

New model for the emplacement, bioturbation, and preservation of fine-scaled sedimentary strata

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ABSTRACT

We present a new quantitative model for the formation and preservation of sedimentary fabric based on interacting sedimentation and bioturbation. The model is one-dimensional and is forced by fluctuation of the sedimentation rate, which affects deposition of sediment possessing primary (depositional) fabric. Primary fabric is modified by bioturbation, which is represented as a depth-limited reaction term. Model output includes depth in seabed and preservation quotient, a measure of relative preservation of primary versus biogenic fabric at each depth. The required parameters (sedimentation rate and bioturbation rate) can be derived from studies of seabed processes; model output can be compared directly to observations of both modern and ancient sedimentary strata.

Keywords: bioturbation, sedimentation, event layer, model, stratigraphy.

INTRODUCTION

It has been recognized for decades that the degree to which primary physical stratification in aquatic sediments is preserved or destroyed by bioturbation (sediment mixing by organisms) depends on competing rates of sediment burial and bioturbation. Rapid sediment deposition or physical reworking tends to result in physically stratified sedimentary fabric (herein referred to as primary fabric), whereas bioturbation obliterates physical stratification and generates biogenic fabric. Measurements of sedimentation rates and bioturbation intensity are now routine (e.g., Boudreau, 1994, >100 observations), and a number of studies have provided qualitative and semiquantitative approaches to assess bioturbation and stratification in sedimentary fabric (Moore and Scruton, 1957; Guinasso and Schink, 1975; Nittrouer and Sternberg, 1981; Droser and Bottjer, 1986; Wheatcroft, 1990). However, no quantitative method exists for predicting the extent of stratification or bioturbation preserved in sedimentary fabric. In this paper we present a mathematical model for the formation and preservation of sedimentary fabric as a result of the combined actions of deposition and bioturbation. This model provides a link between the study of depositional and post-depositional sedimentary processes in modern settings and the interpretation of environmental processes, modern and ancient, from fine-scaled stratigraphy.

Two separate approaches have emerged in analyzing preservation potential of sedimentary fabric or structures. One describes the evolution of individual event layers in terms of mass conservation, with sedimentation and bioturbation represented as advection and diffusion processes, respectively (Guinasso and Schink, 1975; Wheatcroft, 1990). Examples of

such event layers include sandy storm beds in otherwise muddy sediment (Aigner and Reineck, 1982), tektite layers in deep-sea sediments (Guinasso and Schink, 1975), and clay-rich oceanic flood layers in coarser shelf sediments (Wheatcroft and Borgeld, 2000). The second approach (Moore and Scruton, 1957) assesses the degree to which sedimentary fabric and structures are either physical or biological in origin. Droser and Bottjer's (1986) effort to quantify bioturbation introduced the ichnofabric index, which classifies strata in terms of the relative volume of biogenic versus physical sedimentary structures. Howard (1975) also addressed this problem, describing sedimentation and bioturbation as processes competing to either bury and preserve primary fabric or replace it with biogenic fabric. This concept can be quantified as an advection-reaction relationship, wherein primary fabric is the tracer, sedimentation is represented by advection, and bioturbation is characterized as an irreversible reaction term acting on primary fabric and producing biogenic fabric.

SEDIMENTATION-BIOTURBATION MODEL

Preserved sedimentary fabric is described here as the result of competing processes of sedimentation and physical reworking (the source of primary sedimentary fabric) and bioturbation. We assume that bioturbation is continuous in time and affects only the upper layers of sediment, to a maximum bioturbation depth L_B . In the model, a freshly deposited sediment layer, with sedimentary fabric 100% physical in origin, is buried by sedimentation, and as burial depth to the layer increases, the layer slowly traverses the bioturbated zone. If negligible subsequent physical reworking is assumed, the layer undergoes ir-

reversible biogenic changes from the time it is deposited until it is buried below L_B .

Model Formulation

The present model tracks the evolution of sedimentary fabric from 100% primary to some proportion of biogenic. Let V denote the total volume of sediments, V_B the bioturbated volume, and $Q = V - V_B$ the volume of sediments that retains primary fabric in a layer between the depths $z_1 \leq z < z_2$ and beneath a unit area of the seabed. Following a standard approach in diagenetic models (Berner, 1980), horizontal variations are neglected, and the z axis is positive downward, with the origin at the sediment-water interface. The evolution of Q can be written as

$$\frac{d}{dt}Q + F(z_1) - F(z_2) = B, \quad (1)$$

where the quantity $F(z)$ is the volume of undisturbed sediment crossing the horizontal surface z in unit time and B is a sink term describing the destruction of Q inside the layer. In the absence of bioturbation ($B \equiv 0$), the quantity Q within the layer can change only when sediment is brought in or extracted from the layer, through the boundaries z_1 and z_2 , by the volume fluxes $F(z_1)$ and $F(z_2)$ (i.e., through erosion and deposition). Alternatively, if the flux balance is exactly zero, Q will change only if bioturbation is active in the layer between z_1 and z_2 (e.g., Q is constant for $z_1 > L_B$). The local form of conservation equation 1 is

$$\left(\frac{\partial}{\partial t} + \frac{\partial}{\partial z}\omega\right)q = b, \quad (2)$$

where ω is the burial velocity, b is the local bioturbation rate, and t is the time. The non-dimensional variable $0 \leq q \leq 1$, the preservation quotient, is simply the local fraction of the original unit volume that retains primary fabric. Boundary and initial conditions are

$$\begin{aligned} q(z, t = 0) &= f(z), \\ q(z = 0, t) &= g(t). \end{aligned} \quad (3)$$

Note that the condition $q \geq 0$ requires $b = 0$ if $q = 0$. A finite bioturbation depth also implies $b(z > L_B, t, q) = 0$.

In general, we expect both burial and bioturbation rates to be functions of time, depth,

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and the local preservation state. For example, burial rate ω may be depth dependent owing to consolidation (Berner, 1980); bioturbation can dilate, bind, or compact sediment, thus influencing sediment erosion potential (Nowell et al., 1981); and sediment deposition and erosion are likely to influence benthic communities (Rhoads and Young, 1970). The bioturbation rate b may be influenced by sediment type (e.g., organic content or grain size) and is a strong function of organism type, feeding strategy, size, and density, which are related to depth in seabed, depositional environment, and other environmental variables. However, quantitative observations relating such environmental processes to bioturbation rate are rare. For muddy continental-shelf sediments, consolidation is most rapid near the sediment-water interface, and erosion depths tend to be much less than bioturbation depths (e.g., the Eel River Shelf [Wheatcroft and Borgeld, 2000], with notable exceptions such as the Amazon Shelf [Kuehl et al., 1995]). Therefore, we restrict the present model to the first-order question of interacting sedimentation and bioturbation, and we ignore erosion, consolidation, and temporal variations in b . For deposition processes, the boundary condition in equation 3 can be replaced by the simpler $q(z = 0, t) = 1$, for freshly deposited layers.

General Solution

The time evolution of the preservation quotient q is described by the linear hyperbolic equation 2, which can be written as a system of two ordinary differential equations by using the method of characteristics:

$$\frac{dz}{dt} = \omega(z, t), \quad (4)$$

$$\frac{dq}{dt} = b(z, q). \quad (5)$$

At a given time, each layer is specified by its depth z . The burial of a layer due to sedimentation is represented in phase space (z, t) by its trajectory, the curve $z(z_0, t)$, where z_0 is the initial depth of the layer (Fig. 1). Equation 4 defines the trajectory of a given layer in (z, t) space. Equation 5 describes the evolution of the preservation quotient q along the trajectory. Biogenic reworking acts on the layer for as long as the trajectory stays inside the bioturbated zone $0 \leq z \leq L_B$.

A simple bioturbation rate model that satisfies $b(z > L_B, q) = 0$ and $b(z, q = 0) = 0$ is

$$b(q, z) = -\alpha(z)q, \quad (6)$$

representing bioturbation as a first-order reaction with rate constant $\alpha(z)$. With equation 6, the evolution equation 5 can be integrated

along the trajectory. The general solution of the system (equations 4 and 5) along the trajectory $z(z_0, t)$ is

$$q = q_0 \exp \left[- \int_{z_0}^z \frac{\alpha(s)}{\omega(s)} ds \right], \quad (7)$$

where $q_0 = q(z_0)$. The integral in equation 7 is readily computed for a wide class of functions α and ω .

Bioturbation rates are generally considered to decrease with increasing depth in the seabed, because organism densities generally decline with increasing depth (Bromley, 1996). Nevertheless, estimates of bioturbation using natural sediment radiotracers (such as ^{234}Th and ^{210}Pb) commonly assume a constant biodiffusivity (i.e., the biodiffusion coefficient D_b remains constant) for $z < L_B$, and $D_b = 0$ for $z > L_B$ (see Boudreau, 1994, for summary). This is because the depth dependence of D_b is poorly documented and radiotracer estimates of D_b may not be very sensitive to any depth dependence of bioturbation, owing to the additional influences of burial rate and radioactive decay on radiotracer distributions. In the following we examine the effects of bioturbation by solving equation 7 for both depth-constant bioturbation and for bioturbation rate decreasing exponentially with depth.

ANALYTICAL EXAMPLES

We represent event-layer deposition as a strong sediment pulse $\omega_S(t)$ superimposed on a background of constant-rate (ω_0), comparatively weak fair-weather deposition. Bioturbation is assumed to continue during deposi-

tion. The burial speed is independent of z , and trajectories during burial are parallel at all depths, irrespective of the initial position (Fig. 1). For simplicity, we represent the deposition event as a square pulse starting at $-\Delta t$ and ending at Δt .

$$\omega(t) = \omega_0 + \omega_S(t), \quad (8)$$

where

$$\omega_S(t) = \begin{cases} 0 & \text{for } t < -\Delta t \\ \Omega & \text{for } -\Delta t \leq t \leq \Delta t \\ 0 & \text{for } t > \Delta t. \end{cases}$$

The total thickness of the event layer is $L_S = 2\Omega t$, where Ω is the rate of supplemental deposition produced by the event. The upper panel of Figure 1 plots burial rate ω versus time (equation 8), normalized to the half-duration of the depositional event divided by the thickness of the bioturbated zone.

Depth-Constant Bioturbation

If bioturbation rate is independent of z , the final preservation state for a given sediment layer (the solution for q for $t \rightarrow \infty$) does not depend on the exact form of the trajectory, but is determined by an integral parameter, the residence time t_R (transit time in Wheatcroft, 1990), i.e., the total time spent within the bioturbated zone. For the conditions specified in equation 8, the preservation quotient is

$$q = q_0 \exp(-\alpha t_R). \quad (9)$$

Figure 1 shows the corresponding distribution

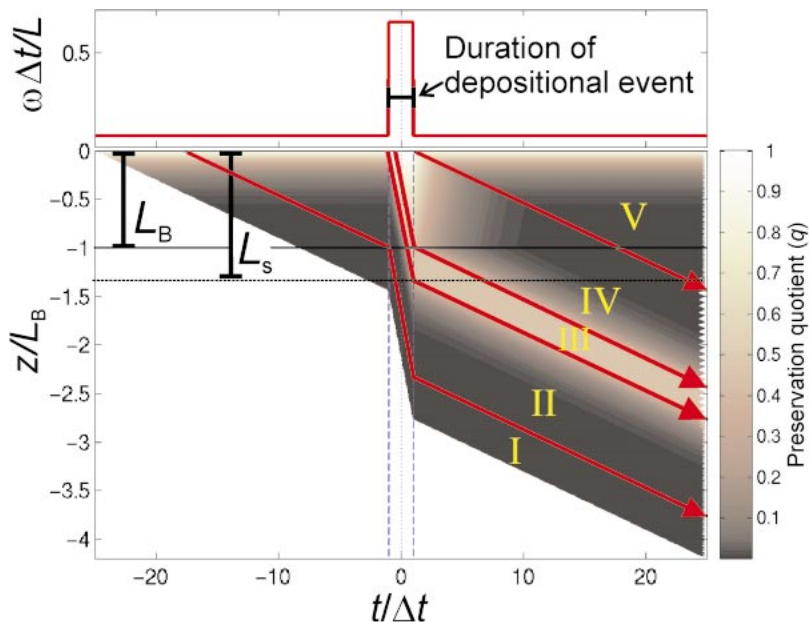


Figure 1. Preservation quotient distribution vs. normalized time and depth for depth-constant bioturbation (equation 9, $\alpha = 0.5$). Deposition event is represented as square pulse with maximum thickness $L_S = 1.2L_B$ and ratio of event rate to background burial rate of $\omega_0/\Omega = 0.1$. Arrows represent trajectories. Regions I–V and variables are described in text.

of q . A point in (z, t) space represents a sediment layer; as time passes, the position of the layer changes. The trajectory of the layer is the succession of different positions occupied at different times by the layer. Five trajectories in Figure 1 are represented by arrows. Regions separated by the trajectories have different characteristics, depending on the relationship between their deposition time and the time evolution of the deposition event. Regions III and IV constitute the event layer. Regions I and V are not affected by the deposition event, because the corresponding layers are either buried below L_B before the event or are deposited after the event. Region II is deposited before the event, but has a residence time above L_B shortened by event deposition. Layers in region III, buried below L_B during the event, are characterized by the shortest residence time and therefore are the best preserved (q has a maximum in region III). Note that along a line of constant t and outside the bioturbated zone, residence times (and the distribution of q) are symmetrical with respect to the center of region III.

Depth-Dependent Bioturbation

In the case of a depth-dependent bioturbation rate, the details of the layer trajectory become important. In this example, we assume that bioturbation follows first-order kinetics, at a rate that decreases with increasing depth:

$$\alpha(z) = \alpha_0 \exp(-\beta z), \quad (10)$$

where α_0 is the surface bioturbation rate and β is a constant that controls attenuation of α with depth. Equation 7 becomes

$$q = \begin{cases} \exp\left(-\frac{\alpha_0}{\beta} \frac{e^{-\beta z} - 1}{\omega_0 + \Omega}\right) & \text{if } z(\Delta t) \geq L_B \\ \exp\left(-\frac{\alpha_0}{\beta} \left[\frac{e^{-\beta z} - e^{-\beta z(\Delta t)}}{\omega_0} + \frac{e^{-\beta z(\Delta t)} - 1}{\omega_0 + \Omega} \right]\right) & \text{if } z(\Delta t) < L_B. \end{cases} \quad (11)$$

Figure 2 illustrates depth profiles of q under two event-deposition scenarios, with both depth-dependent and constant α , for a point in time after the event layer has been buried below bioturbation depth L_B by fair-weather deposition (i.e., when $dq/dt = 0$ for the event layer). For cases where the bioturbation rate decreases with depth, the distribution of q is no longer symmetrical around the center the event layer. Pre-event sediments remain longer in the upper parts of the bioturbated zone, where bioturbation is more intense, whereas sediments closer to the base of the bioturbated zone are mixed less rapidly, emerging with better-preserved primary fabric. Figure 2 il-

lustrates clearly that preservation potential is highest for basal parts of event layers that are thicker than the zone of bioturbation ($L_S > L_B$), and also shows the asymmetry of q produced by depth-dependent bioturbation (α). Most published analyses of event-layer preservation (e.g., Howard, 1975; Leithold, 1989; Wheatcroft and Borgeld, 2000) find that stratification is better preserved near the base of an event layer than near the top (where post-event bioturbation is most intense). Our model realizations suggest that depth-dependent bioturbation results in more realistic distributions of fabric preservation. For asymmetrical distributions of α (Fig. 2), the particular shape of the depth dependency does not seem to be as important as the requirement that α decreases with depth.

MODEL PARAMETERS, RESULTS, AND APPLICATIONS

In order to apply this model, rates for the controlling bioturbation and sedimentation processes (α and ω , respectively) must be selected. Both parameters display significant temporal and spatial variability in natural settings and so must be estimated for specific local conditions. Because our model is one-dimensional and does not portray the small-scale lateral heterogeneity observed in cores and outcrop, spatial averaging is necessary for ω , α , and q . Approximations of event-layer thickness, return period, and time-averaged accumulation rate can be used to estimate $\omega(t)$ for a variety of depositional settings; such approximations have been developed for numerous depositional environments (e.g., Sommerfield and Nittrouer, 1999; Bentley and Nittrouer, 1999; Wheatcroft and Borgeld, 2000; Bentley et al., 2002; Keen et al., 2003). Relative estimates of bioturbation intensity versus deposition rate (and resultant dominance of either primary or biogenic fabric) have been made for ancient shelf deposits (e.g., Howard, 1975; Leithold, 1989). For simulations over time scales of 10^2 to 10^3 yr, time series for $\omega(t)$ representing fair-weather and storm sedimentation can be generated by random sampling of probability density functions for $\omega(t)$ versus return period (Bentley and Nittrouer, 1999).

Few published examples of absolute volumetric bioturbation rates exist (Rice, 1986; Tedesco and Aller, 1997), but first-order estimates of α can be derived from radiotracer estimates of the biodiffusion coefficient D_b by assuming that characteristic time scales of biodiffusive mixing (t_{D_b}) over the depth L_B (e.g., $D_b = L_B^2/2t_{D_b}$, after Boudreau, 1997) are roughly equivalent to the time required for total bioturbation of a volume of sediment (turn-over period, $t_B = 1/\alpha \approx t_{D_b}$). For example (Fig. 3), the mean value for $\alpha(z)$ over the depth $0 < z \leq L_B = 10$ cm (where $\beta = 1$

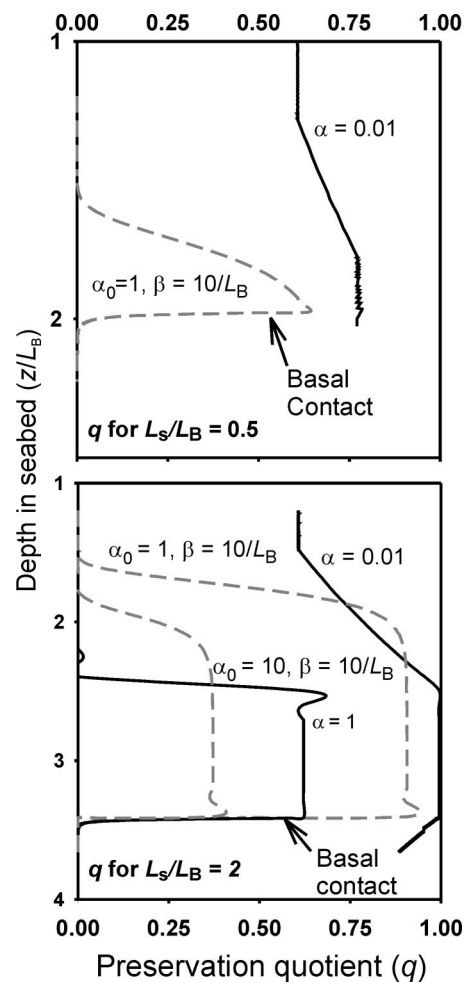
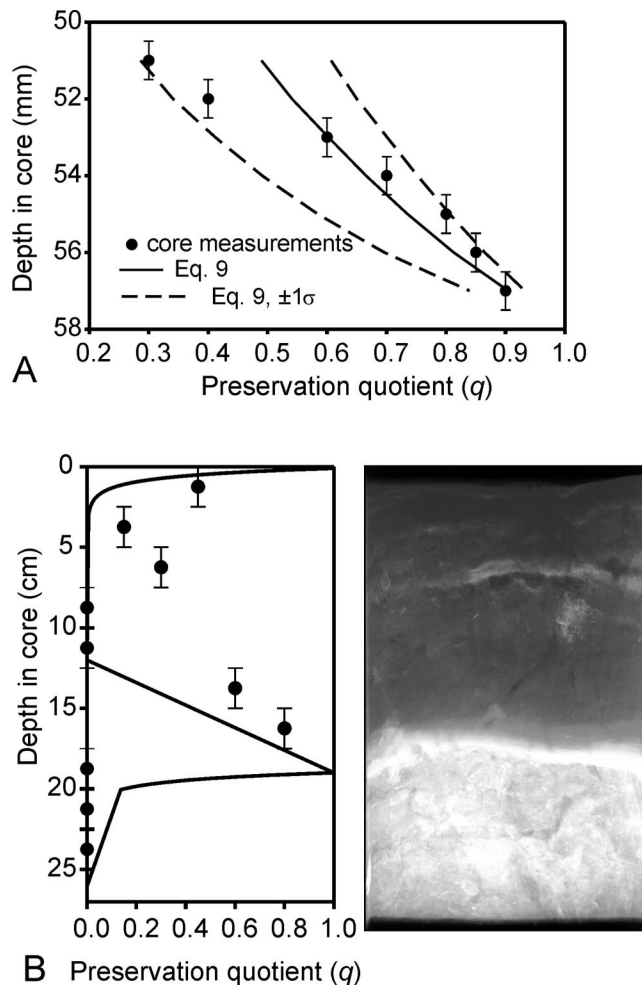


Figure 2. Depth distribution of q for constant and depth-dependent α and for L_S/L_B of 0.5 (top) and 2.0 (bottom). For $L_S/L_B = 0.5$, $\alpha_0 = 10$, and $\beta = 10/L_B$, $q < 0.05$ for all depths. These parameter values are typical for conditions found on muddy continental shelves. Note symmetrical q for constant α and sharp gradient in preservation near base of each event layer. See text for discussion.

cm^{-1} and $1 \leq \alpha[0] \leq 10 \text{ yr}^{-1}$) corresponds to a D_b range of 7–70 $\text{cm}^2\text{-yr}^{-1}$, typical for many marine settings (Boudreau, 1994).

Equation 11 implies that, at any given time, the fabric evolution (i.e., the value of q) is influenced by the ratio of $\alpha(z)/\omega(t)$, not just the absolute values of α or ω . This consideration expands our model's utility for the study of ancient settings, where variations in the ratio $\alpha(z)/\omega(t)$ can be important to fabric evolution, but absolute values of α or ω are difficult to estimate. For ancient deposits, estimates of L_S , L_B , and relative α could be derived from "frozen profiles" of trace fossils, produced by rapid deposition of event layers onto a colonized seafloor (e.g., Howard, 1975; Bromley, 1996, p. 284). Thus, this relationship between α and ω can be used to evaluate a range of scenarios that could produce observed fabric distributions.

Figure 3. Preservation quotient q from model calculations and sedimentary fabric analyses for two contrasting depositional settings. A: Eckernförde Bay, southwest Baltic Sea; all data are from Bentley and Nittrouer (1999). Pelletized layers in bay sediments are fair-weather deposits that are intensely bioturbated by resident fauna of small polychaetes. Winter storms deposit sediment layers thicker than bioturbation depth (~1 cm), resulting in preservation of basal parts of storm beds. Modeled q is calculated from transit times and bioturbation rates by using equation 9 (see text). Core observations are from point counts of fecal pellet density in petrographic thin sections, and transit times are estimated from radionuclide chronologies. **B:** Inner continental shelf, northern Gulf of Mexico; q is estimated from both core data (dots) and model results (solid line); X-ray radiograph of event bed is to right (adapted from Keen et al., 2003). Using equation 7 (see text) and depositional chronologies from Bentley et al. (2002), Keen et al. (2003) modeled preservation potential of event layer produced by Hurricane Camille in 1969 near Biloxi, Mississippi, and compared model results with estimates from X-ray radiographs of box cores. Stratified sandy base of event layer is clearly visible both in profile of q and X-ray radiograph. For both A and B, modeled and observed estimates of q are similar, although some minor features in core data are not accounted for by model.



Like α , the preservation quotient q is essentially a new term with no history in geologic literature. For ancient deposits, outcrop analysis of stratified and bioturbated fabric distributions would provide data for comparison with model results. Similarly, for modern sediments, analyses of X-ray radiographs for ratios of stratified versus mottled and/or burrowed sediment provide explicit values of q for model comparison (Bentley, 1998; Bentley and Nittrouer, 1999; Keen et al., 2003). Two example applications drawn from modern marine settings are illustrated in Figure 3. In each case, rates of bioturbation and sedimentation are estimated from radioisotope geochronology and known storm occurrences. Independent estimates of q in cores are drawn from fabric analysis of petrographic thin sections (Bentley and Nittrouer, 1999) and X-ray radiographs (Keen et al., 2003); such estimates are similar to modeled distributions (Fig. 3).

These examples and our present model do not account for the important influences of

erosion, consolidation, and lateral and temporal variability of sedimentary and biogenic processes. As such, it is only a first step toward a more comprehensive formulation. Yet the simple form of the model allows us to focus on fundamental interactions between bioturbation and sedimentation; thus we can quantitatively evaluate hypotheses of sedimentary fabric development that could previously be addressed only qualitatively.

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