

Experimental and Theoretical Study of Strata Formation in Sedimentary Basins

Chris Paola
St. Anthony Falls Laboratory
University of Minnesota
Minneapolis MN 55414
phone: (612) 624-8025 fax: (612) 624-4398 e-mail: cpaola@umn.edu

Juan Jose Fedele
St. Anthony Falls Laboratory
University of Minnesota
Minneapolis MN 55414
phone: (612) 624-4629 fax: (612) 624-4398 e-mail: fedel001@umn.edu

Grant Number N00014-04-1-0556

LONG TERM GOALS

The long-term goals of our stratigraphy project are to obtain experimental evidence and to develop quantitative models of the formation of strata on continental margins. Experiments and analytical models can greatly contribute to better understand the relationships between variation in forcing functions such as sediment supply, sea-level changes and subsidence, and the resulting strata in depositional basins. These relations will allow, in turn, for

- (1) inferring the history of external forcing from preserved strata (inversion problem) or
- (2) predicting the nature of preserved strata in areas where the forcing history is known.

OBJECTIVES

Our objective has been to develop analytical (or semi-analytical), large-scale, integrated stratigraphic models, i.e. models that use time-averaged versions of underlying transport equations, to predict the evolution of continental margins on geologic time scales. In this context, we have followed two approaches in our EuroSTRATAFORM research program:

- (1) to conduct experiments in our subsiding-floor experimental basin that can be used to test, inform, and refine stratigraphic models in general, and
- (2) to contribute to the development of large-scale coupled, moving-boundary stratigraphic models developed by other PIs (Steckler, Swenson).

Our overall experimental objective is to assemble a group of experimental data sets from which we can measure the response of margin systems to a range of combinations of forcing parameters (e.g. sea level, sediment supply). Our overall modeling objective is to develop physically-based models that can be used to predict stratigraphic geometry, including grain size and facies, in response to imposed variation in the main forcing variables (sea level, subsidence, and sediment supply). The stratigraphic models are oriented to fulfill two basic needs of the larger margin modeling efforts: first, by providing

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2005		2. REPORT TYPE		3. DATES COVERED 00-00-2005 to 00-00-2005	
4. TITLE AND SUBTITLE Experimental and Theoretical Study of Strata Formation in Sedimentary Basins				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Minnesota, St. Anthony Falls Laboratory, Minneapolis, MN, 55414				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
14. ABSTRACT The long-term goals of our stratigraphy project are to obtain experimental evidence and to develop quantitative models of the formation of strata on continental margins. Experiments and analytical models can greatly contribute to better understand the relationships between variation in forcing functions such as sediment supply, sea-level changes and subsidence, and the resulting strata in depositional basins. These relations will allow, in turn, for (1) inferring the history of external forcing from preserved strata (inversion problem) or (2) predicting the nature of preserved strata in areas where the forcing history is known.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			
			Same as Report (SAR)	9	

estimates of the quantity and size distribution material delivered to the shoreline, and secondly by modeling the development of incised valleys and other large-scale stratal surfaces that are buried under marine sediments during marine transgression. Our fluvial models are formulated with the idea that they should work alone, or as modules in more complex margin models developed in concert with other EuroSTRATAFORM investigators.

APPROACH

One of the main focus areas identified in the EuroSTRATAFORM planning document is the dynamic response of the continental margin to changes in sea level (task D4). Field studies are relevant to this, but it is practically impossible to observe in real time in the field the processes that control large-scale stratigraphic geometry. Our approach has been to use both laboratory experimentation and analytical/numerical modeling to help understand the controls on large-scale stratigraphic geometry. Controlled experiments provide well constrained data sets that can be used to test stratigraphic models and to understand first-order principles that we think are present within a wide range of scales. Conversely, physically-based analytical or numerical stratigraphic models provide general frameworks for understanding fundamental patterns or behaviors, and present the advantage that could be easily used for testing and predicting the outcomes of different combinations of hypothetical (but realistic) parameter scenarios and boundary conditions. The experimental work reported has been developed in our experimental basin (the EXperimental EarthScape or XES basin, known informally as "Jurassic Tank") equipped with a programmable subsiding floor [Paola *et al.*, 2001]. Our research efforts during the present year, however, have been focused mainly on the continuation of our ongoing work on theoretical models on the long term evolution of depositional fluvial basins (i.e both sediment sorting and alluvial architecture)

As mentioned, our modeling efforts are focused in formulating analytical, large-scale, integrated stratigraphic fluvial models based on fundamental physical processes: particularly channel-floodplain interaction and downstream sediment sorting. In our models we have included first-order processes in channel belts and distal floodplains, within a diffusion approach to describe the mean-surface dynamics [Paola *et al.*, 1992; Paola, 2000] (we assume that to a first-order approximation, sediment size and surface dynamics are decoupled). Our theoretical modeling is aimed at predicting the long-term laterally averaged fractions of channel-belt versus floodplain deposits, for different conditions of downstream sedimentation rates (subsidence). We have also improved a self-similar solution for the problem of channel sorting that we presented before by identifying two different scalings that are applied to the limiting cases of gravel or sand-bed rivers.

Our ongoing analytical modeling efforts are developed in close collaboration with other EuroSTRATAFORM PIs., principally Michael Steckler (SEQUENCE model), James Syvitski, and John Swenson (moving-boundary framework in shoreline/margin evolution models).

WORK COMPLETED

Experimental work: Our major experimental accomplishment so far has been to run an experiment on continental-margin stratigraphic response to sea-level changes. The experimental motivation, design and major results have been reported in the previous fiscal year.

Theoretical work: We have developed a heuristic formulation that can be used to predict the downstream variation of the laterally-averaged fractions of channel-belt versus floodplain deposits, for different subsidence patterns. The model scheme is based on three different time-scale ranges in

fluvial-basin evolution: (1) a short-time scale related to sediment transport and deposition within channels and channel-formation processes; (2) an intermediate-time scale associated with sedimentation and superelevation of channel-belts; and (3) a long time scale associated with the laterally averaged evolution of the basin as channel belts avulse across the basin. In the model, avulsions are ultimately a consequence of the interplay between the rate at which available space for deposition is created, and the differential rate of vertical accretion between channel belts and distal floodplains. We have presented in previous fiscal year report an expression that can be used for computing the average fractions of channel belt deposits at a given basin cross section but we found now that a better representation of these fractions is given by the following formula derived from the theory of random saturation bombing [Robins, 1944, 1945]:

$$F_c = 1 - (1 - \varepsilon)^N$$

F_c is the fraction of cross-section basin occupied by channel-belt deposits, ε is the ratio of channel-belt to basin width, and N is the average number of avulsions computed from (the full derivation of this was also given in a previous fiscal year report):

$$N = 5 \left(\frac{r_{cb}}{r_{df}} - 1 \right)$$

where r_{cb} and r_{fp} are sedimentation rates in channel belt and distal floodplain, known from the calculation of surface dynamics and from the general mass balance of sediment deposited in floodplains (mud). Since in the random cross-basin coverage by channel belts, the maximal coverage of channel belt deposits can be divided into expected fraction F_c and the expected overlap, this last can be used not only to estimate connectivity of sand bodies but also to approximate the amount of channel reworking (sand or mud) and the variation of sediment flux towards shore due to these effects. The algorithm that predicts the downstream variation of the cross-basin averaged fractions of channel deposits has been included into Steckler's SEQUENCE model and adapted to work for varying conditions of sea level and sediment-water input.

We have also presented previously an initial solution of the general problem of channel-driven downstream fining that assumes self-similar forms for the final substrate grain-size distribution, and that uses a mobility function that summarizes known effects of selective transport, for a given transport process (i.e. bedload or suspension). The solution was developed on the following assumptions:

- (1) observed tendency to maintain constant dimensionless shear stress within channels [Parker *et al.*, 1998],
- (2) size distribution of sediment supplied to a given reach (sorting cannot operate unless there is a range of sizes present), and
- (3) rate of sediment extraction by deposition (sorting by selective deposition cannot operate if there is no deposition). The governing equation is the Exner sediment mass balance for mixtures [Paola and Seal, 1995]. Two different scalings are proposed in the solution for the limiting cases of sand bed or gravel bed rivers, for which the empirically observed values of the Shields parameter differ by an order of magnitude within either the gravel (bedload only) or sand (mixed). The similarity variable for

gravels is $\xi = D - \bar{D}/\sigma_s$ whereas for sands is $\xi = D - \bar{D}/\bar{D}$, where $\bar{D}$ is the mean size and σ_s is the standard deviation of the local sediment size distribution in transport. This scaling allows for a variable coefficient of variation in the cases of sand bed rivers, whereas it also allows for a constant coefficient of variation in the cases of gravel bed rivers. These results agree well with empirical observations [Paola and Seal, 1995; Ferguson *et al.*, 1996].

Besides predicting the final substrate size distribution as a function of the similarity variable ξ , the model also gives analytical expressions for the downstream changes in the mean size and variance, as functions of deposition rates.

RESULTS

The basin model outlined above has been adapted and included in Mike Steckler's SEQUENCE model. Figure 1 shows results from a newer version of Steckler's SEQUENCE model that includes our fluvial sorting algorithms (only two grain sizes were considered for the calculations, sand and mud). Figure 1 shows SEQUENCE's predictions of the mud and sand distributions along the entire fluvial-continental margin system, for two different values of fluvial sediment input, for the same arbitrary cycle of the sea-level change.

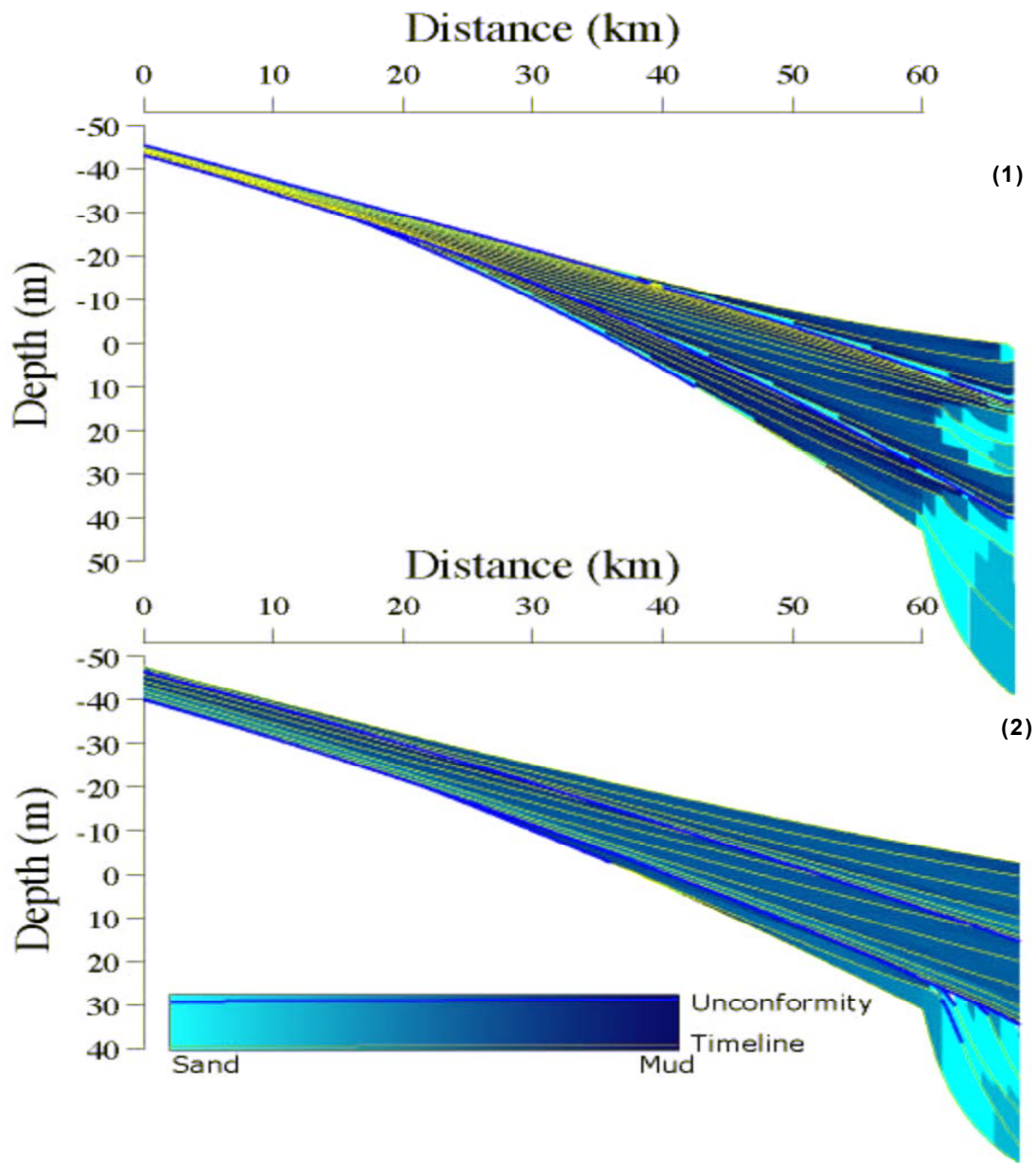


Figure 1: Predictions from Steckler's SEQUENCE model after including our algorithm for downstream variation of the cross-basin averaged fractions of channel deposits: (1) 0.25% alluvial supply, develops a coarse lag (sediment supply is low) and shows interesting changes in sand-mud composition, and (2) 0.95 % of alluvial supply, shows an overall sandier composition with upward fining.

Our similarity solution for the problem of channel-driven downstream fining has been tested by using detailed hydraulic numerical models, for the cases of gravel and sand [Parker *et al.*, 1982; Wright, 2003]. Figures 2 and 3 below illustrate a calculation example using our sorting model for the case of sand bed rivers. In this example, we investigated two basins of the same depositional length L , subject to two different tectonic patterns:

- (1) exponentially decreasing, and
- (2) linearly increasing (passive margin) rates of deposition.

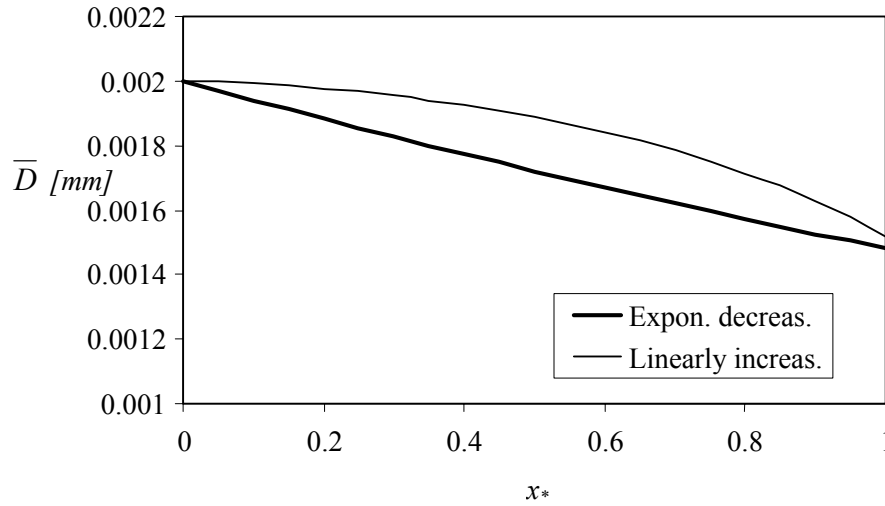


Figure 2: Downstream variation (x^* is a dimensionless distance obtained using a characteristic basin length L) of mean size of sediment in transport, computed using our self-similar solution, for the cases of exponentially decreasing and linearly increasing (passive margin) rates of deposition (sand bed river).

Figure 2 shows the variation of the mean size of material in transport for the two basins, obtained from our analytical expressions. As expected, Figure 2 indicates that fining is positively correlated with deposition rates (in the case of the passive margin, fining rates increase downstream). Figure 3 shows the final (cumulative) substrate size distributions computed using our analytical solution, for the two basins analyzed, and at two different dimensionless locations. Figure 3 indicates that, although the downstream-most distributions are similar for the two basins, intermediate locations show the strong effect on fining of the different sediment-mass distribution by deposition in each case.

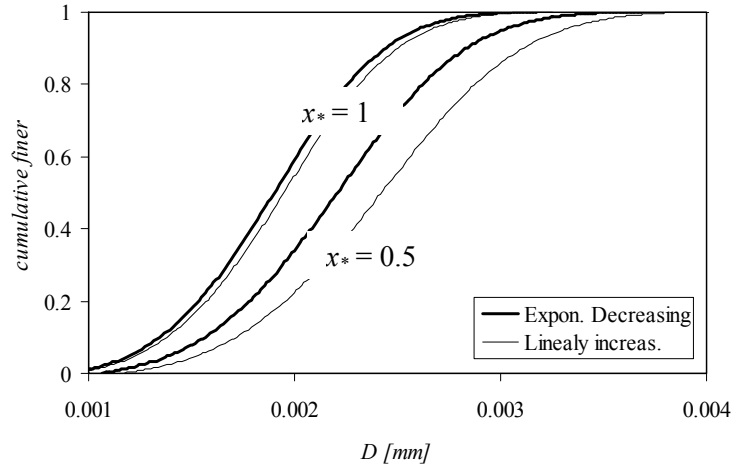


Figure 3: Final substrate (cumulative) size distribution computed using our analytical solution, at two different dimensionless locations, for the two basins analyzed.

IMPACT/APPLICATIONS

Our research will provide not only a means of testing stratigraphic models that can reproduce observed stratal columns but also a better understanding of the effects of controlling parameters and whether the parameter sets used to do this are actually correct. The XES experimental program should provide new insight and data on how processes average across time scales to produce stratigraphy. Our physically-based theoretical models that rely on first principles describing the interaction of channels and floodplains represent a first attempt to formally integrate mean-surface dynamics and the stratigraphic response to externally-forced mechanisms (i.e. subsidence or sediment and water supply).

TRANSITIONS

Data from the XES experiments has already been shared with EuroSTRATAFORM colleagues Lincoln Pratson, James Syvitski, and John Swenson. It will remain available to other colleagues on request as well. We are also continuing our collaborative modeling efforts with Mike Steckler, implementing the models in order to reproduce observed strata in the Adriatic continental margin along the Gargano Peninsula.

RELATED PROJECTS

Our EuroSTRATAFORM research is substantially leveraged in that it is performed within the framework of our NSF Science and Technology Center (STC), the National Center for Earth-surface Dynamics (NCED), headquartered at the St. Anthony Falls Laboratory, University of Minnesota. One of NCED's three research Integrated Projects, Subsurface Architecture, focuses on basin filling and depositional geometry and so complements our ONR work well. NCED support has paid the majority of the cost of the experiments on which our current model is based. Another related effort is our industrial consortium for experimental stratigraphy, which provides general support for XES work and has also supported a set of complementary experiments aimed at understanding the interaction of

linked variation in sea level and sediment supply. The results of this work will be incorporated in the next version of our current river-shoreline model.

REFERENCES

- Ferguson, R., T. Hoey, S. Wathen, and A. Werrity, Field evidence for rapid downstream fining of river gravels through selective transport, *Geology*, 24, 179-182, 1996.
- Paola, C., P.L. Heller and C.L. Angevine, The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory, *Basin Research*, 4, 73-90, 1992.
- Paola, C. and Seal, R., Grain size patchiness as a cause of selective deposition and downstream fining, *Water Resources Research*, 31 (5), 1395-1407, 1995.
- Paola, C., Quantitative models of sedimentary basin filling, *Sedimentology*, 47 (suppl. 1), 121-178, 2000.
- Paola, C., J. Mullin, C. Ellis, D.C. Mohrig, J.B. Swenson, G. Parker, T. Hickson, P.L. Heller, L. Pratson, J. Syvitski, B. Sheets, and N. Strong, Experimental stratigraphy, *GSA Today*, 11 (7), 4-9, 2001.
- Parker, G., P. Klingeman, and D. McLean, Bedload and size distribution in paved gravel-bed streams, *J. Hydraulic Div., ASCE*, 108, 544-571, 1982.
- Parker, G., Paola, C., Whipple, K.X. and Mohrig, D.C., Alluvial fans formed by channelized fluvial and sheet flow. I: theory, *Journal of Hydraulic Engineering*, 124(10), 985-995, 1998.
- Robins, H.E., On the measure of a random set, *Annals of Mathematical Statistics*, 15, 70-74, 1944.
- Robins, H.E., On the measure of a random set II, *Annals of Mathematical Statistics*, 16, 342-347, 1945.
- Wright, S., Modeling downstream fining in sand-bed rivers I, Formulation, and II, Application. Ph.D. Thesis, *University of Minnesota*, 2003.

PUBLICATIONS

- Pratson, L., Swenson J., Kettner A., Fedele J., Postma G., Niedoroda A., Friedrichs C., Syvitski J., Paola C., Steckler M. and Hutton E., Modeling the continental shelf formation in the Adriatic Sea and elsewhere, EuroSTRATAFORM special issue of *Oceanography*, Nittrouer and Syvitski, Editors, 2004.
- Fedele J. and Garcia M., Long-wavelength submarine bedforms created by gravity underflows. Part I: Conservative density currents, submitted to *J. Geophysical Research*, 2004, [under revision].
- Fedele J. and Garcia M., Long-wavelength submarine bedforms created by gravity underflows. Part II: Dilute turbidity currents, submitted to *J. Geophysical Research*, 2004, [under revision].
- Fedele J. and Paola C., A similarity solution for the problem of channel-driven sediment fining, submitted to *J. Geophysical Research* (2005) [submitted].