Upscaling Simple Models for Energetic Shelf Sediment Transport

Carl T. Friedrichs
School of Marine Science, Virginia Institute of Marine Science
The College of William and Mary, Gloucester Point, VA 23062-1346
phone: (804) 684-7303 fax: (804) 684-7195 email: cfried@vims.edu

Award Number: N00014-03-1-0144
http://www.vims.edu/~cfried/Euro

LONG-TERM GOALS

In the context of STRATAFORM and EuroSTRATAFORM, the long-term goal of this project is to contribute toward simultaneously understanding (i) short term oceanic processes that erode, transport and deposit sediment in the margin system and (ii) the creation of the preserved stratigraphic architecture, seafloor morphology and sediment facies on continental margins. In order for models at such disparate time-scales to interact, they must communicate through expressions which upscale the underlying physical processes. Under Modeling Task D5, the EuroSTRATAFORM white paper specifically states: "Coherent techniques will be developed for upscaling individual processes/events into long-term stratigraphic-architecture and seascape-evolution models."

Another conclusion common to recent ONR Coastal Geosciences programs is recognition of the dominant role played by episodic, high energy events in driving both sediment transport and bed formation. During STRATAFORM, the majority of across-shelf sediment flux was found to be associated with a few major flood/storm events occurring over just one or two weeks every few years. In its section on modeling, the EuroSTRATAFORM white paper similarly states, "Of special concern will be important events of strata formation (e.g., debris flows, extreme floods) that are difficult to observe." Thus another long-term goal of this project is to specifically understand the role of energetic sediment transport in depositing sediment on margins and shaping morphology.

OBJECTIVES

Our Objective 1 is to upscale results of realistic turbulence closure models to produce simple analytical expressions for energetic sediment transport. A wave-resolving (i.e., very short time-step), one-dimensional (highly resolved in z) numerical model with advanced turbulence closure is being used to simulate energetic suspensions of both mud and sand. The numerical simulations are being used to extend our recently derived analytical expressions for fluid mud suspensions towards coarser sediment and reconcile expressions for highly energetic fluid mud and plane bed sand suspensions. For both mud and sand it is anticipated that strong damping of turbulence by stable stratification will play a critical role in determining the maximum possible sediment load for a given energy level.

Our Objective 2 is to, in turn, upscale analytical relations for energetic sediment transport to derive simple expressions for equilibrium shelf profiles and associated deposits. Initial results of upscaling wave-supported gravity flows indicate that the slope of resulting clinoforms increase with greater sediment supply and smaller wave height. For sandier environments, it is anticipated that onshore transport by wave asymmetry will balance offshore transport by gravity. Preliminary results of upscaling sand transport suggest that concave upward equilibrium shorefaces become steeper as wave height decreases, grain size increases or wave period increases. The above results of upscaling transport relations to derive shelf profiles are being compared to global data bases of shelf morphology and also to the output of other numerical models of margin evolution.

APPROACH

Objective 1: To provide guidance in upscaling realistic turbulence closure models under energetic sediment transport conditions, we are running numerical model simulations of sediment stratified bottom boundary layers using the 1-D General Ocean Turbulence Model (GOTM, Burchard, 2002). GOTM is an open source, FORTRAN-based, two-equation (k-epsilon) turbulence closure model which uses the most recent formulations for stability functions shown to perform well in the presence of strong thermohaline stratification. We are adding suspended sediment to this model and are investigating model behavior as one approaches the limit of critical sediment-induced stratification. We are systematically examining the parameter space of varying sediment settling velocity (w_s) from hindered settling in fluid mud ($w_s < 0.1$ mm/s) to sand ($w_s > 10$ mm/s) and the wave period of the bottom boundary layer from storm waves (order 10 s) to tides (order 10 hours). We are comparing these simulations to available field and laboratory data of very high concentration fluid mud layers within momentum deficit layers under waves (e.g., Eel shelf, Traykovski et al., 2000) and tides (e.g., Amazon shelf, Trowbridge and Kineke, 1994) and of critically stratified constant stress layers of sand under waves (e.g., Hanover Wave Flume, Dohmen-Janssen and Hanes, 2002) and of flocculated mud under tides (e.g., York River, Friedrichs et al., 2000).

Objective 2: To date, our upscaling of analytical solutions to morphodynamics relations for shelf profiles have been based on the following two relations (Wright et al., 2001; Scully et al., 2002):

$$\alpha\, g\, s\, C\, \rho_s^{-1} = c_d\, |u|\, u_g, \qquad Ri = g\, s\, C\, \rho_s^{-1}\, |u|^{-2} \qquad (1, 2)$$

In Eq. (1) and (2), α is the sine of the bed slope, g is the acceleration of gravity, ρ_s is the density of siliceous sediment and s is its submerged weight relative to sea water, C is the depth-integrated mass concentration of suspended sediment within the wave boundary layer, c_d is the bottom drag coefficient, and Ri is the gradient Richardson number. The key velocities associated with Eqs. (1,2) are the downslope velocity of the gravity current (u_g), the rms amplitude of wave orbital velocity (u_w) and the absolute amplitude of the instantaneous velocity, $|u| \approx (u_w^2 + u_g^2)^{1/2}$, all evaluated near the top of the wave boundary layer.

For wave-supported gravity flows on the Eel River shelf, Wright et al. (2001) and Scully et al. (2002) showed that observed transport and deposition rates could be explained by Eqs. (1) and (2) in combination with a feedback mechanism which maintains Ri in (2) near its critical value of $Ri_c = 1/4$. For $Ri < 1/4$, turbulence associated with intense shear instabilities suspends additional sediment, increasing C and Ri, while for $Ri > 1/4$, decreased generation of shear instabilities reduces turbulence and causes sediment to settle. Because the maximum sediment load is determined by the critical Richardson number, this approach for predicting sediment concentration is not dependent on detailed sediment or bed properties. Combining (1), (2) and the definition of |u| to eliminate |u| and solve for u_g and C then yields the following analytical solutions for the critically stratified case of $Ri = Ri_c$:

$$u_g = u_w\, (\alpha\, Ri_c\, c_d^{-1})\, \{1 - (\alpha\, Ri_c\, c_d^{-1})^2\}^{-1/2} \qquad (3)$$

$$C = Ri_c\, \rho_s\, u_w^{2}\, g^{-1}\, s^{-1}\, \{1 - (\alpha\, Ri_c\, c_d^{-1})^2\}^{-1}, \qquad (4)$$

Eqs. (3) and (4) indicate that across-shelf sediment flux due to wave-supported gravity flows (u_g C) increases with wave orbital velocity and bed slope.

WORK COMPLETED

In FY03 we continued the process of publishing our related work from the ONR STRATAFORM project (Wright et al., 2002; Friedrichs, 2003; Parsons et al., 2003; Scully et al., 2003). With respect to Objective 1, we successfully translated the GOTM model from FORTRAN into MatLab and completed initial numerical experiments into energetic, critically stratified bottom boundary layers (Scully and Friedrichs, 2003). With respect to Objective 2, we have successfully upscaled our analytical models to derive relations for the landward portion of equilibrium clinoforms and subaqueous deltas (Friedrichs and Wright, 2003a,b,c; Pratson et al., 2003).

RESULTS

Our latest results with respect to Objective 2 (Friedrichs and Wright, 2003a,b,c) apply the above relations to solve for the shape of the landward portion of a stable, sediment bypassing clinoform. The convex upward portion of a subaqueous delta or clinoform subject to wave-supported gravity flows will be at equilibrium if there are no across-shelf gradients in gravity driven flux and the available river sediment supply matches the capacity of wave-supported gravity flows to remove sediment. In other words, the equilibrium profile requires

$$u_g\, C = Q_r, \qquad (5)$$

where Q_r is the supply of riverine sediment per unit distance along-shelf. Applying linear wave theory,

$$u_w = \omega\, (H/2)\, (\sinh kh)^{-1}, \qquad (6)$$

where H is wave height, ω is radian frequency, h is water depth, and k is wave number given by the dispersion relation

$$k = \omega^2\, (g \tanh kh)^{-1}. \qquad (7)$$

Combining Eqs. (3) – (6) to eliminate u_g, C and u_w gives the following relation for equilibrium bathymetric slope:

$$\alpha\, \{1 - (\alpha\, Ri_c\, c_d^{-1})^2\}^{-3/2} = 8\, (\omega H)^{-3}\, (\sinh kh)^3\, Q_r\, s\, g\, c_d\, Ri_c^{-2}\, \rho_s^{-1}. \qquad (8)$$

Eq. (8) predicts that the slope of an equilibrium profile dominated by wave-supported gravity flows increases with greater water depth and sediment supply and decreases with increasing wave height and wave period (via k) (Figure 1a). Equilibrium slope increases with water depth to compensate for the effect of decreasing bottom orbital velocity. Slope increases with sediment supply simply because a greater slope is required transport a larger sediment supply offshore. Slope decreases with increased wave period because a greater period decreases the decay of u_w with depth. Finally, equilibrium slope decreases with increased wave height to compensate for the effect of greater u_w. Figure 1b displays equilibrium profiles predicted by our theory along with a comparison of the theory to the observed depths of clinoforms at STRATAFORM, EuroSTRATAFORM and other sites. The model offers a first-order explanation of the delta-front/shelf profiles that exist off the mouths of the Eel, Waiapu, Po, Rhone and Ganges Rivers (Friedrichs and Wright, 2003a).

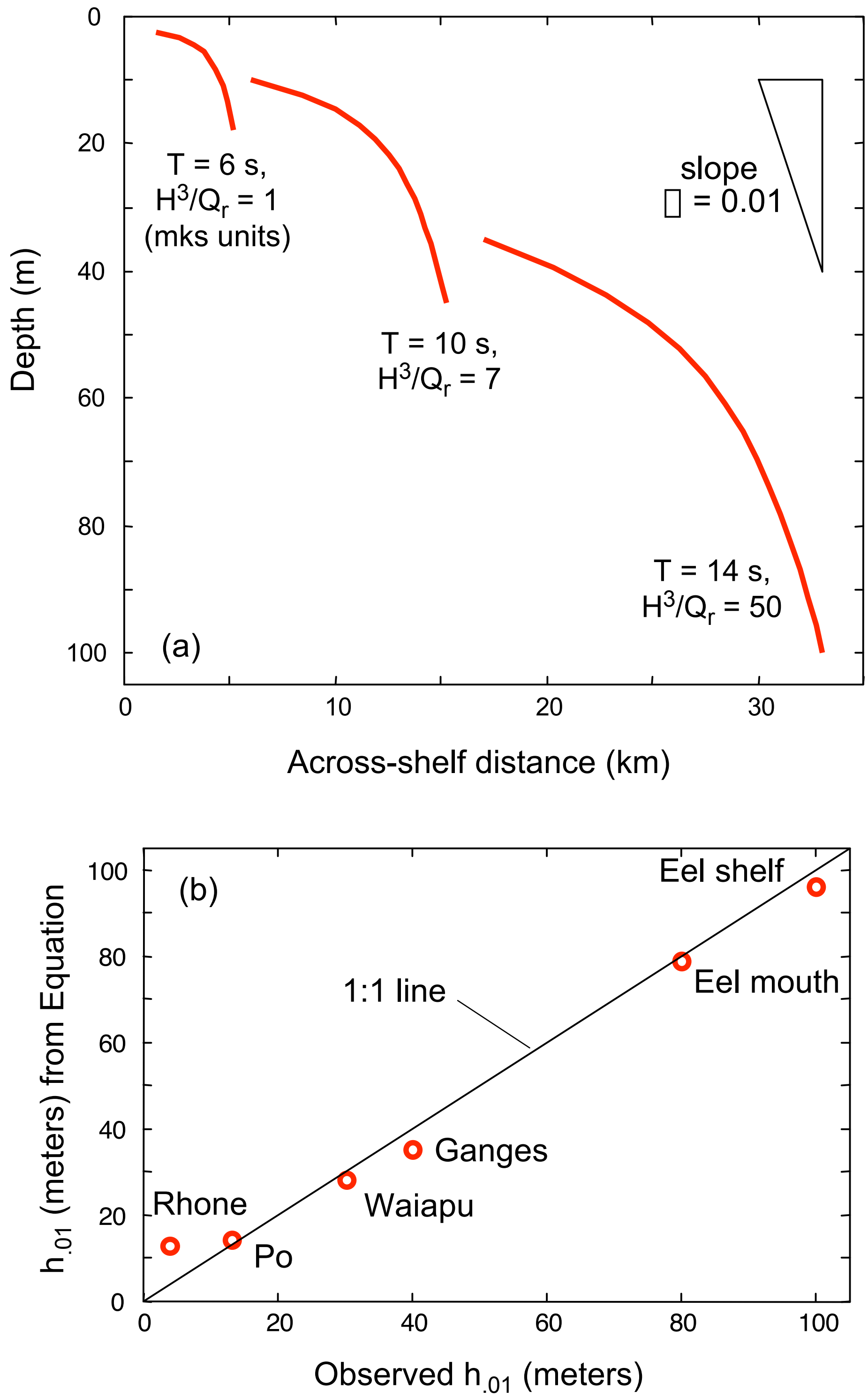

Figure 1. (a) Equilibrium concave-downward shelf profiles predicted by Eq. (8) (T is wave period). The deepest profile is similar to the Eel, the intermediate profile is similar to the Ganges-Brahmaputra and Waiapu, and the shallowest profile is similar to the Po and Rhone. (b) 1:1 line along with comparison of depths at which bathymetric profiles reach a slope of 0.01 ($h_{.01}$) as observed and as predicted by Eq. (8). From Friedrichs and Wright (in press).

Our results with respect to objective 1 are more preliminary. However, our initial implementation of the GOTM model has been encouraging. We have successfully translated the GOTM code from FORTRAN to MatLab and have begun numerical experiments including sediment induced stratification. Our initial results (Scully and Friedrichs, 2003) suggest that several distinct types of high energy, high concentration suspensions can be reproduced by the GOTM model with the key variables being sediment grain size and oscillatory hydrodynamic period. For cases where the settling time is long compared to the wave period, fluid muds develop up to a sharp lutocline at the top of the oscillatory boundary layer. This first scenario compares favorably to observations of hindered settling of fluid muds on the Amazon and Eel shelves. Where the settling time is short compared to the oscillatory period, a critically stratified constant stress layer results, where strong concentration gradients are present mainly near the bottom of the boundary layer. This second scenario compares favorably to observations of sandy sheet flow under waves in the nearshore and to suspensions of flocculated mud under tides in estuaries.

IMPACT/APPLICATIONS

A present limitation in long-term modeling of continental margin evolution is realistic inclusion of hydrodynamic processes driving shelf deposition. Based on field observations collected over the last 20 years, complex wave-averaged currents driven by winds and pressure gradients have been thought to be mainly responsible for cross-shelf sediment transport and flux convergence on energetic accretionary shelves. Unfortunately, it may be exceedingly difficult to predict wind- and pressure-driven near-bed currents with sufficient accuracy to produce realistic deposits over geological time-scales. The ONR STRATAFORM project, however, recently identified a distinctly different mechanism for across-shelf mud transport associated with gravity-driven flows of fluid mud within the wave boundary layer. Gravity flows within the WBL can be realistically modeled based on knowledge of fine sediment supply, approximate wave height and bathymetry if one assumes that the critical Richardson number within the WBL determines the maximum capacity of the gravity flow to transport mud. Complex, externally forced mean currents do not appear to play a critical role in this newly identified transport mechanism. Thus the analytical model presented here has the potential to greatly reduce the complexity and computational limitations presently limiting our ability to perform realistic long-term simulations of the geologic evolution of many continental margin environments.

TRANSITIONS

Our data on bed stresses and resulting sediment resuspension from earlier years of our STRATAFORM project have been made available to others and are being used to verify various bottom boundary layer and sediment transport models. Our data can easily be accessed via data reports (which include data summaries on diskettes) and via the VIMS STRATAFORM website: http://www.vims.edu/physical/projects/CHSD/projects/ONR/index.html. Published papers by others which have directly utilized VIMS data include Morehead and Syvitski (1999), Ogston et al. (1999, 2000), Reed et al. (1999) and Zhang et al. (1999). Additional papers by non-VIMS authors incorporating VIMS data are in preparation. Our analytical formulation for sediment flux and deposition by critically-stratified, gravity flows has already been incorporated into long-term simulations of margin stratigraphic development by James Syvitski's group (Syvitski et al., 2001, 2002). Our analytical approach has also been made available to other modelers, such as Fan, Harris, Niederoda, Reed, Swift, and Traykovski, all of whom are at various stages of incorporating gravity flows into more complex numerical simulations of shelf sedimentation.

RELATED PROJECTS

The following active projects involving Friedrichs also focus on coastal sediment transport:

1. Forecasting Scour Related Mine Burial Using a Parameterized Model. Office of Naval Research (www.vims.edu/physical/projects/CHSD/projects/MBP).

2. Sediment Dynamics of a Microtidal Partially-Mixed Estuary. National Science Foundation (www.vims.edu/physical/projects/CHSD/projects/CAREER).

REFERENCES

Burchard, H., 2002. Applied turbulence modelling in marine waters. Lecture Notes in Earth Sciences, Vol. 100, Springer, Berlin, 229 pp.

Dohmen-Hanssen, C.M., and D.M. Hanes, 2002. Sheet flow dynamics under monochromatic nonbreaking waves. Journal of Geophysical Research, 107 (C3): 13-1 – 13-21.

Friedrichs, C.T., 2003. Sediment effects. In: H. Baumert, J. Simpson, and J. Sündermann (eds.), Marine Turbulence: Theories, Observations and Models. Cambridge University Press, Cambridge, UK, in press.

Friedrichs, C.T., and L.D. Wright, 2003a. Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths. Coastal Engineering, in press.

Friedrichs, C.T., and L.D. Wright, 2003b. Analytical model for equilibrium shelf provides near river mouths. ONR Po and Apennine Sediment Transport Array (PASTA) Meeting, Woods Hole Oceanographic Institution, Woods Hole, MA, 25-26 July.

Friedrichs, C.T., and L.D. Wright, 2003c. Equilibrium subaqueous deltas associated with gravity driven sediment transport near river mouths. ONR EuroSTRATAFORM Annual Meeting, Aix-en-Provence, France, 26-29 October.

Friedrichs, C.T., L.D. Wright, D.A. Hepworth, and S.-C. Kim, 2000: Bottom boundary layer processes associated with fine sediment accumulation in coastal seas and bays. Continental Shelf Research, 20: 807-841.

Morehead, M.D., and J.P. Syvitski, 1999. River-plume sedimentation modeling for sequence stratigraphy: application to the Eel margin, northern California. Marine Geology, 154: 29-41.

Ogston, A.S. , D.A. Cacchione, R.W. Sternberg, and G.C. Kineke, 1999. Mechanisms of sediment dispersal and the influence of floods on the northern California continental shelf. Coastal Ocean Processes Symposium, a Tribute to William D. Grant, Technical Report WHOI-99-04, Woods Hole Oceanographic Institution, Woods Hole, MA, p. 171-174.

Ogston, A.S., D.A. Cacchione, R.W. Sternberg, and G.C. Kineke, 2000. Observations of storm and river flood-driven sediment transport on the northern California continental shelf. Continental Shelf Research, 20: 2141-2162.

Parsons, J.D., C.T. Friedrichs, P. Traykovski, D. Mohrig, J. Imran, J.P.M. Syvitski, G. Parker, P. Puig and M.H. Garcia, 2003. The mechanics of marine sediment gravity flows. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence, in review.

Pratson, L., P. Wiberg, M. Steckler, D. Cacchione, J. Karson, E. Mullenbach, J. Swenson, C. Nittrouer, B. Murray, G. Spinelli, C. Fulthorpe, D. O'Grady, G. Parker, N. Driscoll, R. Burger, C. Paola, D. Orange, M. Wolinsky, M. Field, C. Friedrichs, and J. Fildelez, 2003. Seascape evolution on clastic continental shelves. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence, in review.

Reed, C.W., A.W. Niedoroda, and D.J.P. Swift, 1999. Modeling sediment entrainment and transport processes limited by bed armoring. Marine Geology, 154: 143-154.

Scully, M.E., and C.T. Friedrichs, 2003. Numerical modeling of wave- and tide-supported, critically-stratified high energy suspensions using GOTM k-epsilon turbulence closure. ONR EuroSTRATAFORM Annual Meeting, Aix-en-Provence, France, 26-29 October.

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2002. Application of an analytical model of critically stratified gravity-driven sediment transport and deposition to observations from the Eel River continental shelf, northern California. Continental Shelf Research, 22: 1951-1974.

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2003. Numerical modeling results of gravity-driven sediment transport and deposition on an energetic continental shelf: Eel River, Northern California. Journal of Geophysical Research, 108 (C4): 17-1 – 17-14.

Syvitski, J.P.M., C. Friedrichs, P. Wiberg, and C. Reed, 2001. Representing Shelf Bottom Boundary Transport in 2D-SedFlux: Stratigraphic Formation on Continental Margins. Annual Conference of the International Association for Mathematical Geology, Cancun, Mexico, 6-12 September.

Syvitski, J.P.M, E.W.H. Hutton, C. Friedrichs, P. Wiberg and C. Reed, 2002. Coupled land-sea numerical sediment-transport models and the formation of shelf stratigraphy IAS/SEPM Environmental sedimentology Workshop on Continental Shelves, Hong Kong, 7-10 January.

Traykovski, P., W.R. Geyer, J.D. Irish, and J.F. Lynch, 2000. The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. Continental Shelf Research, 20: 2113-2140.

Trowbridge, J.H., and G.C. Kineke, 1994. Structure and dynamics of fluid muds on the Amazon continental shelf. Journal of Geophysical Research, 97: 865-874.

Wright, L.D., C.T. Friedrichs, S.C. Kim, and M.E. Scully, 2001. Effects of ambient currents and waves on gravity-driven sediment transport on continental shelves. Marine Geology, 175: 25-45.

Wright, L.D., C.T. Friedrichs, and M.E. Scully, 2002. Pulsational gravity-driven sediment transport on two energetic shelves. Continental Shelf Research, 22: 2443-2460.

Zhang, Y., D.J.P. Swift, S. Fan, A.W. Niedoroda, and C.W. Reed 1999. Two-dimensional numerical modeling of storm deposition on the northern California shelf. Marine Geology, 154: 155-167.

PUBLICATIONS

Friedrichs, C.T., 2003. Sediment effects. In: H. Baumert, J. Simpson, and J. Sündermann (eds.), Marine Turbulence: Theories, Observations and Models. Cambridge University Press, Cambridge, UK [in press, refereed].

Friedrichs, C.T., and L.D. Wright, 2003. Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths. Coastal Engineering [in press, refereed].

Friedrichs, C.T., L.D. Wright, D.A. Hepworth, and S.-C. Kim, 2000: Bottom boundary layer processes associated with fine sediment accumulation in coastal seas and bays. Continental Shelf Research, 20: 807-841 [published, refereed].

Kim, S.C., C.T. Friedrichs, J.P.-Y. Maa, and L.D. Wright, 2000. Estimating bottom stress in a tidal boundary layer from acoustic Doppler velocimeter data. ASCE Journal of Hydraulic Engineering, 126: 399-406 [published, refereed].

Parsons, J.D., C.T. Friedrichs, P. Traykovski, D. Mohrig, J. Imran, J.P.M. Syvitski, G. Parker, P. Puig and M.H. Garcia, 2003. The mechanics of marine sediment gravity flows. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence [submitted, refereed].

Pratson, L., P. Wiberg, M. Steckler, D. Cacchione, J. Karson, E. Mullenbach, J. Swenson, C. Nittrouer, B. Murray, G. Spinelli, C. Fulthorpe, D. O'Grady, G. Parker, N. Driscoll, R. Burger, C. Paola, D. Orange, M. Wolinsky, M. Field, C. Friedrichs, and J. Fildelez, 2003. Seascape evolution on clastic continental shelves. In: C.A. Nittrouer, J. Austin, M. Field, M. Steckler, J.P.M. Syvitski, and P. Wiberg (eds.), Continental Margin Sedimentation: Transport to Sequence [submitted, refereed].

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2002. Application of an analytical model of critically stratified gravity-driven sediment transport and deposition to observations from the Eel River continental shelf, northern California. Continental Shelf Research, 22: 1951-1974 [published, refereed].

Scully, M.E., C.T. Friedrichs, and L.D. Wright, 2003. Numerical modeling results of gravity-driven sediment transport and deposition on an energetic continental shelf: Eel River, Northern California. Journal of Geophysical Research, 108 (C4): 17-1 – 17-14 [published, refereed].

Wright, L.D., C.T. Friedrichs, S.C. Kim, and M.E. Scully, 2001. Effects of ambient currents and waves on gravity-driven sediment transport on continental shelves. Marine Geology, 175: 25-45 [published, refereed].

Wright, L.D., C.T. Friedrichs, and M.E. Scully, 2002. Pulsational gravity-driven sediment transport on two energetic shelves. Continental Shelf Research, 22: 2443-2460 [published, refereed].

Wright, L.D., S.-C. Kim, and C.T. Friedrichs, 1999. Across-shelf variations in bed roughness, bed stress and sediment transport on the northern California shelf. Marine Geology, 154: 99-115 [published, refereed].

HONORS/AWARDS/PRIZES

Friedrichs, C.T., 2000. Faculty Early Career Development (CAREER) Award. Awarded by the National Science Foundation (NSF). Description from NSF website: The CAREER Award is NSF's most prestigious award for new faculty members. The CAREER program recognizes and supports the early career-development activities of those teacher-scholars who are most likely to become the academic leaders of the 21st century.

Friedrichs, C.T., 2000. Presidential Early Career Award for Scientists and Engineers (PECASE). Awarded by President Clinton. Description from PECASE website: The PECASE Award is the highest honor bestowed by the United States government on young professional at the outset of their independent research careers. Eight Federal departments and agencies join together annually to nominate the most meritorious young scientist and engineers who will broadly advance the science and technology that will be of the greatest benefit to fulfilling the agencies' missions.

Friedrichs, C.T., 2001. Class of 1964 Distinguished Professorship. Awarded by the College of William and Mary. From William and Mary memo: Distinguished professorships for associate professors are designed to recognize and reward excellence in research or creative activity and a demonstrated commitment to teaching, and to encourage faculty to remain at the College. Recipients of these professorships will already enjoy a reputation for excellence in scholarship and teaching which suggests that they may be candidates for other distinguished professorships in the future.