Quantitative Chemical Mass Transfer in Coastal Sediments During Early Diagenesis

Dr. Samuel J. Bentley, Sr.
Coastal Studies Institute and Department of Oceanography and Coastal Sciences
Louisiana State University
Baton Rouge, LA 70803 USA
phone: (225) 578-2954 fax: (225) 578-2520 email: sjb@lsu.edu

Award Number: N00014-00-1-0768
http://busycon.csi.lsu.edu/bentley/

LONG-TERM GOALS

The objectives of this study are: to measure rates and depths over which macroinvertebrates in selected functional groups transport sediment and create sedimentary structure; and, to derive quantitative mechanistic models for these property distributions. These observations and models will be integrated into mass-transport modeling of dissolved and particulate materials in marine sediments developed under this program. This work is a collaborative effort among Dr. Samuel Bentley (Louisiana State University), Dr. Carla Koretsky (Western Michigan University) and Dr. Yoko Furukawa (Naval Research Laboratory), originally started in 1997 under ONR322GG funding. We will focus on the synthesis of results during this phase.

OBJECTIVES

The specific objectives are:

1. Sub-millimeter characterization of the dynamics of redox fluctuation in the immediate vicinity of burrows in laboratory mesocosms and field test sites.
2. Millimeter-scale characterization of the response of sedimentary microbial community to the redox dynamics.
3. Fabric characterization of sediment constituents (pores, minerals, microorganisms and organic matter) and their interactions.
4. Model development to bridge the static and dynamic biogeochemical and fabric data to the net chemical mass transfer.
5. Millimeter- to centimeter-scale characterization of sedimentary particle dynamics in laboratory mesocosms and field test sites.
6. Model development to mathematically describe the macrofaunally-induced particle dynamics.

APPROACH

This report primarily addresses work conducted toward Objectives 3, 5, and 6, listed above. Field and laboratory observations of bioturbation and resultant fabric have been incorporated into models that describe emplacement and evolution of sedimentary fabric as functions of interacting event-sedimentation and bioturbation.

Our studies have shown that the interaction of time-dependent sediment erosion and deposition with quasi-steady-state bioturbation is responsible for the heterogeneous sedimentary fabric typical of many shelf settings (e.g., Bentley et al., 2002; Keen et al., in press). Based on this reasoning, we proposed a model for the formation and evolution of sedimentary fabric based on a time-dependent adaptation of the advection-reaction equation, wherein advection represents sedimentation, and reaction represents bioturbation (Bentley and Sheremet, 2003). Conceptually, sediment deposited on the seabed initially possesses sedimentary fabric that is 100% physical in origin. Once an organism has "interacted" with physical fabric, whether by ingesting sediment or creating a burrow, that modified fabric becomes irreversibly biogenic (assuming no subsequent physical reworking, an admittedly flawed assumption). Thus, this model tracks the transformation of sedimentary fabric from physical to biogenic, rather than tracking sediment particles or a geochemical tracer. The relevant equations are:

$$\frac{\partial A}{\partial t} = -\left[\frac{\partial\, \omega(t) A}{\partial z}\right] - \left(\eta(z) A\right) \qquad \text{eq. 1}$$

Subject to the boundary conditions

$$z = 0, J(A,t) = \omega A$$

$$z = L_b, \frac{\partial A}{\partial z} = 0 \qquad \text{eqs. 2, 3}$$

where z = depth in sediment, ω = burial rate (cm y^{-1}), L_b = maximum depth of bioturbation, A = horizontal area (limit of volume as $dz \rightarrow 0$) characterized by primary physical sedimentary fabric, J is flux of new unbioturbated sediment, and the depth-dependent volumetric bioturbation rate η (y^{-1}, or $cm^3\ cm^{-3}\ y^{-1}$) is described by

$$\eta(z) = \eta_0 \exp(-\alpha z), \qquad \text{eq. 4}$$

where α is a depth-attenuation coefficient.

WORK COMPLETED

Our focus during this final year of funding has been on publishing the results of our efforts. Field and modeling studies of particle deposition and bioturbation in our northern Gulf of Mexico study areas have been presented in Bentley et al. (2002), Keen et al. (in press), and Velardo et al. (2003). These studies have documented the formation of coastal event layers due to hurricane-associated sedimentary processes, and the postdepositional modification of these layers due to bioturbation. In addition, event-layer development and bioturbation in the Eel Shelf/STRATAFORM study area were assessed in Bentley and Nittrouer (in press). Models for the evolution of sedimentary fabric, based on our field studies and equations 1-4 above, have been presented in Bentley and Sheremet (2003), and Keen et al. (in press). Results from these efforts are described below.

RESULTS

With an analytical solution for equations 1-4 above, Bentley and Sheremet (2003) 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 deposition. 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:

$$\omega(t) = \omega_0 + \omega_s(t), \quad \text{where} \quad \omega_s(t) = \begin{cases} 0 \ \ for\ t < -\Delta t \\ \Omega \ \ for\ -\Delta t \le t \le \Delta t \\ 0 \ \ for\ t > \Delta t. \end{cases} \qquad (5)$$

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 vs. time (equation 5), normalized to the half-duration of the depositional event divided by the thickness of the bioturbated zone. The specific example shown here represents bioturbation at a depth-constant rate, but a depth-variable solution has been published as well (Bentley and Sheremet, 2003). If bioturbation rate is independent of *z*, the final preservation state for a given sediment layer (the solution for *q* for $t \to \infty$) 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 5, the preservation quotient is

$$q = q_0 \exp(-\alpha t_R) . \qquad (6)$$

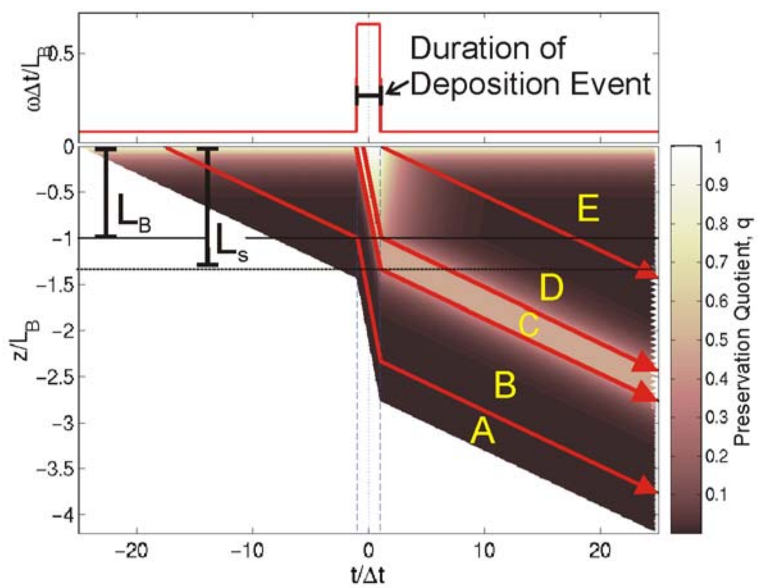

Figure 1. Preservation quotient distribution vs. normalized time and depth for depth-constant bioturbation (equation 6, α = 0.5). Deposition event is represented as a square pulse with maximum thickness $L_S = 1.2L_B$ and a ratio of event rate to background burial rate of $\omega_0/\Omega = 0.1$. Arrows represent trajectories. Regions I-V are described in text.

Figure 1 shows the corresponding distribution 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.

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.

IMPACT/APPLICATIONS

The continued development of RT models to incorporate biologically created temporal and spatial heterogeneity will allow us to:

(1) predict the course of sedimentary structure evolution for the purpose of sediment stability, acoustic, mine burial, and permeability modeling.
(2) predict the mobility and bioavailability of contaminants following pollution events, dredging, engineering projects, remediation projects, or normal sedimentation for the purpose of site evaluation and planning.
(3) determine the parameters necessary for the particle suspension component of the coastal water optics model (e.g., shear strength of bioturbated seabed and organic carbon content of fluid mud and suspended sediments; Keen and Stavn, 1999) for the streamlined interpretation of optical signals from coastal waters.

TRANSITIONS

Models describing burrow formation (or genesis of sediment heterogeneity) and particle mixing (including rates of change at the sediment-water interface) will have direct relevance to studies of object burial and remote sensing of the shallow seafloor. Preliminary models derived from this work are being used by the NRL-SSC Ocean Modeling Group to assess the preservation potential of fine-scale stratigraphy in the coastal ocean (Bentley et al., 2002; Keen et al., in press).

RELATED PROJECTS

This is a collaborative effort between Dr. Samuel Bentley (Louisiana State University), Dr. Carla Koretsky (Western Michigan University) and Dr. Yoko Furukawa (Naval Research Laboratory), originally started in 1997 under ONR322GG funding. Physical modeling efforts are also being coordinated with Dr. Tim Keen (NRL-SSC).

REFERENCES

Bentley, S.J., and Sheremet, A., A new model for the emplacement, bioturbation, and preservation of sedimentary strata. Geology 31: 725-728..

Keen, T., S. J. Bentley, C. A. Blain, and W. C. Vaughan. 2003. The generation and preservation of multiple hurricane beds in the northern Gulf of Mexico. Marine Geology [in press].
Keen, T. R. and R. H. Stavn. 1999. Developing a capability to forecast coastal ocean optics: Minerogenic scattering. 6th International Conference on Estuarine and Coastal Modeling, Proceedings, 178-193.
Velardo, B.M., and S.J. Bentley, Impacts of Tropical Systems on the Sedimentary Fabric of the Mississippi Sound. Gulf Coast Association of Geological Societies Transactions 53: 600-610.
Wheatcroft, R.A., 1990. Preservation potential of sedimentary event layers. Geology 18, 843-845.
Wheatcroft, R.A., and Borgeld, J.C., 2000, Oceanic flood deposits on the northern California shelf: large-scale distribution and small-scale physical properties. Continental Shelf Research 20: 2163-2190.
Wheatcroft, R.A. and D.E. Drake. 2003. Post-depositional alteration and preservation of sedimentary event layers on continental margins, I. The role of episodic sedimentation. Marine Geology 199, p. 123-137.

PUBLICATIONS

Bentley, S.J., and Sheremet, A., A new model for the emplacement, bioturbation, and preservation of sedimentary strata. Geology 31: 725-728.

Bentley, S.J., Y. Furukawa, and W. C. Vaughan. 2000. Record of Event Sedimentation in Mississippi Sound. 2000 *Transactions of the Gulf Coast Association of Geological Societies* **50**, 617-625.

Bentley, S.J., T. R. Keen, C. A. Blain, W. C. Vaughan, and J. Barnes. 2001. The Origin and Preservation of a Major Hurricane Event Bed in the Northern Gulf of Mexico: Hurricane Camille, 1969. *Marine Geology* 186: 423-446.

Bentley, S.J., and Nittrouer, C.A., 2003, Emplacement, modification, and preservation of event stratigraphy on a flood-dominated continental Shelf: Eel River Shelf, Northern California. Continental Shelf Research [in press].

Furukawa, Y., S.J. Bentley, A. Shiller, D. Lavoie, and P. Van Cappellen, 2000, Early diagenesis driven by biologically enhance oxygen flux in North Key Harbor, Dry Tortugas National Park, Florida. Journal of Marine Research 58: 493-522.

Furukawa, Y., S.J. Bentley, and D. Lavoie, 2001, Dynamic Bioirrigation Modeling in Experimental Benthic Mesocosms: Effects of Infauna Metabolism and Dissolved Oxygen Transport. Journal of Marine Research 59:3

Keen, T., S. J. Bentley, C. A. Blain, and W. C. Vaughan. 2003. The generation and preservation of multiple hurricane beds in the northern Gulf of Mexico. *Marine Geology*, in press.

Velardo, B.M., and S.J. Bentley, Impacts of Tropical Systems on the Sedimentary Fabric of the Mississippi Sound. Gulf Coast Association of Geological Societies Transactions 53: 600-610.

HONORS/AWARDS/PRIZES

Award to S. J. Bentley, Louisiana State University Award for Excellence in Teaching, May 2003.

Award to S. J. Bentley, 2003 James Lee Wilson Award from the Society for Sedimentary Geology in recognition of "Excellence in Sedimentary Geology by a Young Scientist."