Community Sediment Model (CSM) Science Plan

Summary

The goal of the proposed meeting is to focus on the following tasks: (1) determine the time scales on which the CSM models will operate, and how models aimed at different time scales will be coupled; (2) map the environments and associated process sets for each time scale, and evaluate the state of knowledge for each of these; (3) decide on protocols for program architecture, languages, data structures, interfaces, and standards for process subroutines and modules; and (4) decide on the best strategy for making CSM results and computational methods available for education.

The CSM project is ambitious with models in three-dimensions, with allowance for simplification to two dimensions when appropriate. The models will couple suites of processes and environments to represent dispersal systems holistically. They will span time scales ranging from individual events (seconds to years) through geologic time (i.e. the life span of an orogen or sedimentary basin, tens to hundreds of millions of years). The models will address both basic science and applied problems such as risks associated with landslides and storm- and flood-related sedimentation (on the short-term end) and controls on geometry of commercial water and hydrocarbon reservoirs (on the long-term end). Nothing approaching the CSM project in scope or level of cross-disciplinary integration has ever been attempted in the sediment-dynamics community. Teams will work up short 'white papers' to collectively produce a science plan addressing the four basic issues listed above by the end of 2001.

Introduction and history of meeting

A group of earth system modelers have recently launched an international effort to develop a suite of modular numerical models able to simulate the evolution of landscapes and sedimentary basins, on time scales ranging from individual events to many millions of years. We term this program the Community Sedimentary Model (CSM). Ideas behind the CSM concept were discussed by participants of an international workshop, Numerical Experiments in Stratigraphy (University of Kansas, May 15-17, 1996), with formal presentation of these findings at the third annual conference of the International Association of Mathematical Geology (Barcelona, 1997: Syvitski, et al, 1997). The formal CSM idea, however, took shape at a panel convened by the Geology/Paleontology Program of NSF in March 1999. That panel identified a Community Sedimentary Model as a high priority NSF research initiative in sedimentary geology, and since then the concept has been widely discussed in the North American sediment-dynamics community.

The history behind a Community Sedimentary Model began in the mid-1960s, with a very interesting article (Bonham-Carter and Sutherland, 1967; also see Harbaugh and Bonham-Carter, 1970). Graeme Bonham-Carter coded up sediment transport equations related to a river's discharge into the ocean, to provide us with new insights into the formation of sedimentary deposits. The exercise was completed at a time when application of the Navier-Stokes equation to sediment transport remained in its infancy, and when we fed computer cards into memory poor, slow speed mainframes. Ten years later saw the first volume describing the full spectrum of numerical models related to ocean dynamics (Goldberg et al, 1977). The emphasis of these articles was on getting the dynamics correct and this resulted in some papers (e.g. Smith, 1977; Komar, 1977) being conceptually ahead of available field tools and data.

Through the next decade, as computers advanced with our ability to develop code, the soft-rock community applied its maturing understanding of hydraulics and sediment transport to the formation and modification of sedimentary deposits. In 1988, a large representation of this community met in the mountains of Colorado, and the concept of quantitative dynamic stratigraphy (QDS) was born (Cross, 1989). At the meeting, mechanistic view of QDS was contrasted with the more rapidly maturing rule-based (sometimes known as geometric-based) stratigraphic models (see Syvitski, 1989, for discussion). The need to understand local to regional boundary conditions, either over long periods of simulated time, or for conditions where we have little field data (i.e. extreme event modeling) went on to change the way sedimentologists conducted their field and numerical experiments.

Through the next decade, the QDS community and discipline grew and influenced the field of both sedimentology and stratigraphy (Agterberg and Bonham-Carter, 1989; Martinez and Harbaugh, 1993; Franseen et al., 1991; Harff et al., 1998; Harbaugh et al., 1999; Paola, 2000; Syvitski and Bahr, 2001). Now we approach a time when these marvelous individual efforts can be multiplied in their effectiveness if better coordinated, and openness is developed between the modelers and field-oriented geoscientists.

The earth system sediment models, like the established Community Climate Model or the Princeton Ocean Model, would be based on algorithms that mathematically describe the processes and conditions relevant to sediment transport and deposition, and would incorporate all the important input and boundary conditions that define a sedimentary system. The effort, to be coordinated and funded by government agencies and industry, would see sedimentary modelers determine the optimum algorithms, input parameters, feedback loops, and observations at the relevant scales necessary, to better predict sedimentary processes and ultimately to better provide an understanding of the earth system. The Community Sedimentary Model could then be applied to when the earth was abiotic, hotter or colder, when there was no flocculation, when the moon was closer, or the oceans were more saline. The model would be valuable to those working on modern environmental applications, future global warming scenarios, natural disaster mitigation efforts, natural hazard efforts, reservoir characterization, oil exploration, and national security. It could be argued that the new satellite databases and the large scale 3-D geophysical datasets can only realize their full potential in collaboration with a Community Sediment Model.

A focussed initiative in predictive sedimentary dynamics would help us:

- Improve assessment of risk from natural hazards such as landslides, mudflows, floods, and coastal storms
- Improve predictive capability at all scales of stratal architecture, and consequently improves our ability to explore and exploit energy and mineral source rocks and reservoirs
- Better manage natural scenic landscapes
- Understand the role of basin water storage and chemical processing in the hydrologic cycle
- Understand the role of sedimentary basins as incubators of the deep biosphere
- Understand the manner in which sedimentary basins and erosional landscapes control carbon and other elemental cycles
- Better interpret the record of global and regional climate change.

Meeting Justification
The time is right for this initiative for four reasons.

1) The manpower and skills are now available. Contemporary earth science departments are housing engineers, oceanographers, meteorologists, and hydrologists trained in computational science. Taken together the sedimentary community is more integrated, more quantitative, and more connected with the climate, hydrological and ocean communities then ever before. The community now has the necessary skills that are required to take their discipline to the next level.

2) A critical mass of basic algorithms describing sedimentary processes is now available. Advances over the last decade in understanding and quantifying sedimentary processes have led to first-order models of sedimentary processes in all the relevant sedimentary environments and to landscape evolution models capable of exporting sediment in response to prescribed initial and boundary conditions (Harbaugh et al., 1999; Howard, 1994; Paola, 2000; Rinaldo and Rodriguez-Iturbe, 1997; Slingerland et al., 1994).

Although each subsystem requires much additional work, and difficult scaling issues remain, for the first time their assembly could allow us to explore the complex behavior of the interconnected whole.

3) The community sees the need and has already begun to mobilize.

4) This approach maximizes community efforts through a sharing of knowledge and expertise.

Why a Community Model?
University researchers working together can produce a more reliable and more flexible simulation model than any single agency. The code is free, thus eliminating the endless rewriting of the same initial algorithms with concomitant more time spent on new advances. A Community Sedimentary Model architecture also creates honesty in what modelers claim and allows for faster verification and comparison of different approaches on new data sets. Communication is greatly increased among users and coders; a community is built. If a new component of the model is developed, and the identified community agrees on the substantive improvement, then the new component replaces the old component and a new version of the model is released. An integrated model will allow hypothesis testing, sensitivity experiments on key parameters, even the identification of new thrusts in the science. This effort has strong support from the petroleum industry whose own research labs have pioneered initial attempts.

To accomplish the development of a Community Sedimentary Model we need a national strategy that includes and rewards both individual initiatives and community focus. A suggested model would be to create a few national centers of excellence with nodes to the dispersed but linked community. Agencies like NSF should underwrite much of the effort, but not all. Industry together with the national labs should also participate with substantial support. The centers of excellence would need funded coders and numerical analysts, and participants would need on-going improvements in computer hardware.

A grass roots realization of the need for and the promise of, a Community Sedimentary Model has arisen in at least four sub-communities.

- A panel convened in March 1999, by the Geology/Paleontology Program of NSF identified a Community Sedimentary Model as a high priority NSF research initiative in sedimentary geology.

- The proposed science plan of the NSF-funded Source-to-Sink Program calls for "the progressive development of a community-level suite of earth surface dynamics models for mass routing, deposition, and morphodynamic prediction as a conceptual framework and as a central focus for the Source-to-Sink project" (MARGINS Science Plan, Source-to-Sink Studies). The NSF Source to Sink Margins Report states: " Numerical modeling will be an important component to many studies and the development of robust models may control the (*where*, *how and*) sequence of observations. In cases where models exist, they can help delineate the variable that must be measured... In the context of a large interdisciplinary effort special attention should be paid to designing tests and calibration of mathematical models".

- A workshop convened by the U. S. Geological Survey calls for the development of widely accepted sediment transport models. The report indicated the need for: "freely available code, state-of-the-art hydrodynamics and sediment algorithms with modern, modular coding, comprehensive documentation, and demonstrated performance on a suite of community-defined test cases". (Sherwood, C. R., Signell, R. P., and Harris, C. K., 2000, Report on Community Sediment Transport Modeling Workshop, Woods Hole, MA).

- The U.S. Office of Naval Research sponsored program called STRATAFORM (STRATA FORmation on Margins) demonstrates the Navy's needs and desires for a collaborative effort to develop an integrated predictive model for the shelf sedimentary system.

Numerical models that define the development of landscapes and sedimentary architecture are the repositories of our understanding of basic physics and thermodynamics underlying sedimentology. They force scientists to confront their knowledge level, and their pyramid of assumptions upon which they view the world. A Community Sedimentary Model would push scientists to confront nature in terms of:

- whether one process should be coupled or uncoupled with respect to another;
- whether a particular process is deterministic or stochastic
- levels of simplification (1D, 2D, 3D)
- whether analytical solutions have yet been formulated for a particular process
- whether processes can be scaled across time and space
- developing adequate databases on key parameters from field or laboratory measurements

An outline of the Community Sediment Model program

We stress that the purpose of the proposed meeting is to produce a framework design for the CSM, so here we present only a broad outline of some of its key aspects (e.g. Fig. 1):

1. The CSM will not be one model but rather a suite of closely related models. The fundamental reason a 'one size fits all' approach to modeling will not work is that the morphodynamic problems listed above require temporal and spatial resolutions that vary over many orders of magnitude. A summary model aimed at large-scale stratigraphic processes cannot resolve individual events and make detailed predictions about specific situations. On the other hand, although possible in principle, it is wasteful and clumsy to tackle relatively simple questions about system response on very long time scales by calculating the detailed evolution of thousands or millions of individual events. Moreover, the very nature of problems may change with time scale. For instance in the much better studied case of atmospheric dynamics, Mahlman (1998) points out that whereas weather prediction is an initial-value problem whose sensitivity to initial conditions prevents it from being solved indefinitely far into the future, modeling climate (the average weather, and in some ways analogous to morphodynamics on geologic time scales) is a boundary value problem that can in principle be solved exactly.

   At this point we expect a minimum of two modeling levels: a short-term, high-resolution (event-based) level something like the SEDSIM (Tetzlaff and Harbaugh, 1989) or SEDFLUX (Syvitski et al., 1998a; Syvitski et al., 1998b) models, and a long-term (averaged) level (Carey et al., 1999; Paola et al., 1992; Robinson and Slingerland, 1998; Steckler, 1999; Steckler et al., 1993; Swenson et al., 2001). Paola (2000) suggested that channel-dominated morphodynamic systems could be divided into three distinct dynamical levels, which might suggest a three-part modeling structure as well.

2. The CSM effort will stress integration of processes and environments. This philosophy embodies our belief that much of the complexity of natural systems reflects the interplay of environments dominated by different processes and connected by dynamic, moving boundaries. The linkages between these environments are strong enough that many important problems, both scientific and applied, cannot be solved without accounting for them. However, our emphasis on integration will not preclude work on individual sub-processes as part of the CSM effort. To keep the project focused, this work must be directed to sub-processes for which lack of understanding is a significant limiting factor in developing the integrated models. One of the goals of the proposed meeting is to carry out a systematic evaluation of the state of understanding of sediment transport processes and environments so that we can identify those areas for which detailed modeling is critical for the integrated effort (see Table 1.)

3. The dynamics of the Earth's surface involves a very wide range of processes, including (beyond sediment dynamics) aspects of hydrology, soil science, meteorology, oceanography, tectonics, macro and microbiology, and aqueous geochemistry. To keep the CSM effort within reasonable limits, we cannot address all these research areas at once. The initial emphasis will be on the main processes that build landscapes and the stratigraphic record: sediment production, fluvial erosion and deposition, mass flows, subaqueous waves and currents, turbidity currents, and biological and chemical sediment production (including carbonates, biogenic silica, and evaporites). The CSM effort will also include biological and chemical effects that directly influence sediment production and transport (e.g. stabilization of hillslopes by plants) but at least in its initial stages, stop short of work in which the biology or chemistry is the main focus (e.g. stream ecology or soil geochemistry). Tectonic processes obviously must be included, particularly at long time scales, since they provide crucial forcing and boundary conditions, but tectonics *per se* will not be the main focus of CSM. The same is true for post-depositional modification: for instance, at least the long-term CSM models must include compaction, because it is an important subsidence mechanism. To some extent this involves consideration of diagenetic processes but again these are secondary to the main CSM effort. With regard to all such potentially linked but secondary aspects of morphodynamic systems, we will support and encourage parallel efforts by other groups, and work to maintain awareness of such efforts (e.g. climate models, basinal fluid flow models) and insure that our model structures are as compatible as possible with existing models, and designed to make coupling to future models as easy as possible.

4. Education will be an important part of the CSM effort from the outset. This goes beyond the normal role of education as part of NSF's mission. We are aware of the extent to which the two main disciplines that will be affected by the CSM effort, geomorphology and sedimentary geology, have traditionally been two of the more descriptive areas of the Earth sciences. It is thus crucial that the CSM effort go beyond simply making our software and data products widely available and user-friendly, though we will certainly do this. The best ways to do this should be decided at the meeting by the community.

Table 1. The power of integration (from the NSF Source to Sink MARGINS report)

- landscape-evolution models should be able to predict fluvial discharge of sediment, including hyperpycnal events that could transport sediment to deep portions of the margin
- seascape-evolution models should be merged with landscape-evolution models to provide a holistic view of the Earth surface
- model development should go hand in hand with field data acquisition with mutual feedback to both
- models will be the storehouse of new knowledge regarding the fundamental advances in physics and theory, and thereafter translated to numerical schemes
- flow-routing models using climate information should predict hydrologic response in rivers and lead to stochastic models of sediment delivery to margins
- models should be able to investigate sediment transport events that fall outside of the observational record and would otherwise impact land and seascape morphology and sediment architecture

- integration across scales and environments will require partner ships between modelers and observations
- integration will require forward models, inverse one- and two-dimensional models, and models of margin sequences.

What the meeting will accomplish

All of us have now participated in discussions at various meetings on the CSM, and we are convinced that the concept has widespread support. Now it is time to flesh it out. The goal of the meeting is to convert a promising but fairly vague idea into a framework document that can form the basis of real proposals. To do this, we have to accomplish the following tasks:

(1) Determine how to partition the wide range of time scales on which the CSM models will operate, and how models aimed at different time scales will be coupled. Are there natural time breaks in sedimentary systems at which the systems make a transition from one behavioral mode to another? If so, what physics control them, and how do modeling strategies change from level to level? If there are no real breaks, then can we build model systems in which averaging windows can be varied smoothly from short to long?

(2) Map the main process sets for each time scale, and evaluate the state of knowledge for each of these. The main sedimentary environments do not change with time scale, but the important processes within them and the way the processes are handled do. For example, the continental shelf is one of the main central sedimentary environments. A short-term, event based shelf model might focus on resolving individual storms and the beds they produce, or on distributing sediment from a single river flood at a known location. An intermediate-term model might focus on things like long-term migration of large-scale bars and banks, fluctuations in carbonate production due to climate changes, and redistribution of sediment by avulsion of fluvial sources. A long-term model might average all of these processes and efficiently model large-scale changes in shelf topography due to sea-level variation and tectonics. In all three cases, we must identify the most important processes and take stock of the current state of understanding of each of them. Only after this is done can we realistically set priorities for developing CSM modules.

(3) Decide on protocols for program architecture, languages, data structures, interfaces, and standards for process subroutines and modules. We cannot develop a detailed blueprint for CSM models in a single workshop. We can, however, establish (with the help of colleagues with experience in collaborative modeling) a set of criteria for program design, and plan a smaller workshop focused on developing the detailed blueprint from this. We will address the following:

- *Strategy and tactics:* Should the CSM standard strictly specify things like object-oriented structure? What is the best way to supply a central CSM core into which user-supplied process modules can be plugged? Can the CSM be flexible enough to incorporate different modeling approaches (e.g. rule-based versus traditional deductive), or must we decide on this at the outset? For the traditional case, is it important to make specific tactical choices early, like requiring a particular discretization technique (e.g. finite element) or mesh style (e.g. deforming-grid)? What kind of program architecture will be best able to take full advantage of foreseeable advances in computer design (e.g. advances in parallel computing)?

- *Languages and module compatibility:* Is there any reason to prefer one of the major languages, and if not, how can we minimize compatibility problems when linking modules for specific sub-processses? What standards must be set for module interfaces?

- *Data structures:* To what extent must the CSM blueprint specify the detailed form of data structures (e.g. stratigraphic columns), and what form might these structures take?

- *User interface:* In outline form, what might the user interface look like? To what degree should the CSM blueprint specify details to achieve a consistent 'look and feel' for the interface?

- *Platforms:* What platforms should the various forms of CSM be designed to run on? Which, if any, forms will be simple enough to run on the web?

(4) Decide on the best strategy for making CSM results and computational methods available for education. As mentioned above, we are cognizant of enormous potential impact the CSM effort could and should have in education in geomorphology and sedimentary geology. After all, it will do us little good to develop a set of models that are revolutionary in their scope and power if our students cannot use them intelligently. To get the discussion going, we will propose the following:

- *Student versions of the programs:* These would use a 'workbench' style, and would be aimed more at ease of use and clear demonstration of basic effects than at simulating real complex systems. They would include exercises using the models, as well as a simplified framework that would allow students to code their own plug-in modules and see how they perform.

- *Documentation:* Using the web, we would provide documentation that not only explains how to use the software, but in effect forms a self-study course in modeling earth systems. The documentation would explain (at a minimum) how the software works, what physics are included, what the approximations are and why they were made, details of the algorithms, and how they are implemented numerically.

Meeting plans

Organizing Committee. The meeting will be organized by the three PIs of this proposal (Prof. James P. Syvitski, University of Colorado; Prof. Chris Paola, University of Minnesota, Prof. Rudy Slingerland, Penn State University. The organizers will be responsible for overseeing all aspects of the meeting and insure that a useable report is produced at the end of it. Funds are requested from NSF to provide some administrative help.

Venue. The headquarters of INSTAAR (University of Colorado).

Summary

This NSF-sponsored meeting will lay the groundwork to develop the numerical tools and analytical skills for integrating the knowledge being developed by both terrestrial and marine sediment communities. The meeting will help move the entire community into the next level of science.

References

Agterberg, F.P. and Bonham-Carter, G.F., editors, 1989. Statistical Applications in the Earth Sciences. Geological Survey of Canada Paper 89-9, 588 p.

Bonham-Carter, G.F. and Sutherland, A.J., 1967. Diffusion and settling of sediments at river mouths: A computer simulation model: Transactions of the Gulf Coast Association of Geological Societies, v. 17, p. 326-338.

Carey, J. S., Swift, D. J. P., Steckler, M., Reed, C. W., and Niedoroda, A., 1999, High resolution sequence stratigraphic modeling: effects of sedimentation processes, *in* Harbaugh, J., Watney, L., Rankey, G., Slingerland, R., Goldstein, R., and Franseen, E., eds., Numerical Experiments in Stratigraphy: SEPM, Memoir.

Cross, T.A. editor, 1989. Quantitative Dynamic Stratigraphy, Englewoods Cliff, NJ, Prentice Hall, 624 p.

Goldberg, E.D., McCave, I.N., O'Brien, J.J. and Steele, J.H. editors, 1977. The Sea, Volume 6, Marine Modeling. New York, Wiley Interscience.

Franseen, E.K., Watney, L.W., Kendall, C.G., and Ross, W., editors, 1991. Sedimentary Modeling: Computer simulations and methods for improved parameter definition. Kansas Geological Survey, Bulletin 233, 524 p.

Harbaugh, J.W., Whatney, L.W., Rankay, E., Slingerland, R., Goldstein, R., and Franseen, E. editors, 1999. Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and Computer Simulations. SEPM special publication. No. 62, 362 p.

Harff, J., Lemke, W., and Stattegger, K., editors, 1998. Computerized Modeling of Sedimentary Systems. Springer-Verlag, Berlin, 452 p.

Howard, A. D., 1994, A detachment-limited model of drainage basin evolution: Water Resources Research, v. 39, no. 7, p. 2261-2285.

Komar, P.D., 1977, Computer simulation of turbidity current flow and the study of deep -sea channels and fan sedimentation, in Goldberg, E.D., McCave, I.N., O'Brien, J.J., and Steele, J.H., eds., The Sea Volume 6, Marine Modeling: Wiley Interscience, New York, p. 603 - 621.

Mahlman, J. D., 1998, Science and nonscience concerning human-caused climate warming: Annual Review of Energy and the Environment, v. 23, p. 83-106.

Martinez, P.A. and Harbaugh, J.W., 1993. Simulating Nearshore Environments. Computer Methods in Geosciences v. 12, Pergamon Press, 265 p

Paola, C., 2000, Quantitative models of sedimentary basin filling: Sedimentology, v. 47 (suppl. 1), p. 121-178.

Paola, C., Heller, P. L., and Angevine, C. L., 1992, The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory: Basin Research, v. 4, p. 73-90.

Rinaldo, A., and Rodriguez-Iturbe, I., 1997, Fractal river basins: chance and self-organization: Cambridge, UK, Cambridge University Press, 547 p.

Robinson, R. A. J., and Slingerland, R. L., 1998, Origin of fluvial grain-size trends in a foreland basin: the Pocono Formation on the central Appalachian Basin: Journal of Sedimentary Research, v. 68, no. 3, p. 473-486.

Slingerland, R., Harbaugh, J. W., and Furlong, K., 1994, Simulating Clastic Sedimentary Basins, PTR Prentice Hall Sedimentary Geology Series: Englewood Cliffs, New Jersey, PTR Prentice Hall, 211 p.

Smith, J.D., 1977, Modeling of sediment transport on continental shelves, in Goldberg, E.D., McCave, I.N., O'Brien, J.J., and Steele, J.H., eds., The Sea Volume 6, Marine Modeling: Wiley Interscience, New York, p.539 - 577.

Steckler, M. S., 1999, High resolution sequence stratigraphic modeling: 1. The interplay of sedimentation, erosion and subsidence, *in* Harbaugh, J., Watney, L., Rankey, G., Slingerland, R., Goldstein, R., and Franseen, E., eds., Numerical Experiments in Stratigraphy: SEPM, Memoir.

Steckler, M. S., Reynolds, D. J., Coakley, B. J., Swift, B. A., and Jarrard, R., 1993, Modeling passive margin sequence stratigraphy, *in* Posamentier, H. W., Summerhayes, C. P., Haq, B. U., and Allen, G. P., eds., Sequence Stratigraphy and Facies Associations: International Association of Sedimentologists, Special Publication, p. 19-41.

Swenson, J. B., Voller, V. R., Paola, C., Parker, G., and Marr, J. G., 2001, Fluvio-deltaic sedimentation: A generalized Stefan problem: European Journal of Applied Mathematics, v. in press.

Syvitski, J.P.M., 1989. The process-response model in Quantitative Dynamic Stratigraphy. In: T.A. Cross (ed.) Quantitative Dynamic Stratigraphy. Prentice-Hall, N.Y., p. 309-334.

Syvitski, J.P.M., and Bahr, D.B., editors, 2001. Numerical Models of Marine Sediment Transport and Deposition. Computers and Geoscience Special Issue. (in press).

Syvitski, J. P. M., Morehead, M., and Nicholson, M., 1998a, **HydroTrend**: A climate-driven hydrologic-transport model for predicting discharge and sediment to lakes or oceans: Computers & Geosciences, v. 24, no. 1, p. 51-68.

Syvitski, J. P. M., Nicholson, M., Skene, K., and Morehead, M. D., 1998b, **Plume** 1.1: Deposition of sediment from a fluvial plume: Computers & Geosciences, v. 24, no. 2, p. 159-171.

Syvitski, J., Pratson, L., Perlmutter, M., de Boer, P., Parker, G., Garcia, M., Wiberg, P., Steckler, M., Swift, D., and Lee, H.J., 1997. **EarthWorks**: A large scale and complex numerical model to understand the flux and deposition of sediment over various time scales. In: V. Pawlowsky-Glahn (Editor) Proceedings of IAMG'97 The third annual conference of the International Association of Mathematical Geology. CIMNE-Barcelona, 1997, v. 3 p. 29-33.

Tetzlaff, D. M., and Harbaugh, J. W., 1989, Simulating Clastic Sedimentation, Computer Methods in the Geosciences: New York, Van Nostrand Reinhold, 196 p.