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A model for death assemblage formation: Can sediment shelliness be explained?

by Eric N. Powell¹

ABSTRACT

A numerical model for carbonate (shell) accumulation in marine sediments is proposed. Sediment shelliness is controlled by carbonate addition, taphonomic loss, carbonate reorganizing processes, and sedimentation rate. Using representative rates of carbonate production, taphonomic loss, and sedimentary carbonate content, the model shows that insufficient carbonate is produced today in many environments to explain sedimentary carbonate content and that most produced carbonate must be preserved despite a generally high capacity for taphonomic loss. An anthropogenically-produced decrease in carbonate production over the last ~100 yr may explain the former. Representative rates of burial and sedimentation, and a temporal and spatial offset between carbonate production and organic matter decomposition can permit most produced carbonate to be preserved in sediments where taphonomic capacity greatly exceeds the carbonate production rate. The requirement that most carbonate be preserved, despite the observation that most individuals are not, indicates that most adults are preserved and reinforces the finding that biomass is a valuable community attribute for paleoecologic analysis. The requirement that most carbonate be preserved indicates that taphonomic loss must be restricted to the nearsurface in most habitats rather than being distributed throughout the bioturbated zone. The distribution and concentration of carbonate in sediments are partially decoupled from preservational processes because many processes affecting carbonate distribution have little effect on preservation. The time scales of the two differ. Preservational processes usually occur on time scales too short to be recorded as variations in carbonate content with depth. Evidence of preservational processes probably resides solely in the taphonomic signature of shells, hence emphasizing the importance of taphofacies analysis.

1. Introduction

How fossil assemblages form has been a primary question in paleontology. In recent years, fossil assemblages have been described from a variety of points of view including their taphonomic attributes, e.g. taphofacies (Speyer and Brett, 1986; Davies *et al.*, 1990; Staff and Powell, 1990), their modes of origin, e.g. autochthonous vs. parautochthonous (Kidwell *et al.*, 1986; Powell *et al.*, 1989), and their morphology and shell content, e.g. types of shell beds (Kidwell, 1986a; Kidwell *et al.*, 1986; Kidwell and Aigner, 1985). Even in low energy environments such as central bays or

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the continental shelf, substantial variation exists in shell content laterally and downcore. Variation occurs on all scales, regional (100s of km), local and micro (meters or less) (e.g. Staff and Powell, 1990; Bosence, 1989; Cummins *et al.*, 1986a). Variation on each of these scales is also apparent in the fossil record and very likely is important in paleoecologic reconstruction and taphofacies analysis (e.g. Miller, 1988; Miller and DuBar, 1988; Westrop, 1986). How is this variation produced?

Descriptive models of several types have been applied to the interpretation of variation in assemblage composition (e.g. Wilson, 1988; Kidwell, 1986a; Speyer and Brett, 1986), each based on a suite of coincident or sequential community, edaphic, chemical and physical processes explaining various aspects of a fossil assemblage's characteristics. Very few numerical models have been used (e.g. Strauss and Sadler, 1989; Barron, 1989; Bosence and Waltham, 1990). In this paper, I will develop a numerical model and try to use data available on modern communities, sediments, and death assemblages to answer a basic question: what controls sediment shelliness? The model will be a simple one because, even in the modern, many important data are lacking, but I hope to provide a basis for the quantitative consideration of how fossil assemblages form.

2. The model

a. Basic approach. I will first describe the model, then present results of model simulations addressing basic problems of shell preservation. Readers not mathematically inclined may wish to only glance over the section describing the model itself; most of the results and discussion do not require an in-depth understanding of the equations used. Those so inclined, however, will find it useful to pay particular attention to the coordinate system employed (Fig. 1), the concept of t_{∞} , and the assumptions underlying the model as described in this section. In describing the model, I will first discuss the coordinate system used, then present the primary equation upon which the model is based, and finally consider each of the components of the primary equation in detail.

To a large extent this model was foreshadowed by the conceptual models of Kidwell (1986a) and Powell *et al.* (1989). For convenience, the definitions of the symbols used and their units are listed in Table 1. To simplify the mathematics, I will follow specific stratigraphic horizons (z_i) over time within the coordinate system of Figure 1. Time (t) is the x -axis in the coordinate system (Fig. 1). The y -axis of the coordinate system, z , is an invariant position in the core equivalent to a stratigraphic horizon. These horizons are specific locations within the sedimentary column-like positions of layers in a laminated core (not the laminae themselves, just their position). As sediment accumulates at the surface, the sedimentary surface moves farther away from any z horizon just as sediment accumulation in a bay gradually makes the bay shallower but does not change the real position of any sedimentary layer within the stratigraphic column. Of course, to an outside observer, the layer

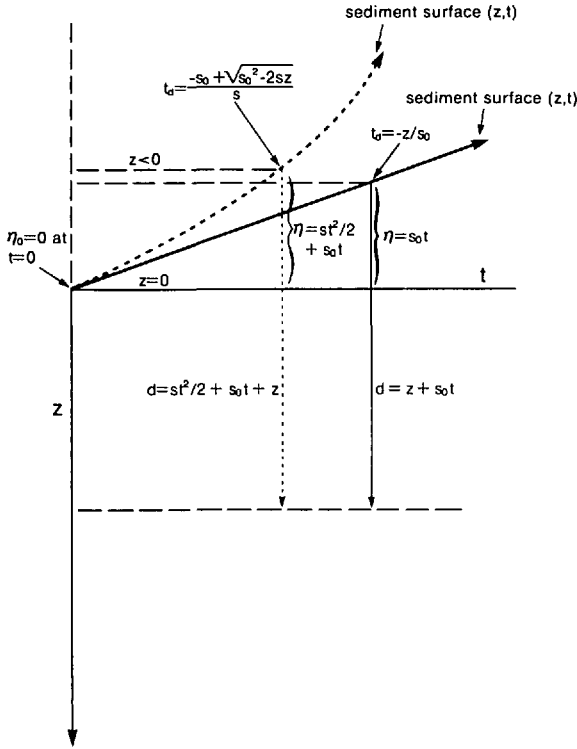


Figure 1. The coordinate system for the model. Symbols are defined in Table 1.

would be found deeper in the sedimentary column as time passed just as it appears to be in the model.

The specific position of any sedimentary parcel (or lamina in an unmixed core), i , at any time can be described in terms of its position in the sedimentary column, z , and two other attributes, d , and η . The second element, d , is the actual distance of the parcel below the sediment surface at any time, t . Note that d varies with time (t) and position (z), as sediment is deposited or eroded with time. Because the model must begin somewhere, stratigraphic horizons, z , will be positive or negative depending upon their relationship to the original sediment surface which is always $z = 0$, but d is always positive downward. The final variable describing the position of a sedimentary parcel is η . The true depth of the sedimentary parcel, d_i , differs from its fixed position in the coordinate system, z_i , by η , a measure of the amount of sediment added during a given period of time. Note that η varies only with time and represents the net effect of sedimentation and erosion on the sedimentary column. For example, if a sedimentary parcel was 1 cm below the surface at the beginning of the simulation ($z = 1$), its initial depth would be $d = 1$ and $\eta = 0$. After a few years, 5 cm of sediment may have been deposited. The parcel would still be at $z = 1$, but its depth would be $d = 6$ cm and $\eta = 5$ cm.

Table 1.

General designations

- i A sediment parcel.
- j A species or group of similar species.
- ξ The fraction of an assemblage devoted to any species j , dimensionless.

Coordinate system

- z The y -axis of the coordinate system of the model equivalent to a stratigraphic horizon, in cm. At $t = 0$, the sediment surface is $z = 0$.
- $\Delta z(t), z_0$ $\Delta z(t)$, a distance traveled by a shell through the z coordinate system by means of burial, in cm; z_0 represents the starting point for the shell, usually the location of death.
- t Time, the x -axis of the coordinate system of the model, in yr.
- d The depth any sedimentary parcel lies below the sediment surface, in cm.
- η The amount of sediment accumulated after a given time, the net of sediment depositional and erosional processes, in cm.
- η_0 An amount of sediment accumulated or lost prior to a change in the function governing sedimentation rate in the model.

Definitions of stratigraphic locations

- t_d The birthday of a sedimentary horizon, z_i , in yr.
- t_∞ Literally the final value reached in integrating all processes over an infinite time; as used here, the time required for most ($\sim 98\%$) of the processes of carbonate addition, taphonomy and burial to be completed. t_∞ is associated with a depth, d_∞ , termed the depth of final burial.
- d_∞ The depth of final burial; the depth in the core corresponding in age to t_∞ , in cm.
- β_{\min} The β value used to calculate t_∞ .
- d_τ The depth of the bottom of the taphonomically-active zone (TAZ), in cm.
- t_s The time period corresponding to the depth where the rate of taphonomic loss balances the rate of carbonate addition, in cases where the rate of taphonomic loss at the surface is higher than the rate of carbonate addition, but declines more rapidly with depth than the rate of carbonate addition.

Sedimentation rate and burial

- S_o, s Descriptors of the sedimentation rate, S_o in cm yr^{-1} , s in cm yr^{-2} .
- E Descriptor of the erosional rate, in cm yr^{-1} .
- W Sinking or burial rate, in cm yr^{-1} . W is the rate at which carbonate moves downward with respect to the z coordinate and should be distinguished from S_o which adds or subtracts sedimentary horizons (z_i) at the surface.
- $\alpha_w, \beta_w, \gamma_w$ Descriptors of the burial rate, α_w in cm yr^{-1} , β_w in cm^{-1} , γ_w dimensionless.

b. Sedimentation rate. The importance of time-dependent variation in sediment accumulation (Kidwell, 1986a; 1988) demands that sedimentation rate be permitted to vary over time. The amount of sediment accumulated, η , gets larger or smaller over time depending on the rates of sedimentation and erosion. Hence,

$$\frac{d\eta}{dt} = S_o + st \quad (1)$$

Table 1 (Continued)

Carbonate production and taphonomic loss

C_j	The carbonate content at any $[z, t]$ for any species or suite of similar species, in $\text{g CaCO}_3 \text{ cm}^{-3}$. For simplicity, C_j is generally written as C .
$C_o(z)$	The carbonate content present at the beginning of a simulation, in $\text{g CaCO}_3 \text{ cm}^{-3}$.
$C_s(-z/S_o)$	The carbonate added to the sediment surface by processes other than in situ biological production, generally taken as 0, in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$
A_j	The rate of carbonate addition for any species or suite of similar species, in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$. For simplicity, A_j is generally written as A .
A_p	The rate of in situ carbonate production by living animals, in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$.
A_{pt}	The total yearly carbonate production for any species or suite of similar species, in $\text{g CaCO}_3 \text{ cm}^{-2} \text{ yr}^{-1}$.
$\alpha_a, \beta_a, h_a, \gamma_a$	Descriptors of the carbonate production rate, α_a in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$, β_a in cm^{-1} , h_a in cm , γ_a dimensionless.
T	The rate of taphonomic loss for a given sedimentary environment, in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$. T applies to the assemblage rather than being species specific.
T_T	The sediment's total capacity for taphonomic loss, in $\text{g CaCO}_3 \text{ cm}^{-2} \text{ yr}^{-1}$.
$\alpha_\tau, \beta_\tau, h_\tau, \gamma_\tau$	Descriptors of the taphonomic loss rate, α_τ in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$, β_τ in cm^{-1} , h_τ in cm , γ_τ dimensionless.
T_A	The rate of taphonomic loss due to abrasion, in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$.
T_B	The rate of taphonomic loss due to bioerosion, in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$.
T_D	The rate of taphonomic loss due to dissolution, in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$.
$\alpha_{fo}, \alpha_{f1}, \beta_f, \gamma_f$	Descriptors of taphonomic feedback, α_{fo}, α_{f1} in $\text{g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$, β_f in $\text{cm}^3 \text{ g CaCO}_3^{-1}$, γ_f dimensionless.
$\alpha_o, \alpha_1, \omega, \rho$	General symbolism used to denote parameters of a sine wave, with α_o being the long-term drift, α_1 the descriptor for the amplitude of the sine wave and ω and ρ descriptors of the sine wave's period and starting position, respectively; α_o, α_1 in units compatible with the location of their use in Eq. (7), ω in yr^{-1} , ρ dimensionless.

where S_o is the long-term average sedimentation rate, long-term being defined relative to the time scale involved (e.g. Faas and Carson, 1988; Nichols, 1989; Nittrouer *et al.*, 1985), and s denotes a time-dependent change in the long-term rate. Eq. (1) is a simple acceleration used here for simplicity. $d\eta/dt$ might take other forms in other applications. When $\eta = \eta_o$ at $t = 0$,

$$\eta = S_o t + st^2/2 + \eta_o \quad (1)$$

If sedimentation rate is consistent ($s = 0$) and $\eta_o = 0$ at $t = 0$, Eq. (2) reduces to

$$\eta = S_o t, \quad (2)$$

and the amount of sediment accumulated is a simple function of the long-term rate and the elapsed time. Note that a long-term net sedimentation rate must be included to allow accumulation of shell carbonate, if nothing else, since shell adds to sediment

volume. Shorter-term variations in surface position, produced by storm reworking and burial for instance (Nittrouer and Sternberg, 1981; Davies *et al.*, 1989a), will be dealt with elsewhere in the model. For most simulations, I will use Eq. (3) to describe sediment accumulation. In this case, the amount of sediment accumulated is simply the product of the sedimentation rate (cm yr^{-1}) and the number of years.

As sediment accumulates after $t = 0$, the initial time-step of the model, the sediment surface rises above $z = 0$, the original surface. These new stratigraphic horizons originate at $t = t_d$, the horizon's birthday (Fig. 1). The horizon's birthday occurs when

$$d = st^2/2 + S_o t + \eta_o + z = 0, \quad (3)$$

so the birthday is

$$t_d = (-S_o + \{S_o^2 - 2s(\eta_o + z)\}^{0.5})/s \quad (4)$$

which, for the conditions of Eq. (3), namely $s = 0$ and $\eta_o = 0$ at $t = 0$, reduces to

$$t_d = -z/S_o. \quad (5)$$

Eq. (6) is simply a definition of the time a sedimentary parcel is added to the sedimentary surface during a simulation.

c. The primary equation. In the coordinate system of Figure 1, the equations for most processes determining shell carbonate content at any position in the coordinate system (z_i) after any time can be written solely in terms of t . In the following, shell carbonate will be defined as the gravel-sized carbonate content of marine sediments which normally is composed predominantly, but not exclusively, of molluscan shells, and non-shell carbonate as the carbonate of less than gravel size regardless of the likelihood that its ultimate origin is from skeletal hardparts. In considering an entire assemblage, ξ_j will represent the fraction of the assemblage devoted to any species j , so that the assemblage as a whole can be reconstructed as the summation of a series of species.

I will present the primary equation [Eq. (7)] for the model first. In subsequent subsections, I will consider each element of the primary equation in turn. In doing so, I will consider sedimentation rate to be zero or positive ($d = z + S_o t$); that is, I will not consider the case of an erosional surface. Equations for the erosional case are simple modifications of the cases presented hereafter, where $d = z - E_o t$.

Sediment shelliness is controlled by four processes, (1) carbonate addition (\approx *in situ* biological production in many habitats), (2) carbonate (taphonomic) loss of which dissolution, abrasion, and bioerosion are important examples, (3) carbonate reorganizing events such as storm reworking and burial, which permit shells to rapidly bypass the taphonomically-active surface zone, and (4) sedimentation rate which controls the birthday and current depth of any sedimentary horizon. Accordingly, for any stratigraphic horizon z_i , the change in carbonate content for any species

with time is

$$\frac{\partial C_{ij}}{\partial t} = A_j(t) - \xi_j(t)T(t) + \frac{\partial(WC_{ij})(t)}{\partial z} \quad (7)$$

where C_{ij} is the amount of carbonate present at any time in any stratigraphic horizon z for any species in g cm^{-3} ; A_j is the rate of carbonate addition (item 1) in $\text{g cm}^{-3} \text{ yr}^{-1}$ for any species; T is the rate of carbonate loss (item 2) in $\text{g cm}^{-3} \text{ yr}^{-1}$; ξ is the fraction of carbonate represented by species j

$$\xi = C_j(z, t) / \sum_{j=1}^n C_{ij}(z, t); \quad (8)$$

and W is the sinking or burial rate (item 3) in cm yr^{-1} . Eq. (7), then, is a mathematical expression for the first three processes identified at the beginning of this paragraph. The fourth process, sedimentation rate, will be included in the equations for A , T , and W , so that the carbonate content for any species j at any time t in any stratigraphic horizon z_i will be a function of the time-varying rates of addition (A), loss (T) and burial (W) modulated by the sedimentation rate.

Both burial rate W and taphonomic loss T in Eq. (7) are assumed to be attributes of the environment; all carbonate is treated equivalently. Consequently, no subscript j is used. In contrast, addition rate A is considered a species-specific attribute, hence the use of the subscript j . In the following subsections, I will discuss the specific attributes of A , W , and T in more detail. For convenience, I will drop the subscripts i and j from A , C and ξ henceforth; they will always be implied. In addition, I will assume that the maximal carbonate content at any depth must be $< \sim 0.8 \text{ g dry wt cm}^{-3}$ [obtained by using a density of $2.7 \text{ g CaCO}_3 \text{ cm}^{-3}$ and an estimated water content for a typical sandy sediment of 70% by volume [Webb (1969)—Hay and Southam (1977)] have a higher number for more consolidated sediments]. Sediments from Copano Bay, Texas, an area intensively studied by Staff *et al.* (1986), and which will be used as an example throughout this text, average $0.64 \text{ g dry wt cm}^{-3}$.

d. Biological production (A_p). Carbonate addition can result from a variety of processes including transportation and biological production. I will consider only quiet-water environments; hence, in Eq. (7) most carbonate addition should occur by local carbonate production: $A = A_p$. Most shell carbonate should be added at the surface, but infauna will contribute some subsurface shell carbonate. Hence

$$A_p(d) = \alpha_a e^{-\beta_a(d-h_a)^{\gamma_a}} \quad (9)$$

can describe the depth distribution of shell carbonate input for any species or suite of similar species at any time. Eq. (9) is an exponential equation that can be fit to a variety of standard expectations for carbonate addition as a function of depth-in-

core. By using Eq. (9), I assume only that the rate of carbonate addition eventually declines downcore; it may decline from the surface downward or first have a subsurface maximum. The variables α_a , β_a , h_a , and γ_a can be chosen to describe any species or group of species with similar life-styles. On a simplistic level, β and γ describe the distribution of the process (carbonate addition in this case) over the stratigraphic column, h describes the location of the maximum rate ($h = 0$ is the sedimentary surface), and α describes the magnitude of the process. For example, infauna dying at depth would have a subsurface maximum ($h_a > 0$, $\gamma_a > 1$). In communities dominated by epifaunal or semi-epifaunal animals, addition would be highest at the sediment surface ($\gamma_a = 1$, $h_a = 0$). In this case,

$$A_p(d) = \alpha_a e^{-\beta_a d}. \quad (10)$$

The primary equations for the remaining processes, taphonomic loss and burial, will make the same simple assumption; that the rates eventually decline downcore. Of course, setting values for the four variables may require additional considerations.

For ease of presentation by analytical solution, I will now consider an epifaunal species described by Eq. (10) in more detail. In our coordinate system, when sedimentation rate is temporally invariant ($d\eta/dt = S_o$), the depth of the sedimentary horizon is a function of sedimentation rate and time: $d = z + \eta = z + S_o t$. So, the carbonate content at any stratigraphic horizon z , at any time t is

$$\frac{\partial C(z)}{\partial t} = A_p(t) = \alpha_a e^{-\beta_a(z+S_o t)}. \quad (11)$$

Eq. (11) must be solved separately for $z \geq 0$ and $z < 0$ because some sedimentary horizons are present at the beginning ($z \geq 0$) and some are added during the simulation as sediment accumulates ($z < 0$). Remembering that z is positive downwards with $z = 0$ being the initial sediment surface, solving Eq. (11) for the stratigraphic horizons present initially ($z \geq 0$) yields

$$C(z, t) = C_o(z) + [(\alpha_a e^{-\beta_a z} / \beta_a S_o)(1 - e^{-\beta_a(z+S_o t)})], \quad (12)$$

where $C_o(z)$ is the amount of shell carbonate present at $t = 0$. Eq. (12) describes the total shell carbonate content for an epifaunal species at any stratigraphic horizon z ($z \geq 0$) after time t , given a steady biological input described by Eq. (10) and a steady sedimentation rate [Eq. (3)] [recall that for convenience the subscripts i and j have been deleted from all elements of Eq. (7)].

Solving Eq. (11) for stratigraphic horizons borne during the simulation ($z < 0$) yields,

$$C(z, t) = C_s(-z/S_o) + [(\alpha_a / \beta_a S_o)(1 - e^{-\beta_a(z+S_o t)})], \quad (13)$$

where C_s is the carbonate content added with the sediment, by planktonic rain or transportation for instance, but not by *in situ* biological production. I will assume transportation is inconsequential, hence $C_s = 0$, and drop C_s from further uses of Eq. (13).

After a very long time, a sedimentary horizon will lie deep within the sedimentary column. At this time, taken as $t = \infty$ (and defined more precisely in a later section), the amount of shell carbonate added to a given stratigraphic horizon can be estimated, for $z \geq 0$, as

$$C(z, t \rightarrow \infty) = C_o(z) + (\alpha_a e^{-\beta_a z} / \beta_a S_o); \quad (14)$$

and, for $z < 0$, as

$$C(z, t \rightarrow \infty) = \alpha_a / \beta_a S_o. \quad (15)$$

To estimate the amount of shell carbonate added to a sedimentary horizon, in the epifaunal case, requires an estimate of three parameters, the sedimentation rate, S_o , and the parameters describing the distribution and magnitude of biological production, α_a and β_a . These parameters describe how much carbonate should be present at any depth in the absence of taphonomic loss and any sedimentary reorganizing process such as burial which moves carbonate from one sedimentary horizon (z_i) to another.

The total amount of carbonate produced yearly, in the epifaunal case, is

$$A_{pT} = \int_{d=0}^{d=d_i} \alpha_a e^{-\beta_a d} dd = \alpha_a / \beta_a (1 - e^{-\beta_a d_i}) \approx \alpha_a / \beta_a. \quad (16)$$

Accordingly, for the epifaunal case, the value of α_a can be obtained knowing the yearly rate of carbonate production and the value of β_a , which is determined from the definition of t_∞ described in a later section. Consequently, over a sufficiently large depth, d (and for $z < 0$), Eq. (15) becomes

$$C(z, t \rightarrow \infty) = C_s(-z/S_o) + (A_{pT}/S_o). \quad (17)$$

So, in certain restricted cases, carbonate content is the ratio of the rate of carbonate addition and the sedimentation rate, and, in all cases, the maximum possible carbonate content of the sediment is given by this ratio. Although the equation cannot be solved analytically for $\gamma \neq 1$ in Eq. (9), numerical simulation shows the analogous result is true for infaunal species; carbonate content is a function of carbonate addition and the sedimentation rate.

e. Taphonomic loss (T). Barring sediment reorganizing processes, carbonate content for any species [$C(z, t)$] is simply the difference between carbonate production and

carbonate loss (T). Hence

$$\frac{\partial C(z)}{\partial t} = A_p(t) - \xi(t)T(t). \quad (18)$$

Recall that taphonomic loss is a function of the environment, hence ξ distinguishes that fraction of the environmental effect imposed on the species in question. Recall that this assumes that taphonomic loss is indiscriminate of species composition. (In calculating $C(z)$ from Eq. (18), I maintain $C(z, t) \geq 0$ over all t and compute ξ as the fraction of total carbonate represented by any given species [Eq. (5)].)

Taphonomic processes include abrasion (T_A), bioerosion (T_B) and dissolution (T_D). Each of these taphonomic processes proceeds at highest rate at or near the sediment water interface and the rate declines rapidly with depth (Powell *et al.*, 1989). Abrasion and bioerosion are nearly restricted to the sediment surface (May and Perkins, 1979), but dissolution may proceed at significant, albeit declining, rates well into the sediment column (Boudreau, 1987; Sayles and Curry, 1988; Aller, 1982; Emerson and Bender, 1981). Accordingly, following Mackin and Swider (1989) and Middelburg (1989), for dissolution

$$T(d) = \alpha_\tau e^{-\beta_\tau(d-h_\tau)^{\gamma_\tau}} \quad (19)$$

where τ represents a taphonomic parameter. Abrasion and bioerosion can be modeled by Eq. (19) as well by using a large value for β_τ . The sediment's total capacity for taphonomic loss ($\text{g CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$) (T_T) is described by an equation of the form of Eq. (16).

Solving Eq. (19) yields equations of the form of (12), (13)–(15), assuming taphonomic loss is a constant over time and that no subsurface maximum exists ($h_\tau = 0$, $\gamma_\tau = 1$). I will assume that weight is an adequate surrogate for surface area in estimating taphonomic loss (Schink and Guinasso, 1977a). The relationship of surface area to dissolution rate is complicated (Walter and Morse, 1985; Acker and Byrne, 1989) making a conversion of weight to surface area difficult. I will further assume that breakage does not destroy shell carbonate. Non-shell carbonate, if necessary, can be tracked independently as a separate "species." Finally, in considering dissolution (T_D), I will assume that sediment oxygen demand is a reasonable estimate of the environment's capacity for acid production (Powell *et al.*, 1989) and that acid formed in any horizon, z_i , goes unused if not used therein. Horizons without carbonate do not donate their acid to adjacent horizons for instance. Whether all acid produced very near the sediment surface is available to dissolve carbonate, were it present, or whether a significant portion escapes (diffuses) into the water column before reacting presents a quandary (Sayles and Curry, 1988; Takahashi and Broecker, 1977). I will assume that reaction rates considerably exceed diffusion rates.

Accordingly, as $t \rightarrow \infty$, for $z < 0$, the carbonate content of the sediment is the difference between the total carbonate added and the total lost normalized by the

sedimentation rate

$$C(z, t \rightarrow \infty) = 1/S_o(A_{pT} - T_T) \quad (20)$$

for $C(z, t) \geq 0$ over all t .

f. Burial. Burial might also preserve carbonate. I restrict the term burial to short-term reorganizing processes like storm resuspension and bioturbation that move shells downward with respect to the z coordinate system. The relative importance of bioturbation and physical resuspension remains in question (Davies *et al.*, 1989a; Powell *et al.*, 1989; Meldahl, 1987) but either one, if rapid enough, could bury carbonate below the taphonomically-active zone (TAZ), if the TAZ were sufficiently shallow. Burial processes must be distinguished from net sedimentation. In the coordinate system of Figure 1, net sedimentation results in the birth of sedimentary horizons, but carbonate remains in the horizon where it was originally added. Burial, on the other hand, transports carbonate across sedimentary horizons independent of the sedimentation rate. In the model, only burial processes can move shells from the stratigraphic horizon in which they were initially placed at death to another deeper (or shallower) horizon. Granting that an individual event of physical burial is instantaneous relative to most time scales and extends to a discrete depth, I assume that the sum of the depth distributions of all events taken over an appropriate time scale (as discussed later) approximates an exponential curve similar in gross aspect to that which might be expected from bioturbation. Short-term events such as storm reworking do vary the level of the sedimentary surface on short time scales, but I will assume that no net effect occurs. Put another way, all net effects will be defined as part of the long-term net sedimentation rate.

Large storms, with long return intervals relative to the sedimentation rate, will, of course, not be adequately described. Since most carbonate must be preserved, however, on shorter time scales (Cummins *et al.*, 1986b), such rare events can have little to do with normal preservation in most habitats (although they may greatly affect the final distribution of carbonate within the sedimentary column) and will be modeled independently of the normal burial process. I emphasize that storm events of sufficient size to produce classic storm deposits (e.g. Davies *et al.*, 1989b) occur rarely in comparison to the rate of taphonomic loss. Shells condensed into these deposits must have been "preserved" for some time prior to the storm event. The age of shells on beaches is a good example (Powell and Davies, 1990).

Consequently, including burial in Eq. (18) (after Schink and Guinasso, 1977a,b; 1978) yields Eq. (7) where burial rate (W) is

$$W(t) = \alpha_w e^{-\beta_w d^{1/w}} = \alpha_w e^{-\beta_w (z+S_o t)^{1/w}} \quad (21)$$

[In evaluating Eq. (7), to prevent instability in the model, I utilized $(A_p^{t+1,z} + A_p^{t,z})/2 + C(t, z)$ in calculating ξ and $\partial(WC)(t)/\partial z$ rather than $C(t, z)$.]

g. *Sundries*. Cycles are modeled as sine waves, following Koerschner and Read (1989). On a simplistic level, β and γ describe the distribution of a process over the stratigraphic column whereas α describes the process' magnitude. Consequently, I assume β and γ are relatively invariant properties of species, taphonomic loss and burial at any location, so that variation in α is the principal source of temporal variability. Then

$$A_p(d) \text{ or } T(d) \text{ or } W(d) = [\alpha_0 + \alpha_1 \sin(\omega t + \rho)]e^{-\beta(d-h)^\gamma} \tag{22}$$

[for computational purposes, when $\alpha_0 + \alpha_1 \sin(\omega t + \rho) < 0$, I let $\alpha_0 + \alpha_1 \sin(\omega t + \rho) = 0$].

Assuming Kidwell's (1986b) linear relationship between shell content and gravel-dwelling organisms represents the first-order portion of an exponential curve, that is assuming a maximum effect exists, taphonomic feedback can be modeled by

$$\alpha_a = \alpha_{f0} + \alpha_{f1} (1 - e^{-\beta_f[\Sigma C_j(z, t)]^\gamma}) \tag{23}$$

where α_{f1} measures the maximum added or minimum taken away from a base production rate α_{f0} depending upon carbonate content, β_f modulates the strength of this effect, and $\Sigma C_j(z, t)$ is the total carbonate present in any horizon at any particular time for all species.

h. *Definition of depth of final burial, TAZ, and t_∞* Kidwell (1986a) defined the depth of final burial as "a sufficient depth . . . for a hardpart: (1) to attain a refuge from further small-scale episodes of exhumation and exposure . . . and (2) to escape destructive early diagenetic porewater regimes." I will define that position in the sediment as the point where 98% of all carbonate addition, taphonomic loss, and sediment reorganization has occurred. Because this is approximately equivalent to integrating Eq. (7) over infinite time, I will use the terms t_∞ and d_∞ to describe this location. In mathematical terms,

$$t_\infty \approx (4/\beta_{\min})^{1/\gamma}/S_0 \tag{24}$$

(for $z = 0$) and β_{\min} is usually the lowest β value used in Eq. (7). The corresponding depth, d_∞ is

$$d_\infty \approx (4/\beta_{\min})^{1/\gamma}. \tag{25}$$

(Note that the factor 4 simply sets one of many percentile values that might be used for the completion of the process, akin to an α level in statistical usage.) Solving Eq. (25) for β provides a mechanism to estimate β for equations like (15) and (16). An epifaunal species, for instance, might die at the sediment surface. Its depth range for carbonate addition, d_∞ , might be estimated as 1 cm; accordingly $\beta_a = 4$ in this instance.

I will define the taphonomically-active zone (TAZ) as the depth zone $d = 0$ to $d = d_r$ that accounts for 98% of the sediment's taphonomic capacity (see also Powell *et al.*, 1989). The depth of the base of the TAZ can be obtained from Eq. (25) using β_r rather than β_{\min} . Note that a distinction exists between the TAZ where taphonomic loss occurs and the depth of final burial as defined by d_∞ . Shells may be added to the sedimentary column below the TAZ through biological mortality, the filling of old burrows or other burial processes. These depth horizons would continue to collect shell carbonate and thus not have reached the invariant condition defined by d_∞ yet would be below the TAZ. In some cases, such processes may affect shell position in and the carbonate content of a sedimentary horizon yet not be important in the initial preservation of the carbonate.

3. Results and discussion

a. Perspective. The fact that carbonate addition, carbonate loss and burial all are depth dependent and, hence, time dependent (since d is a function of both: e.g. $d = z + S_p t$) requires that downcore variations in carbonate content with depth-in-core occur in one of only three ways.

(1) By definition, downcore variation in carbonate content must occur whenever the ages of a series of contiguous depth horizons are much less than the depth of final burial. In these depth horizons, indicated hereafter by $d \ll d_\infty$, carbonate is still being added, lost or reorganized.

(2) At the depth of final burial (at d_∞ , as previously defined), temporally invariant conditions, described by Eq. (8) and (20) for example, will yield an invariant carbonate content. No downcore variation will exist. On the other hand, predictable temporal variations in processes such as carbonate production or loss, a long-term cycle from Eq. (22) for example, may produce predictable downcore variations in carbonate content below the depth of final burial. Although no downcore variations in carbonate content occur in the former case and predictable downcore variations occur in the latter, both are similar, in a sense, because the governing processes have not really changed (the equations used remain unaltered).

(3) Aperiodic or unpredictable variations in processes such as carbonate production or loss may produce downcore variations in carbonate content. In this case, the magnitude of some process; e.g., α_w , α_r , or α_a , changes in an unpredictable manner.

Examples of cases 1, 2 and 3 will be given in later sections. Initially, I will focus on the conditions yielding predictably variable and constant carbonate contents with depth-in-core below d_∞ and the distinction between the assemblages above and below the depth of final burial.

b. Biological production. To what extent is sediment shelliness a product of biological production? Initially, I assume an invariant sedimentation rate, that the sediment's shell carbonate content and its depth distribution is solely a product of biological

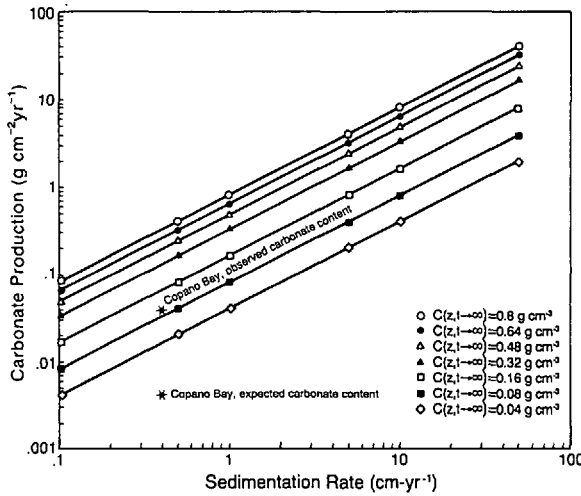


Figure 2. Expected carbonate contents $C(z, t \rightarrow \infty)$ in the absence of taphonomic loss, calculated using Eq. (17).

production (A_p) (no taphonomic loss or reorganization), that no taphonomic feedback occurs and that the function governing biological production is temporally invariant on an appropriately chosen time scale but depth-dependent. Accordingly, from Eqs. (14) and (15), the distribution of carbonate with depth-in-core, at t_∞ , is even; that is C is a constant (for $z < 0$), and the quantity of carbonate preserved per volume depends upon the sedimentation rate and the carbonate production rate. Under these conditions downcore variations in carbonate content, besides the necessary decline near the sediment surface (where $d \ll \infty$), require variations in sedimentation rate (S_o) or the rate and distribution of carbonate addition described by α_a and β_a over time or some additional terms in the model.

Powell *et al.* (1989) observed that carbonate production rates generally ranged between 50 and 1000 g CaCO₃ m⁻² yr⁻¹ in most non-reefal benthic habitats (see also Sarnthein, 1973). Using Eq. (15), and sedimentation rates of 10 to 30 cm 100 yr⁻¹ for estuaries and a factor of 10 lower for continental shelves (e.g. Nichols, 1989; Hay and Southam, 1977) permits an estimate of the amount of carbonate expected in sediments if no taphonomic loss occurs. Figure 2 shows the expected carbonate content of a sedimentary horizon at t_∞ given a known sedimentation rate and carbonate production rate. Finding lower values than expected indicates that some carbonate was not preserved. Finding higher values than expected indicates an inaccurate sedimentation rate or carbonate addition rate. Comparing Figure 2 to measured carbonate production rates shows that taphonomic loss may be required to explain sediment shelliness on clastically-dominated continental shelves, but not so for estuaries. Taking a specific case, Cummins *et al.* (1986b) measured a carbonate production rate of 44 g CaCO₃ m⁻² yr⁻¹ in Copano Bay, Texas. Sedimentation rate is

30 cm 100 yr^{-1} (Shepard and Moore, 1960). These data yield an expected sediment carbonate content of $.015 \text{ g CaCO}_3 \text{ cm}^{-3}$. Sediments in Copano Bay are generally 10 to 15% carbonate by weight, 0.08 to $0.12 \text{ g CaCO}_3 \text{ cm}^{-3}$, or nearly a factor of 10 more than can be explained if all measured carbonate production is preserved.

Copano Bay production rates are below average but not atypical enough to prevent this result from being a general trend (Powell *et al.*, 1989). In contrast, the carbonate content of the central Texas shelf ranges around 5% (Shepard and Moore, 1955). Taking a sedimentation rate of $5 \text{ cm } 100 \text{ yr}^{-1}$ (Berryhill *et al.*, 1976; not an unusual rate—Diester, 1972; Einsele *et al.*, 1977; Kershaw *et al.*, 1988) requires an annual input of just $25 \text{ g CaCO}_3 \text{ m}^{-2}$, a relatively low value for continental shelves (Powell *et al.*, 1989). Carbonate production rates on the Texas shelf, when measured, should be adequate to explain sediment shelliness. So, although production rates on some continental shelves may be adequate to account for their carbonate contents, the carbonate production rates may be barely adequate or insufficient in bays, if Copano Bay is a good example, to explain their carbonate contents, even without any taphonomic loss. The view that estuaries would be filling with shells if not for taphonomic loss (e.g. Lucke, 1935) would appear to be incorrect. Carbonate production rates barely support sediment shelliness in bays. Put another way, most carbonate must be preserved in bays and a substantial fraction on continental shelves, despite the vicissitudes of taphonomy, judging from the Copano Bay area. Obviously, data comparing carbonate production rates and carbonate contents in other areas is sorely needed.

In Copano Bay, carbonate production is insufficient to explain carbonate content even in the absence of any taphonomic loss. Postponing the conundrum posed by the failure of taphonomic processes to destroy most produced carbonate, only three explanations for the mismatch between carbonate production and carbonate content in bays are possible. (1) Estimated sedimentation rates are too high. A rate of $30 \text{ cm } 100 \text{ yr}^{-1}$ is not extraordinary however (Olsen *et al.*, 1978; Boothroyd *et al.*, 1985; Faas and Carson, 1988). (2) Some carbonate is not derived from *in situ* production. Cummins *et al.* (1986a,b) found little evidence for transportation however. (3) The estimated carbonate production rates are too low. Carbonate production rate may decline in response to man's intervention (Reise and Schubert, 1987; see also Bosence, 1989). (Natural trends in carbonate preservation, discussed by Sundquist (1985) and Wilkinson and Walker (1989) for instance, occur over time scales too long to explain the observations here.) A reduction in carbonate production rate is the only realistic solution in Copano Bay. Judging from the data reviewed by Powell *et al.* (1989), this might be a frequent phenomenon worldwide.

By the same token, the highest carbonate production rates, though exceptional, nevertheless range sufficiently high in most environments (Powell *et al.*, 1989) that shelly intervals (shell beds) could be produced solely by *in situ* biological production

at most sedimentation rates. [Of course, shell beds are not all produced directly by biological production (Kidwell, 1986a).]

c. Taphonomic loss. Generally, the environment's capacity for taphonomic loss (T_T) exceeds the carbonate production rate (A_{pT}) (Powell *et al.*, 1989) so that little carbonate should be preserved. Carbonate budgets agree (Cummins *et al.*, 1986b; Aller, 1982; Smith, 1971). In Copano Bay, for example, most individuals that died were not preserved (Cummins *et al.*, 1986b). How can the evidence of taphonomic loss be meshed with the necessities of carbonate preservation previously discussed? First the environment's capacity for carbonate loss must be circumvented. Secondly, most carbonate must be preserved while most individuals are not. It is important to realize that even if the environment's capacity for taphonomic loss is generally lower than the carbonate production rate, the necessity of preserving most carbonate will require that most of the environment's taphonomic capacity not be realized unless that capacity is extremely low.

Circumventing taphonomic loss can be accomplished in one of four ways.

(1) A depth offset may exist between the processes of carbonate production and taphonomic loss so that some carbonate is added near the bottom of the TAZ.

(2) A time offset may exist between carbonate production and loss so that carbonate production and taphonomic destruction do not occur simultaneously.

(3) Burial processes may move shells rapidly through the TAZ.

(4) Not all of the environment's capacity for taphonomic loss may be realized. Some acid may diffuse into the overlying water, for example, or shells may become more resistant to taphonomic loss over time.

The effectiveness of each of these alternatives depends upon the depth distribution of taphonomic loss (β_T) which is determined by the depth of dissolution, since abrasion and bioerosion are mostly confined to the sediment-water interface. Although a continuum certainly exists, two extreme conditions can be delineated and considered. In one case bioturbation extends the TAZ deep into the sediment. One can define "deep" in comparison to those processes moving material through the sediment column in horizons whose ages are less than t_∞ , the time of final burial. These processes include net sedimentation, storm resuspension and redeposition, bioturbational condensation and the like. In this case, the TAZ is roughly equivalent to the depth of final burial. Aller (1982), Emerson *et al.* (1984) and Sayles and Curry (1988), for instance, consider cases where dissolution may proceed at substantial rates below the sediment surface. In the alternative, the TAZ extends only a little below the sediment-water interface (β_T large) and is much shallower than the depth of final burial. In this case, the depth of final burial is determined by processes like bioturbation and infauna dying in place. Emerson (1981), Boudreau (1987) and Takahashi and Broecker (1977) offer examples. If the bottom of the TAZ is defined by the bioturbate zone (β_T small), then taphonomic loss extends into sedimentary

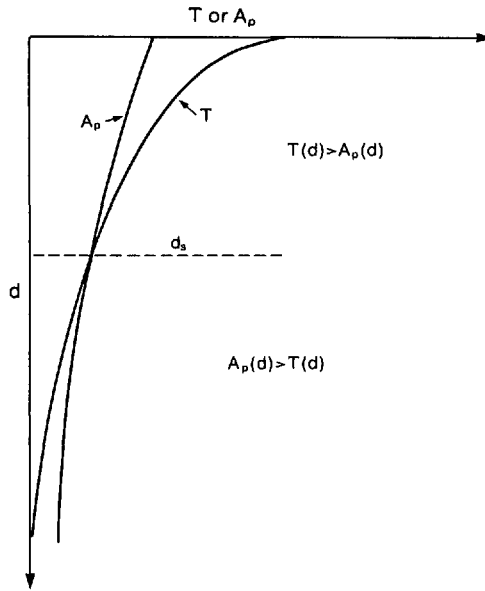


Figure 3. One idealized distribution of taphonomic processes and carbonate addition with depth yielding preservation despite a carbonate destruction rate that exceeds the carbonate production rate. The crossover point d_s occurs at $t = t_s$.

horizons of relatively great age and less carbonate will be preserved. Rates of shell movement through the TAZ are simply too slow. If the bottom of the TAZ is just below the sediment surface (the second case, with β_τ large), then many processes exist that might move carbonate below the TAZ where it can be indefinitely preserved.

Taking the four possible mechanisms for circumventing taphonomic loss in turn, consider first the case of a depth offset between production and the processes of taphonomic destruction. If the rate of taphonomic loss declines more rapidly with depth than that of carbonate production (Fig. 3) ($\alpha_\tau > \alpha_a, \beta_\tau > \beta_a$), carbonate will be preserved despite a higher capacity for taphonomic loss ($T_\tau > A_{pT}$). In Figure 4, the rate of carbonate addition is the same for 3 species, one epifaunal, one semi-epifaunal and one infaunal; only the depth distribution of addition is changed (by varying α, β, h, γ). Infauna are preferentially preserved in this case because the rate of addition exceeds taphonomic loss in deeper horizons. If both taphonomic capacity and carbonate addition obey a simple exponential equation [like Eq. (19)], ($\alpha_\tau > \alpha_a, \beta_\tau > \beta_a, \alpha_w = 0$) and dissolution obeys the assumptions previously outlined, the fraction of carbonate addition actually preserved can be calculated from Eq. (18) and the depth where both taphonomic loss and carbonate production rates are equal. In our coordinate system, this location is expressed as a time (t_s) (Fig. 3),

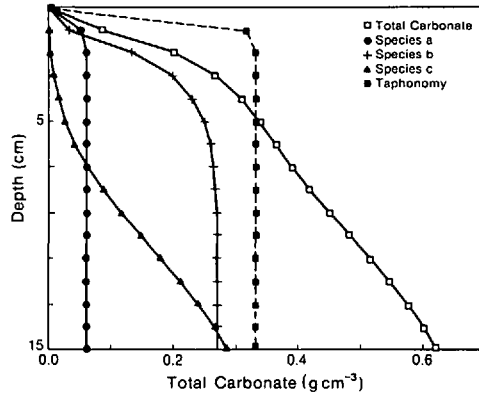


Figure 4. Comparison of carbonate preservation in epifauna (species a), semi-epifauna (species b) and infauna (species c), each calculated from Eq. (18). Rate of carbonate addition, A_{pT} , for each species = $0.1 \text{ g CaCO}_3 \text{ cm}^{-2} \text{ yr}^{-1}$. The depth distribution of carbonate addition, for epifauna, semi-infauna and infauna respectively, is described by: $\beta_a = 6, 0.6, 0.03 \text{ cm}^{-1}$, $\alpha_a = 0.6, 0.06, 0.00985 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\gamma_a = 1, 1, 2$; and $h_a = 0, 0, 10 \text{ cm}$. $\alpha_r = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$. $\beta_r = 6 \text{ cm}^{-1}$, $h_r = 0 \text{ cm}$ and $\gamma_r = 1$. ($S_o = 0.3 \text{ cm yr}^{-1}$). $C_o(z) = 0$. Total time of simulation: 50 yr. Fraction of production preserved: species a, 19%; species b, 82%; species c, 94%.

where

$$t_s = 1/S_o \frac{(\ln \alpha_a - \ln \alpha_r)}{(\beta_a - \beta_r)} - (z/S_o). \tag{25}$$

Figure 5 shows the effect of varying the depth distribution of carbonate addition vs. taphonomic loss at a given addition and loss rate. This is accomplished by varying β_a , one parameter controlling the depth distribution of addition, in this example. Two alternatives exist for the depth distribution of taphonomic loss. A broad zone of

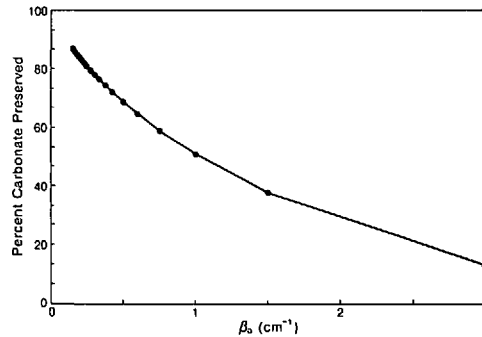


Figure 5. The fraction of added carbonate preserved under varying β_a , for $A_{pT} = \alpha_a/\beta_a = 0.1 \text{ g cm}^{-2} \text{ yr}^{-1}$, under a given taphonomic regime ($\alpha_r = 1.2 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$, $\beta_r = 6 \text{ cm}^{-1}$, $h_r = 0 \text{ cm}$ and $\gamma_r = 1$) and sedimentation rate ($S_o = 1 \text{ cm yr}^{-1}$), as described by Eqs. (18) and (25). Additional assumptions are discussed in the text.

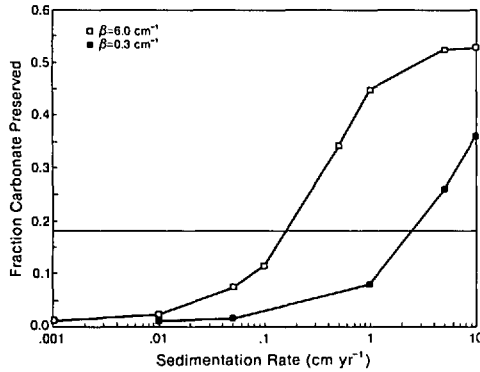


Figure 6. The fraction of carbonate produced that is preserved if both taphonomic loss and carbonate production obey a yearly cycle 6 months out of phase, using Eqs. (18) and (22). Parameters were chosen so that taphonomic loss just equaled carbonate production in the absence of a cycle or for cycles exactly in phase. Both curves: $\alpha_0 = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $h = 0 \text{ cm}$; $\gamma = 1$; $\alpha_1 = 0.5 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\omega = 2\pi \text{ yr}^{-1}$; $\rho_a = \pi$; $\rho_r = 0$. Upper curve, $\beta = 6.0 \text{ cm}^{-1}$; lower curve, $\beta = 0.3 \text{ cm}^{-1}$.

dissolution throughout the bioturbate zone for instance ($\beta_r - \beta_a$ small for $\beta_r > \beta_a$: e.g. 6 – 3 in Figure 5) results in little preservation. Restricting most dissolution to near the sedimentary surface ($\beta_r - \beta_a$ large for $\beta_r > \beta_a$: e.g. 6 – 1 in Figure 5) allows considerable preservation. In either case, the importance of epifaunal and semi-infaunal organisms in most death assemblages suggests that preservation by this process is not necessarily a dominant process, but it emphasizes the fact that a TAZ as deep as the bioturbate layer cannot explain the observed accumulation of carbonate in most shallow-water marine sediments.

In the second of the four alternatives for circumventing taphonomic loss, carbonate production and taphonomic loss may not occur simultaneously at equivalent rates. Most decomposition of organic matter occurs during the warmer months, for instance, whereas carbonate addition may occur throughout the year (e.g. Smith, 1953; Reaves, 1986; McNichol *et al.*, 1988). Molluscs dying during the winter may have a greater chance of preservation. Consider, for example, a sinusoidal variation in production and loss offset by one-half cycle (e.g. a winter maximum in production and a winter minimum in loss). If production and taphonomic loss are out of phase, carbonate can be preserved where it otherwise might not be, provided sedimentation rates are fast enough (Fig. 6). If most taphonomic loss occurs near the sediment surface, significant preservation (30–50% of production in Fig. 6) can occur by this mechanism at sedimentation rates typical of bays and estuaries (0.1–0.5 cm yr^{-1}). If significant taphonomic loss occurs throughout the bioturbate zone, little carbonate can be preserved. Preservation by this mechanism, then, can only occur if bioturbation has little effect on the TAZ and only at relatively high sedimentation rates. Shelf and slope environments should benefit little from this process.

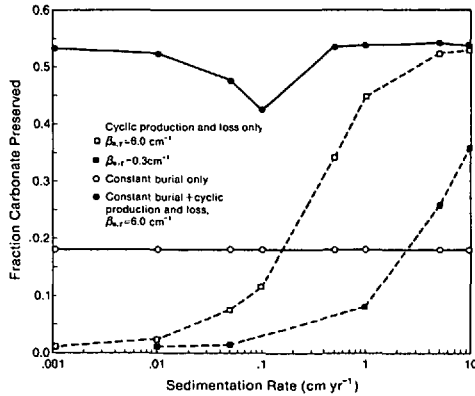


Figure 7. The fraction of carbonate preserved by burial at various sedimentation rates compared to the curves of Figure 6 (dashed). Simulations run so that carbonate addition balances taphonomic loss; no carbonate would be preserved without burial, in the absence of cyclic production and loss. Lower curve, no cyclic carbonate production or taphonomic loss. Upper curve, cyclic carbonate production and taphonomic loss as described in Figure 6. Lower curve: $\alpha_a, \alpha_t = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\beta_a, \beta_t = 6.0 \text{ cm}^{-1}$; $h = 0 \text{ cm}$; $\gamma_a, \gamma_t = 1$; $\alpha_w = 4.0 \text{ cm yr}^{-1}$; $\beta_w = 0.0559 \text{ cm}^{-1}$; $\gamma_w = 1.5$. Upper curve: $\alpha_o = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\alpha_t = 0.5 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\omega = 2\pi \text{ yr}^{-1}$; $\rho_a = \pi$; $\rho_t = 0$.

d. *Burial.* Burial is the third possible mechanism for circumventing the environment's capacity for taphonomic loss. Carbonate preservation by burial is independent of sedimentation rate, as the two are defined here (Fig. 7, lower solid line). The fraction preserved increases with increasing rate of burial (α_w) (Fig. 8), but the effect of burial by itself is relatively small over a wide range of burial rates likely to be

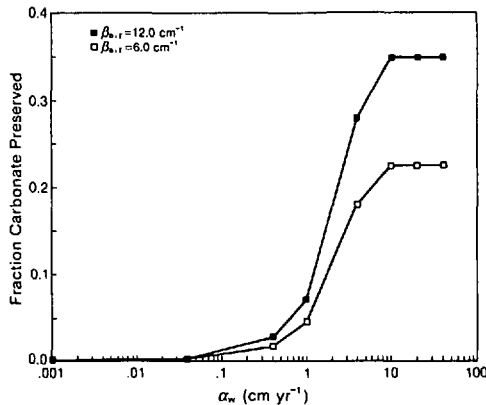


Figure 8. The fraction of added carbonate preserved under varying burial rates (α_w in cm yr^{-1}) under the proviso that carbonate addition and the potential for carbonate loss just balance. Without burial, no carbonate would be preserved. $S_o = 1 \text{ cm yr}^{-1}$; $h = 0 \text{ cm}$; $\gamma_a, \gamma_t = 1$; $\beta_w = 0.0559 \text{ cm}^{-1}$; $\gamma_w = 1.5$. Lower curve: $\alpha_a, \alpha_t = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\beta_a, \beta_t = 6.0 \text{ cm}^{-1}$. Upper curve: $\alpha_a, \alpha_t = 1.2 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\beta_a, \beta_t = 12.0 \text{ cm}^{-1}$.

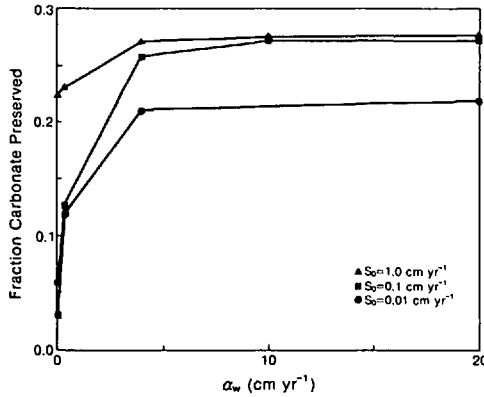


Figure 9. Fraction of added carbonate preserved under varying burial rates (α_w in cm yr^{-1}) under the proviso that carbonate addition approximates the potential for carbonate loss averaged over 1 yr and that burial rates and taphonomic rates have one year cycles but are 6 months out of phase. $\alpha_a = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\beta_a, \beta_r = 6.0 \text{ cm}^{-1}$; $\alpha_{o,r} = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\alpha_r = 0.5 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $h = 0 \text{ cm}$; $\gamma_a, \gamma_r = 1$; $\beta_w = 0.0559 \text{ cm}^{-1}$; $\gamma_w = 1.5$; $\omega_w, \omega_r = 2\pi \text{ yr}^{-1}$; $\rho_w = \pi$; $\rho_r = 0$; sedimentation rate in cm yr^{-1} .

encountered in marine sediments (e.g. Schaffner *et al.*, 1987; Landahl, 1988; Miller and Sternberg, 1988), depending, naturally, on the depth distribution of taphonomic loss. If burial and a cyclic offset between carbonate production and taphonomic loss are combined, preservation exceeds 50% of added carbonate at reasonable burial rates for most sedimentation rates (Fig. 7) with sedimentation rate being the more important mediator only at high sedimentation rates. In most marine habitats, burial far outweighs sedimentation rate in importance; that is short-term events of sediment resuspension and redeposition or bioturbation bury shells much more rapidly than does the net sedimentation rate.

The rate of burial may also be higher during certain seasons (Bale *et al.*, 1985; Anderson *et al.*, 1981; Meade, 1969). In locations where burial rates are higher during the winter (e.g. Uncles and Stephens, 1989) but taphonomic loss proceeds more vigorously during the summer, a cyclic offset between burial and taphonomic loss can also result in enhanced carbonate preservation, but only at high burial rates (Fig. 9). Where bioturbation is most important, burial rates would be highest in the summer (Powell, 1977). No offset would exist and preservation would not be enhanced. If taphonomic loss proceeds most vigorously in the summer, the importance of winter storms should far exceed the importance of bioturbation in the enhancement of preservation.

I emphasize, however, that the agent of burial is not particularly important in this regard, only the rate and timing of burial is important. However, the clear necessity for (1) taphonomic loss to be restricted to the nearsurface for any substantial preservation under any scenario where the environment's capacity for taphonomic

Table 2.

Fraction of carbonate addition preserved in a "typical" bay or continental shelf*

1.

Low burial rates, significant taphonomic loss below the surface, carbonate production one-half of potential taphonomic loss, t_s occurs at $d = 1.8$ cm.

$$\alpha_{ow}, \alpha_{1w} = 2 \text{ cm yr}^{-1}; \alpha_{o_t}, \alpha_{1_t} = 0.15 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}; \beta_t = 1.5 \text{ cm}^{-1}.$$

Fraction preserved = 0.28

2.

Higher burial rates, most taphonomic loss near surface. $\alpha_{ow}, \alpha_{1w} = 4 \text{ cm yr}^{-1}; \beta_t = 6.0 \text{ cm}^{-1}.$

2a.

Relatively low taphonomic loss rate, carbonate production equals loss, t_s occurs at

$$d = 0.43 \text{ cm}; \alpha_{o_t}, \alpha_{1_t} = 0.3 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}.$$

Fraction preserved = 0.75

2b.

Relatively high taphonomic loss rate, carbonate production one-half of potential loss,

$$t_s \text{ occurs at } d = 0.55 \text{ cm}; \alpha_{o_t}, \alpha_{1_t} = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}.$$

Fraction preserved = 0.70

*In all cases, $h = 0$ cm; $\gamma_a, \tau_t = 1$; $\beta_w = 0.0559 \text{ cm}^{-1}$; $\gamma_w = 1.5$; $\omega_w, \omega_t = 2\pi \text{ yr}^{-1}$; $\rho_w = \pi$; $\rho_t = 0$; $\alpha_a = 0.03 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\beta_a = 0.6 \text{ cm}^{-1}$; $S_o = 0.3 \text{ cm yr}^{-1}$ (bay) or 0.01 cm yr^{-1} (shelf).

loss exceeds or is even a significant fraction of carbonate production rates and (2) the overwhelming importance of physical resuspension rather than bioturbation in this depth zone (Grant, 1983; Miller and Sternberg, 1988), suggests that physical reworking is the primary factor in most preservation, although bioturbation may be important in the distribution of carbonate within the sedimentary column (Meldahl, 1987; Powell *et al.*, 1989).

e. Realistic scenarios for preservation. To determine how all of these processes might interact to affect carbonate preservation, consider a possibly realistic case for a typical estuary, viz. burial rates (α_w) of 2 to 4 cm yr^{-1} , but most pronounced in the winter, taphonomic loss rates exceeding production rates by 0 to 50%, a sedimentation rate of 0.3 cm yr^{-1} , and a depth offset between the distribution of carbonate addition and loss such that carbonate addition exceeds loss at depths of 0.5 or 5.0 cm depth.

The fraction preserved is 70 to 75% of carbonate addition if burial rate is kept relatively high even when the potential taphonomic loss exceeds carbonate production by a factor of two (Table 2). Reducing sedimentation rates to values typical of continental shelves (0.01 cm yr^{-1}) does not markedly change the result, but decreasing burial rate significantly reduces preservation. Hence varying burial rates must be extremely important as emphasized by Powell *et al.* (1989) and Aller (1982). Considering the likelihood that carbonate is distributed more patchily than organic matter decomposition on the seafloor, so that taphonomic loss rates deduced from

rates of organic matter decomposition might overestimate the actual amount of carbonate dissolved, preservation of nearly all carbonate is possible even in a taphonomically-active environment. However, when the environment's potential for taphonomic loss exceeds or is a substantial fraction of the carbonate addition rate, sufficient preservation can only occur if most taphonomic loss occurs very near the sedimentary surface. The relatively good preservation of epifauna and semi-infauna in most assemblages and the results of this model require that the extreme case of most dissolution near the sediment surface be generally correct and that bioturbation typically has little effect on the process of preservation, save as a possible mediator for burial.

One can now review the carbonate budgets of Aller (1982) and Cummins *et al.* (1986b), both of whom concluded that carbonate addition and loss just about balanced. In Aller's case, only carbonate bypassing the bioturbate zone was preserved; bypassing occurred either by storm burial or the infilling of old burrows. In either case, carbonate was concentrated at depth and protected from further dissolution in a horizon where dissolution was already low; viz. below the TAZ. Because bypassing was rare, the overall yearly budget of input and loss was nearly equal.

In the case of Cummins *et al.* (1986b), individual shells were tallied and little net accumulation was observed in an area where nearly all carbonate production must be preserved to explain the observed sedimentary carbonate content. In this case, most shells were juveniles and most of these were not preserved, as is usually observed in marine habitats (Powell *et al.*, 1989; Cummins *et al.*, 1986c; Acker and Byrne, 1989). The evidence suggested that taphonomy was both size and age dependent; that is, being a juvenile was important, not just being small (Cummins *et al.*, 1986c). However, juveniles, normally being small, account for little of the added carbonate on a weight basis. Hence nearly all carbonate could be preserved if nearly all adults are preserved. Loss rates for larger shells were lower (Powell *et al.*, 1986) and the substantial agreement in biomass rankings between the living, potentially preserved community and the death assemblage suggests that most large shells were preserved. In fact, the requirement that most large shells be preserved, in light of Cummins *et al.*'s (1986b,c) data, necessitates that the conclusions of Staff *et al.* (1986, 1985) must be expected: biomass-at-death should be one of the best community attributes for paleoecological reconstruction.

f. Sundries on the preservational process and resulting effects on the distribution of carbonate in cores.

i. Juvenile preservation. Feldman (1989), among others, argued that juveniles are better preserved in some paleo-settings than is generally observed today. Whether true or not, the conditions required for most juveniles to be preserved, given their

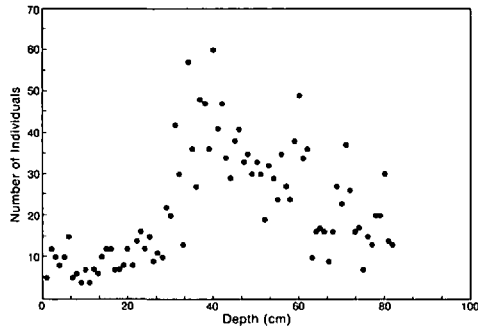


Figure 10. Number of individuals plotted against depth for a core from Copano Bay, Texas at Staff et al.'s (1986) collection site. A plot of biomass at death, a surrogate for shell carbonate content, follows the same trend (Powell *et al.*, 1992).

inherently lower likelihood of preservation by their small size, requires one or more of the following conditions: (a) very low taphonomic loss rates, hence very low decomposition rates of sedimentary organic matter; (b) very high burial rates in an environment where taphonomic loss is restricted to the nearsurface; or (c) very high sedimentation rates in an environment where taphonomic loss is restricted to the nearsurface. High carbonate production rates buffering the local environment will not constrain an inherent bias against juveniles. It is essential to recognize that many juveniles are preserved in present day sediments, but the proportion of juveniles preserved is much lower than the proportion of adults.

ii. Bioturbation vs. storm reworking. The requirement that loss be essentially restricted to the nearsurface of sediments and the conclusion of Aller (1982) that bioturbation enhances dissolution, if generally applicable, casts doubt on the role of bioturbation on shell condensation and the formation of shell layers. Powell *et al.* (1989) argued that bioturbation's role in shell preservation is limited based on the current data, although no adequate field tests have yet been conducted. However, it seems unlikely that significant bioturbational shell burial could be decoupled from taphonomic loss sufficiently to enhance preservation.

Many assemblages are characterized by an increasing carbonate concentration with depth. Copano Bay, Texas is an example (Fig. 10). The term condensed bed might be applied to such assemblages. Storm reworking and bioturbation might be responsible. Substantial addition of infauna would also suffice. Regardless of the process, this sort of concentration gradient is obtained in one of two ways. (1) The carbonate content of younger sedimentary horizons will vary in time as carbonate is added, lost, and reworked down into the sedimentary column. Under appropriate conditions, carbonate concentration will always be lower near the surface and rise to a characteristic value at the depth of final burial ($C(z, t \rightarrow \infty)$) (Fig. 11) because some carbonate addition will occur below the sedimentary surface, taphonomic loss is

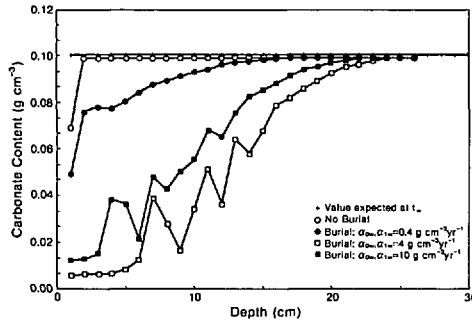


Figure 11. Depth distribution of carbonate under varying burial rates when burial has a 1 year cycle. $\alpha_a = 0.6 \text{ g CaCO}_3 \text{ cm}^{-3} \text{ yr}^{-1}$; $\beta_a = 6.0 \text{ cm}^{-1}$; $h = 0 \text{ cm}$; $\gamma_a = 1$; $\beta_w = 0.0559 \text{ cm}^{-1}$; $\gamma_w = 1.5$; $\omega_w, \omega_r = 2\pi \text{ yr}^{-1}$; $\rho_w = \pi$; $\rho_r = 0$; $S_o = 1 \text{ cm yr}^{-1}$; $\alpha_{ow} = \alpha_{lw} \text{ in cm yr}^{-1}$.

highest at the surface, and burial will continually move shells down into the sedimentary column. (2) The only alternative explanation for increasing carbonate content with depth is that the rate of one or more processes changed and hence the carbonate content characteristic of the depth of final burial varied. Because carbonate content more rarely declines with depth beneath the surface, this later alternative would seem to be the less frequent of the two. One would expect increases and decreases in carbonate content with depth to occur equally frequently if changes in process rates were the more frequent explanation.

Of course, sufficient time is available for both alternatives because an invariant condition characteristic of the depth of final burial generally cannot be obtained in a short time. In a "typical" bay as described in Table 2, for example, d_∞ corresponds to a sedimentary horizon about 60 yr old; for the shelf setting (Table 2), the value would be about 1700 yr. Much can happen in process rates over such time periods. Hence, variation in sedimentary carbonate content with depth probably encompasses a mixture of both processes and the extent to which one dominates over the other might be instructive. A comparison between infauna and epifauna and between species might provide useful information since different responses can be expected among these groups. One might anticipate, for instance, that a declining rate of taphonomic loss might enrich the assemblage in epifauna whereas a steady process of accumulation would not.

iii. *Shell condensation.* The term condensation has been used in the literature to describe an increase in carbonate concentration with depth (e.g. Trewin and Welsh, 1976; Fürsich, 1978; Meldahl, 1987). If simply that, any process, even just carbonate addition [Eq. (8)] could yield a "condensed" bed. By inference, condensation connotes a carbonate concentration greater than would be produced by the processes of addition and loss alone, at t_∞ . Interestingly, steady burial does not yield a condensed bed of this type, but only moves the depth of final burial deeper into the

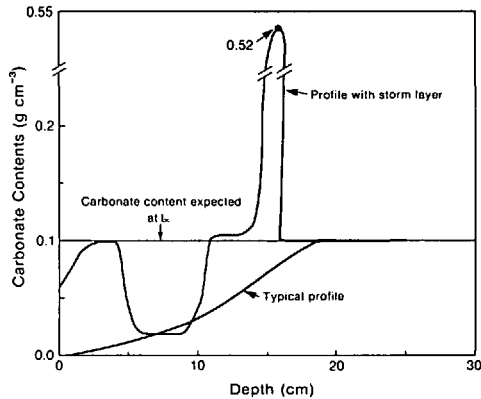


Figure 12. A comparison between the sedimentary record obtained under constant processes of addition, loss and burial and the record obtained when rare storm events also occur. The straight line marks the carbonate concentration characteristic of t_{∞} .

sediment. [Burial processes, of course, must be considered over appropriate time scales since some mixing will always occur (see Boudreau, 1986; Kershaw *et al.*, 1988).] That is, burial cannot yield a higher concentration of carbonate than would be present without it, as defined here, even if burial is a cyclic phenomenon. In the noncyclic case, the concentration cannot exceed $(A_{pT} - T_T)/S_o$. Hence bioturbation cannot yield a condensed bed of this sort.

Condensation beyond the concentration of carbonate characteristic of the environment's production rate and sedimentation rate requires a rapid, transient increase in burial rate as might be associated with storms of recurrence intervals long compared to the sedimentation rate, in order to remain distinct. In this case, the carbonate content should rise and fall rapidly with depth (e.g. Fig. 12). Figure 12 was generated by interposing a rapid transient increase in burial rate on an otherwise constant preservational regime. The local minimum in carbonate content in Figure 12 is necessitated by the removal of carbonate from certain horizons for concentration in others (see Davies *et al.*, 1989b). Consequently, a rise to a generally higher carbonate content, as in Copano Bay, cannot be explained by an aperiodic storm.

To the extent that these lower enriched units, such as in Copano Bay, represent the condition at t_{∞} , the preponderance of study on the upper few to 20 cm of sediment, where $t \ll t_{\infty}$, is unfortunate. One cannot anticipate that the upper section of core appears as it finally would in the rock record after a much longer period of time.

iv. Stratigraphic displacement of epifauna. Burial increases the time, and therefore depth, to t_{∞} . Epifauna should be more affected by burial so that variation in abundance with depth might be used to assess the importance of burial in the assemblage. Any pair of epifaunal and infaunal species will be offset by a characteris-

tic average depth (h) during life, dependent upon the life habitat depth of the infaunal species. Because burial affects epifauna more, this depth offset should be compressed after death. Hence, the distance traveled by the shell through our z coordinate system, is

$$\frac{dz}{dt} = \alpha_w e^{-\beta_w(z+S_o t)^{\gamma_w}}. \quad (26)$$

Choosing for simplicity the boundary conditions $z = z_o$ at $t = 0$, and $\gamma_w = 1.0$, the distance a shell travels from its initial entry point (location of death) to its final resting place due to burial processes can be computed as

$$\Delta z(t) = 1/\beta_w \ln (e^{\beta_w z_o} + (\alpha_w/S_o)(1 - e^{-\beta_w S_o t})) - z_o. \quad (27)$$

The net effect of burial will be to reduce the depth offset between epifauna and infauna found during life, and at death, if in stratigraphic life position. Consider the epifaunal case where death occurs on the sediment surface ($z_o = z - S_o t - h, h = 0$) and an infaunal case where death occurs at 10 cm depth ($z_o = z - S_o t - h, h = 10$). For one case used previously where burial processes extended relatively deeply into the sediment (e.g. Figs. 8 and 9) ($\beta_w = 0.0559 \text{ cm}^{-1}$, $\alpha_w = 4 \text{ cm yr}^{-1}$, $\gamma_w = 1.5$, $S_o = 1 \text{ cm yr}^{-1}$), the distance a shell travels after death, $\Delta z(t \rightarrow \infty)$, can be computed for the epifaunal case ($h = 0 \text{ cm}$) as 8.19 cm and for infauna ($h = 10 \text{ cm}$) as 1.69 cm. Infauna and epifauna initially 10 cm apart would end up 3.5 cm apart. If burial is restricted to a shallower depth ($\beta_w = 0.5 \text{ cm}^{-1}$), the values for $\Delta z(t)$ are respectively 2.0 cm and 0 cm. That is, burial does not affect infauna at all in this case. Infauna and epifauna initially 10 cm apart would end up 8.0 cm apart.

In addition, the offset increases with decreasing sedimentation rate because burial is more effective at lower sedimentation rates. Hence, for a lower sedimentation rate ($S_o = 0.01 \text{ cm yr}^{-1}$), epifauna travel 12.1 cm when burial processes extend deeply into the sediment (β_w small) rather than 8.19 cm and, if burial is restricted to shallower depths (β_w large), 3.95 cm rather than 2.0 cm. The values for infauna are 3.78 cm and 0 cm rather than 1.69 cm and 0 cm. Note that when burial processes affect a relatively larger fraction of the sedimentary column, at the higher sedimentation rate, epifauna and infauna living 10 cm apart are finally preserved 3.5 cm apart. At the lower sedimentation rate, they are finally preserved 1.85 cm apart. Hence burial affects the relative disposition of contemporaneous infauna and epifauna.

g. Preservation of carbonate versus preservation of variations in carbonate with depth. Most variations in carbonate content with depth will be produced by cyclic or aperiodic changes in process rates like the rate of carbonate addition or taphonomic loss. Except early in the formation of the assemblage, at $t \ll \infty$, carbonate distribution does not vary with depth without a change in process rates. Neither carbonate production nor taphonomic loss, if temporally stable, can introduce

variation in carbonate content downcore. Preservation of cyclic or quasi-cyclic changes where rates deviate from and then return to a previous value depends upon the sampling interval, the sedimentation rate and the period of the cycle,

$$\Delta z = 2\pi S_o / \omega \tag{28}$$

where Δz , in this case, is the depth interval of 1 cycle. The required sampling interval to observe the cycle would be $\leq \Delta z/2$. At normal sedimentation rates, 0.3 to 0.01 cm yr⁻¹, and a sampling interval of 1 cm, ω ranges from 0.94 to 0.03 yr⁻¹, yielding minimal observable cycle times of 6.7 to 209 yr. These cycle times are considerably above the time scales of preservation. Hence, there is some decoupling between the processes of preservation and those controlling carbonate distribution within the stratigraphic column. Cycles that are preserved, for example, will have had little to do with carbonate preservation. Storms of recurrence intervals long enough to remain distinct from the burial process, as modeled by Eq. (21) (e.g. Kochel and Dolan, 1986; Barron, 1989; Davies *et al.*, 1989b), will have little to do with preservation unless the only carbonate present in the environment is that produced shortly before the storm. Hence, Davies *et al.* (1989b) observed a distinction between carbonate preservation and carbonate disposition in a microtidal inlet where storms of long recurrence intervals failed to noticeably imprint a taphonomic signature on shells save for their final location and orientation.

All processes might be cyclic, but only cycles in taphonomic loss, carbonate production or sedimentation rate should be preserved. Cyclic variations in burial rate will not. For the mathematically inclined, adding cyclic burial modifies Eq. (26) to

$$\frac{dz}{dt} = (\alpha_{ow} + \alpha_{1w} \sin \omega_w t) e^{-\beta_w(z+S_o t)} \tag{29}$$

which yields, for $z = z_o$ at $t = 0$,

$$\begin{aligned} \Delta z(t) = 1/\beta_w \ln \left(e^{\beta_w z_o} + \alpha_{ow}/S_o (1 - e^{-\beta_w S_o t}) \right. \\ \left. + (\alpha_{1w} \beta_w) (\omega_w - e^{-\beta_w S_o t} (\beta_w S_o \sin \omega_w t \right. \\ \left. + \omega_w \cos \omega_w t)) \right) 1/(\omega_w^2 + \beta_w^2 S_o^2) \Big) - z_o \tag{30} \end{aligned}$$

As $t \rightarrow \infty$

$$\Delta z(t) = 1/\beta_w \ln ((e^{\beta_w z_o} + \alpha_{ow}/S_o + \alpha_{1w} \beta_w \omega_w) 1/(\omega_w^2 + \beta_w^2 S_o^2)) - z_o \tag{31}$$

Hence, evidence of cyclic burial may be observable during the initial stages of assemblage formation, at $t \ll t_\infty$ (given sufficiently small ω_w , β_w , and S_o), but not when finally preserved ($t = t_\infty$) and the amplitude of the youngest cycle should be greatest. Figure 11 gives an example. Accordingly, evidence of frequent burial events is unlikely to be preserved. Evidence of events attributable to burial, some shell beds

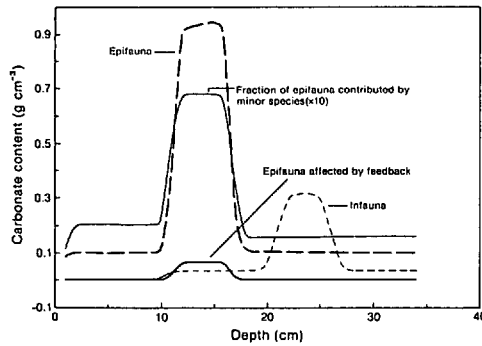


Figure 13. A comparison of profiles for infauna and epifauna during an episode of rapidly increasing or rapidly decreasing sedimentation rate in an area where taphonomic loss rates are inherently low as indicated by a disproportionate increase in the fraction of gravel-loving species. The same profiles would be present under a regime of constant intense burial but one would anticipate the absence of the disproportionate increase in the gravel-loving species. S_0 varied from 1 cm yr^{-1} to 0.1 cm yr^{-1} and back.

for example, can only represent rare or unusually extreme events (e.g. Galli, 1989); the scale of “rare” or “extreme” being modulated by the sedimentation rate.

Other processes can affect the distribution of carbonate in sediments and its concentration but be, to some extent, independent of the preservational processes. Occasional large storms, for instance, may reorganize carbonate but most of the reorganized carbonate must have been previously preserved. Regardless of origin, boundary sharpness for any aperiodic change will be controlled by β and $d\eta/dt$, the sedimentation rate, and these will generally require longer periods than encompass the purview of the preservational process. Accordingly, the generation of shell beds requires two explanations: (1) the reasons for shell concentration and (2) the reasons for shell preservation sufficient to provide an adequate supply.

h. Interpreting sedimentary profiles. Similar profiles depicting changes in rates of processes can frequently be produced by several different processes. I offer several cases as examples. Changing sedimentation rates and carbonate production rates may have results that look grossly similar (Figs. 13, 14) (but see Kidwell, 1986a). Moreover, the result of one process may appear to have resulted from another when the primary preservational effect is of another kind. For example, in Figure 15, changes in burial rate produce a stratigraphic column that mimics that produced by a change in production rate for epifauna because the primary affect was to substantially increase carbonate preservation rather than carbonate reorganization; infauna, already well preserved, record a profile more representative of the burial process. A comparison of profiles for infauna and epifauna during an episode of rapidly increasing or rapidly decreasing sedimentation rate (Fig. 13), when taphonomic loss rates are inherently low, looks similar to one generated by variations in carbonate

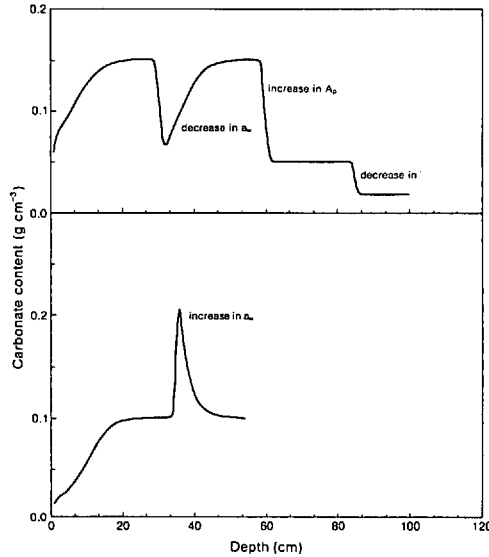


Figure 14. Typical profiles produced by changes in carbonate production or taphonomic loss and changes in the rate of burial. α_w varied from 1.0 to 4.0 cm yr^{-1} and vice versa. T_T varied from .1 to .05 $\text{g CaCO}_3 \text{ cm}^{-2} \text{ yr}^{-1}$. A_{pT} varied from .1 to .2 $\text{g CaCO}_3 \text{ cm}^{-2} \text{ yr}^{-1}$.

production under a regime of constant intense burial where taphonomic loss rates are high (Fig. 14, below 50 cm). However, with rapid burial, one would anticipate the absence of the gravel-loving species among the epifauna which show a disproportionate increase in abundance due to taphonomic feedback in Figure 14 and, consequently, suggests the alternative, a variation in sedimentation rate. Accordingly, evidence of the processes involved requires a more detailed analysis of the species and their distributions.

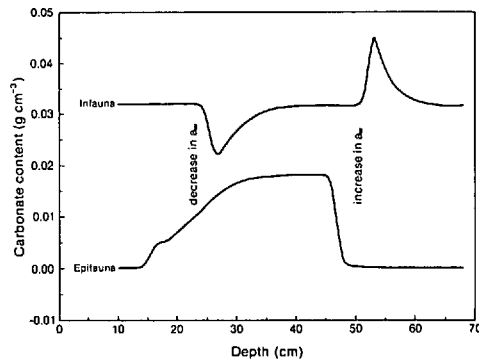


Figure 15. A comparison of profiles for epifauna and infauna during an episode of increasing and decreasing burial under conditions where taphonomic loss is sufficient to destroy most epifauna when burial rates are low. α_w varied from 0.04 to 4.0 cm yr^{-1} and back again.

The necessities of preservation do constrain the mechanisms of carbonate disposition. The mechanisms by which variations in carbonate content with depth are produced (shell layers, for example) must be compatible with the demands of the preservational process, namely the preservation of an adequate amount of carbonate to account for the sediment's carbonate content. In Copano Bay, the lower carbonate content in the upper 25 cm of core (Fig. 10) cannot be explained solely by burial, and, if steady sedimentation rates are assumed in the upper 50 cm as sediment textural data and depth records suggest, variation in carbonate input or taphonomic loss must be surmised. For the case of Copano Bay, assuming a steadily declining sedimentation rate initially followed by a rapid change in burial rate coinciding with a simultaneous decline in production yields similar profiles (simulations 1 and 2, Fig. 16) to Figure 10. Assuming an additional very recent decline in burial rate coincident with the construction of a nearby causeway and bridge (simulation 4) yields an even better fit. Simulation 4 provides one possible scenario for Copano bay although offering no proof of its accuracy. That proof must be found by analyzing the preserved assemblage. Another possibility, varying carbonate production rates rather than burial rates, might work as well. Nevertheless, the scenario reproduces the disposition of carbonate with depth while still allowing for the preservation of about 85% of the carbonate produced in a taphonomically-active environment, a necessity in Copano Bay. Accordingly, a model of this sort may not always be able to prove that a certain sequence of preservational and depositional processes occurred, but it can exclude a variety of otherwise appealing scenarios. Most importantly, a model can be used to address the independent problems of preservation and carbonate distribution. Shell beds, for example, require the preservation of carbonate as well as its concentration and the time scales and processes involved for one can be considerably different from the other.

4. Conclusions

The modeling exercise identifies a variety of important processes and preservational alternatives, but the most important one is the likely prospect that most carbonate is preserved and that preservation may be relatively efficient even in environments where taphonomic processes have the potential for destroying most carbonate produced by the community. Proving the validity of this conclusion depends on an increased understanding of sediment chemistry and the processes of production and burial, but if true, then many fossil assemblages may satisfactorily record the adult, preservable fauna that lived in the community. But it is also important to recognize that evidence of the preservational process is poorly recorded by the distribution of shell carbonate downcore. Downcore variations in shell carbonate record longer-term changes in rates or rapid transient changes produced, for example, by storms. Some of these may have affected preservation, but all need

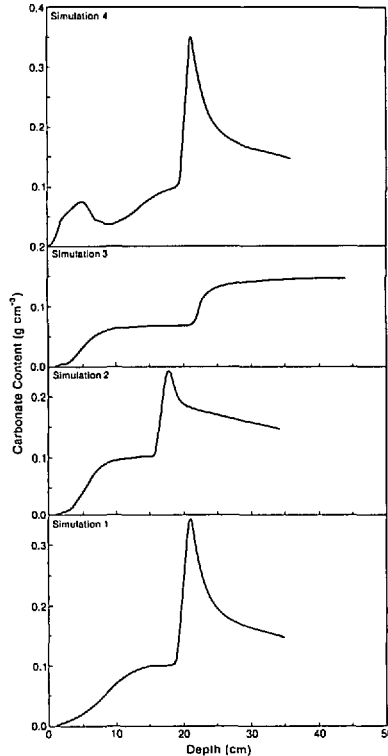


Figure 16. A profile mimicking the case for Copano Bay (Fig. 10). Simulations 1, 2 and 4 all assumed a steadily declining sedimentation rate during deposition of the sedimentary record below 20 cm from 0.6 to 0.3 cm yr^{-1} ; an increase in burial rate at 20 cm from $\alpha_w = 1$ to 4 cm yr^{-1} and a simultaneous decrease in production rate from $\alpha_w = .03$ to $.015 \text{ g cm}^{-3} \text{ yr}^{-1}$. Simulations 1 and 2 differed solely in β_w . In simulation 1, $\beta_w = .0948 \text{ cm}^{-1}$; in simulation 2, $\beta_w = .2683 \text{ cm}^{-1}$. In simulation 3, sedimentation rate was held constant at $.6 \text{ cm yr}^{-1}$ and β_w at $.2683 \text{ cm}^{-1}$, while α_w changed from 1 to 4 cm yr^{-1} as before. In simulation 4, the conditions of simulation 1 were repeated, however γ_w was allowed to increase steadily from 1.5 to 3.0 beginning at 6 cm which resulted in a progressive shallowing of the depth of burial while retaining α_w unchanged.

not have. The best evidence of the preservational process is most likely recorded on the shells themselves as their taphonomic signature (Davies *et al.*, 1989b). This model confirms the importance of taphofacies analysis in understanding the preservation of fossil assemblages. Finally, knowing how frequently current carbonate production rates fall short of rates necessary to explain the carbonate content of sediments would be interesting. Application of studies of Recent death assemblages to the fossil record requires that these assemblages have been little affected by man. Comparison of production rates with carbonate content may be one way to assess man's impact on the composition of Recent death assemblages.

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