse-textured substratum in a setting that was previously characterized by soft, fine-grained sediments, the new colonists, and hence their skeletal remains, can be quite

different from those of the initial concentration. The resulting fossil assemblage is either parautochthonous (but ecologically mixed) or mixed parautochthonous-allochthonous, depending on the source of hardparts in the sedimentologic phase of hardpart concentration (Kidwell and Jablonski, 1983; Kidwell and Aigner, 1985).

Early cementation of current- and wave-generated shell pavements (Sepkoski, 1978; McCarthy, 1977) results in the preferential preservation of hardparts and illustrates diagenetic enhancement of sedimentologic concentrations (area 5 of ternary diagram in Figure 4). Early concretionary cementation of the products of mass mortality enhances biogenic concentrations in a similar way. In both cases, initial concentrations are enriched relative to the failure of dispersed hardparts outside the concentration to survive early diagenesis. Diagenesis can also secondarily enhance biogenic concentrations through compaction of their muddy matrix (Fürsich and Kauffman, 1984).

PALEOECOLOGICAL AND SEDIMENTOLOGICAL APPLICATIONS

This classification is more of a conceptual framework than a precise model for biostratigraphic analysis. The ternary diagram (Fig. 4) is not a graph in the strict, quantitative sense: the axes are unscaled and the boundaries of the fields representing six broad genetic categories are arbitrary. This schematic diagram draws attention to possible interactions among three distinctive sets of processes or agents that are involved in the formation of skeletal concentrations. As in the case of the Konstruktions-Morphologie scheme of Seilacher (1970), the relative roles of end-member agents or processes are difficult to quantify. They refer to variables that are incommensurate, and so the scheme cannot be based on any single data set.

Like all classification systems, our ternary scheme groups phenomena at the expense of loss of detail. For example, hydraulically reworked biogenic concentrations are lumped together with recolonized sedimentologic concentrations in the mixed biogenic-sedimentologic category. The processes involved in the formation of these concentrations act in opposite sequence: the first starts in area 1 and moves down into area 4 of the diagram (Fig. 4), the other begins in area 2 and moves up into area 4. The cost of losing such detailed historical information is outweighed, we feel, by the scheme's ability to accommodate concentrations whose origins are more complex and less clear-cut, such as concentrations formed by repeated cycles of both hydraulic overprinting and recolonization. Because the scheme can include such a variety of concentrations in its six categories, it should facilitate the identification of broad patterns in the fossil record.

Environmental Gradients

Comparative analysis using the ternary scheme is especially worthwhile along environmental gradients. Figure 5 depicts relative abundances of hardpart concentrations expected across an onshore-offshore transect in a terrigenous, nondeltaic depositional setting. This represents our present best estimate of an actualistic biostratigraphic facies model, and is derived from qualitative patterns reported in the published literature and personal observations of modern environments.

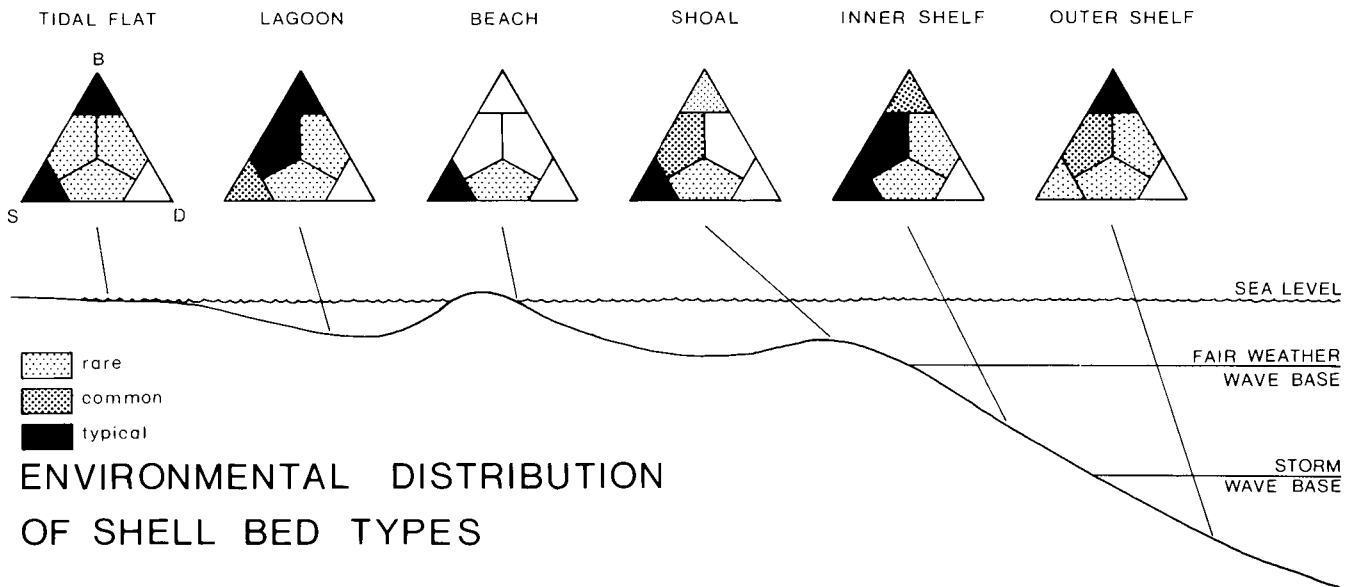


FIGURE 5—Expected relative abundances of skeletal concentrations along an onshore-offshore transect in a marine setting dominated by terrigenous sedimentation. Rates of sediment accumulation are assumed to be constant across the transect. In this preliminary actualistic model, sedimentologic concentrations decrease in abundance from beach to outer shelf because of diminishing water energy at the sea floor, and biogenic concentrations increase in relative abundance.

We suggest a diverse assortment of both biogenic and sedimentologic concentrations in intertidal and backbarrier environments, and an offshore trend of increasing biogenic and decreasing sedimentologic concentrations seaward from the coast. This reflects diminishing energy of physical reworking in deeper, more offshore waters and assumes equivalent rates of sediment accumulation in onshore and offshore settings.

Intertidal and Supratidal Flats

Biogenic concentrations include channel-margin oyster bars, mussel clumps, beds of deep-burrowing bivalves in life position, winnowed lags of shallow-burrowing opportunists, *Arenicola*-graded shell beds, ray pits, and bird nests. Sedimentologic concentrations include those produced by the lateral migration of channels and a variety of shell pavements and spits produced by storm surges.

Lagoons and Bays

Biogenic concentrations include those produced by cohorts of opportunistic species; mass mortalities related to fluctuations in salinity, temperature, or oxygen, as well as to stranding; and colonization of exposed shell by encrusters and other sessile epifauna. Sedimentologic concentrations here are typified by storm lags, flood deposits (plants, freshwater macro-invertebrates), and distal washover deposits associated with barrier beaches.

Beaches

Few species colonize sandy beaches owing to their instability, so biogenic concentrations and hydraulically overprinted biogenic concentrations are usually absent. Bedding plane lags of allochthonous and parautochthonous shells, shell lags in scour structures, aeolian shell pavements, and shell beds

formed through lateral migration of tidal inlets and storm-surge channels are most typical.

Subtidal Shoals

Owing to the relatively high energy of the environment, virtually all biogenic concentrations are reworked to some degree. In addition, many sedimentologic concentrations produced through storm reworking and fair-weather winnowing provide substrata for colonization by benthos, which increases the relative frequency of mixed biogenic-sedimentologic shell beds in this facies.

Open Shelves

Above storm-wave base, sedimentologic concentrations dominate. These are typified by individual and amalgamated shelly storm lags, but also include reworked biogenic concentrations and recolonized sedimentologic concentrations. Further offshore, biologic processes are responsible for the formation of most concentrations (e.g., biostromes, bioherms, clumps, fecal concentrations). Episodes of sea-floor reworking or winnowing are too infrequent in these settings or too low in energy to generate significant numbers of sedimentologic and overprinted-biogenic shell beds. Moreover, bioturbation is likely to remove evidence of physical reworking. Sedimentologic concentrations in this deepest and most distal part of the shelf are largely limited to those formed during very rare storm events and under regimes of reduced net sedimentation. The latter provide excellent opportunities for colonization by shell gravel taxa, as seen in the colonization of relict shell gravels on modern continental shelves. In tide-dominated systems, sedimentologic concentrations will be more common on the outer shelf.

Preliminary Results and Discussion

Our generalizations and expected trends are largely corroborated by the fossil record, where we have independent sedimentologic and paleoecologic evidence for paleobathymetric interpretations. For example, within regressive sequences of the Maryland Miocene (Kidwell, 1984), nearshore shallow-water facies are consistently dominated by a variety of sedimentologic and mixed sedimentologic-biogenic concentrations, whereas offshore facies are characterized by biogenic and mixed sedimentologic-biogenic deposits (Table 1). Each of the four regressive sequences includes benthic assemblages dominated by different infaunal genera, so the observed biostratigraphic trends are not linked to specific organisms or life habits.

A similar, very strong paleobathymetric trend in skeletal concentrations has been recognized in the Pliocene Purisima Formation of central California by Norris (1986). His quantitative assessment indicates that skeletal concentrations from nearshore facies in this high energy setting are primarily sedimentologic in origin, whereas biogenic and mixed biogenic-sedimentologic concentrations predominate in middle shelf facies. The outer shelf is marked by bone beds formed under conditions of sediment starvation. As in the Purisima, the deepest water facies of the Maryland Miocene also contains a starved, condensed bone accumulation (Myrick, 1979; Kidwell, 1984).

The stratigraphic frequency of skeletal concentrations of a single type can also be used as a paleobathymetric criterion within basins. Aigner (1982, 1985) has demonstrated this by contouring the frequency of storm-generated shell beds in the Triassic Muschelkalk of southern Germany. Tempestite frequency decreases offshore owing to the increasing rarity of storm currents with sufficient energy to rework deeper water sediments. The degree of amalgamation of individual concentrations also decreases offshore in this basin. Similarly, Norris (1986) has documented an offshore decrease in the frequency and extent of amalgamation of biogenic as well as sedimentologic shell beds in the Purisima Formation, a pattern that is also apparent, but less clearly developed, in the lower energy, shallow-marine record of the Maryland Miocene (Table 1).

These trends in the relative abundance of types of concentration should be reasonably consistent along paleobathymetric transects, although factors such as coastal energy and seafloor slope will shift the absolute depths and relative widths of the biostratigraphic facies belts. The thickness of individual fossil concentrations and their stratigraphic spacing within facies must also vary significantly with background rates of sedimentation and hardpart supply, both as a function of basin history (e.g., Kidwell and Jablonski, 1983) and climatic regime. Onshore-offshore biostratigraphic trends are expected to depart from the actualistic model further back in the Phanerozoic. The environmental expansion, diversification, and intensification of bioturbation over time (Thayer, 1983) have surely altered the balance of factors involved in skeletal concentration, because bioturbation disperses sedimentologic concentrations and accelerates dissolution of calcareous hardparts (Aller, 1982). The decrease in frequency of flat-pebble conglomerates and other storm lags in shallow subtidal sediments after the early Paleozoic (Sepkoski, 1982) is probably one expression of long-

TABLE 1—Biostratigraphic trends along onshore-offshore gradients in regressive facies tracts of the Maryland Miocene (Calvert and Choptank Formations), showing decreased relative abundance of sedimentologic concentrations in offshore facies. Onshore sand facies indicate intertidal to very shallow subtidal conditions based on sedimentary structures and paleoecology; offshore silty sand facies record subtidal environments below fairweather wave base. PP = Plum Point Member, Calvert Formation. CT = Choptank Formation. Further documentation of these data is in preparation (S.M. Kidwell).

Stratigraphic Interval	Onshore	Offshore	Relative Abundance of Genetic Types		
	Sand Facies	Silty Sand Facies	Sedimentologic	Mixed Origin	Biogenic
CT-0	<i>Mytilus</i>	<i>Turritella-Glossus Tellina</i>	++	+/-	++
			-	++	+
			-	-	+
PP-3	<i>Pandora</i>	<i>Isognomon Turritella Glossus</i>	+	++	-
			-	++	+
			-	++	+/-
PP-2	<i>Chione</i>	<i>Glossus</i>	+	+	+
			-	++	+/-
PP-0	<i>Corbula</i>	<i>Glossus-Tellina</i>	++	+	+
			+/-	++	+

++ = frequent + = occasional +/- = rare - = absent

term change in biostratigraphic patterns that has resulted from biologic evolution.

CONCLUSIONS

1. The straightforward descriptive procedure developed here should be applicable in the field by geologists as well as paleontologists. We have attempted to standardize existing nomenclature for four major features of hardpart concentrations—taxonomic composition, biofabric, geometry, and internal structure—which have genetic significance but are themselves noninferential. This procedure should facilitate systematic characterization of local sections in terms of their skeletal concentrations, which are at present underexploited in the differentiation and mapping of sedimentary facies.
2. We have identified a minimum number of genetic types of skeletal concentration based on three end-member sets of processes and their interactions. This scheme is intended to provide a conceptual framework for biostratigraphic analysis. Genetic classification can be made more precise by the addition of modifiers (for example, single- versus multiple-event biogenic concentrations) and by subdivision (for example, reworked biogenic versus recolonized sedimentologic concentrations within the mixed biogenic-sedimentologic category).

3. The genetic scheme does not specify taxonomic composition, physical scale, or the time scale of formation of skeletal concentrations. It should thus facilitate the recognition of broad biostratinomic trends in the stratigraphic record. Stratigraphic data as well as observations of modern processes indicate that skeletal concentrations are not distributed randomly along environmental gradients. They reflect differences in hydraulic energy, the ecology of skeletonized organisms, rates and styles of bioturbation, rates of sediment accumulation, and diagenetic regimes, among other variables.
4. Expected onshore-offshore trends exhibited by marine skeletal concentrations imply different kinds of post-mortem preservational bias among sedimentary facies and different opportunities for biotic recolonization of skeletal material. These factors further alter the composition of prolific fossil assemblages. Onshore-offshore biostratinomic trends also provide a potentially useful criterion for paleobathymetric interpretation.

ACKNOWLEDGMENTS

This collaboration was made possible by a Heisenberg Fellowship (FTF) and by grants from the Petroleum Research Fund of the American Chemical Society (SMK) and the West German Sondersforschungsbereich Project 53 (TA and SMK), for which we are grateful. We thank D. Jablonski, A. Seilacher, D.J. Bottjer, R.D. Norris, C.E. Brett, and anonymous reviewers for helpful comments and criticism. R.D.K. Thomas provided excellent criticisms and editorial suggestions.

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