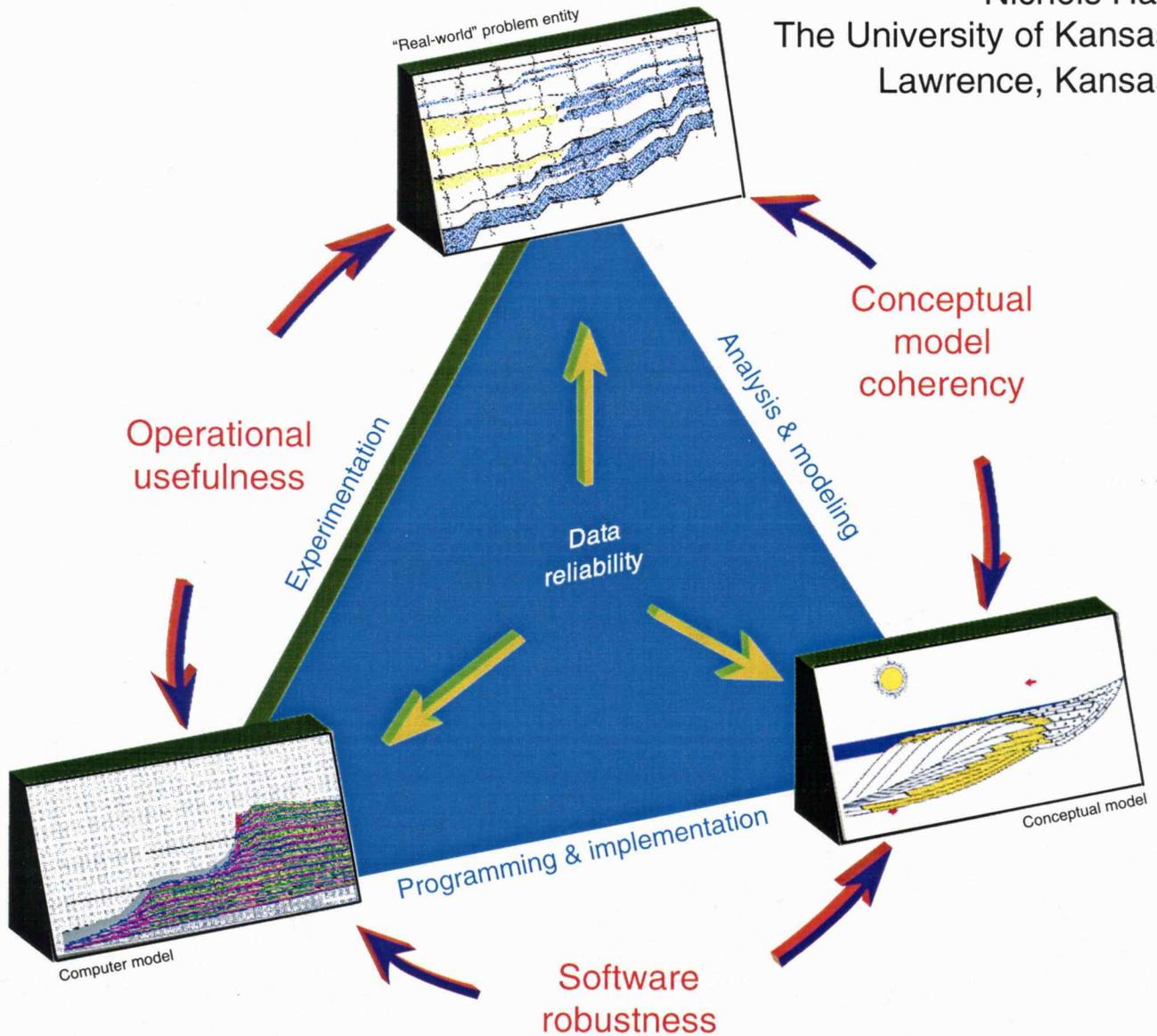


Numerical Experiments in Stratigraphy

An International Workshop



Nichols Hall
The University of Kansas
Lawrence, Kansas



Meeting Hosts

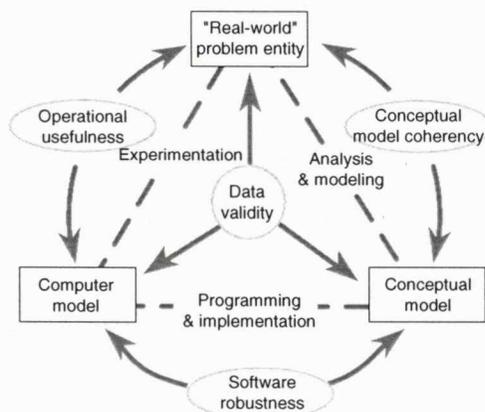
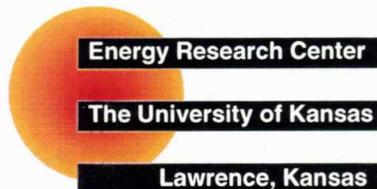
Kansas Geological Survey
Department of Geology
Energy Research Center
at The University of Kansas

Co-Conveners

W. Lynn Watney
Eugene C. Ranney
Evan K. Franseen
Robert H. Goldstein

15-17 May 1996

Numerical Experiments in Stratigraphy



Conveners

W. Lynn Watney
Eugene C. Rankey
Evan K. Franseen
Robert H. Goldstein

Steering Committee

S. Bowman, Marco Polo, Houston, Texas USA
T. Cross, Colorado School of Mines, Golden, Colorado USA
P. de Boer, University of Utrecht, Utrecht, The Netherlands
J. Harbaugh, Stanford University, Palo Alto, California USA
J. Harff, Baltic Marine Institute, Rostock-Warnemunde, Germany
W. Hay, GEOMAR, Kiel, Germany & University of Colorado, Boulder, Colorado USA
U. Nordlund, Uppsala University, Uppsala, Sweden
M. Perlmutter, Argonne National Laboratory, Chicago, Illinois USA
D. Tozloff, Western Atlas, Houston, Texas USA
J. Wendebourg, Institut Français du Pétrole, Rueil-Malmaison Cedex, France

Consultants For Modeling Datasets

Mike Steckler, Columbia University, Palisades, New York USA
Dave Waltham, University of London, Egham, Surrey, United Kingdom

Local Organizing Committee

R. Buddemeier, Kansas Geological Survey
T. Carr, Kansas Geological Survey
J. Doveton, Kansas Geological Survey
Paul Enos, KU Department of Geology
L. Gerhard, Kansas Geological Survey
D. Merriam, Kansas Geological Survey
A. Walton, KU Department of Geology

Topical Breakout Session Chairs

H. Bosscher, Shell International E&P, The Netherlands
S. Bowman, Marco Polo & Rice University, Houston, TX
P. L. deBoer, University of Utrecht, The Netherlands
P. Flemings, Pennsylvania State University, Univ. Park, PA
J. Harbaugh, Stanford University, Stanford, CA
I. Lerche, University of South Carolina, Columbia, SC
M. Lessenger, Colorado School of Mines, Golden, CO
M. Perlmutter, Argonne National Laboratory, Chicago, IL
M. Steckler, Lamont-Doherty Geological Observatory, NY
J. Syvitski, Arctic and Alpine Research Center, Boulder, CO

Credits for Cover Illustrations

Concept for diagram adapted from Sargent, R.G., 1987, An overview of verification and validation of simulation models: Proceedings, 1987 Winter Simulation Conference, Society of Computer Simulation.

"Real-world" problem identity and computer model from Watney, W.L., French, J.A., Doveton, J.H., Youle, J.C., and Guy, W.J., 1995, Cycle hierarchy and genetic stratigraphy of Middle and Upper Pennsylvanian strata in the upper midcontinent; *in*, Hyne, N.J., ed., Sequence Stratigraphy of the Midcontinent, Tulsa Geological Society, Special Publication No. 4, p. 141-192.

Conceptual model modified after Vail, P.R., 1987, Seismic stratigraphy interpretation using sequence stratigraphy, *in*, Bally, A.W., ed., Atlas of Seismic Stratigraphy: AAPG Studies in Geology No. 27, Vol. 1, Tulsa, p. 1-10.

Cover design by Jennifer Sims, Kansas Geological Survey

Table of Contents

	<u>Page</u>
I. Financial Support of the NES Workshop	1
II. Sponsors Supplying Computers for NES Workshop	1
III. Acknowledgments	2
IV. List of Participants, Addresses, and Titles of Papers	3
V. Agenda, Daily Schedule	7
VI. Topical Breakout Sessions	16
VII. Introduction to the NES Meeting, "Of The Making of Earth Science Models There is No End...."	17
VIII. NES Workshop Overview	35
IX. Overview of Model Comparisons, Baltimore Canyon & Mallorca	51
X. Abstracts	59

Financial Support of the NES Workshop

Generous corporate and institutional financial sponsorship is provided by the following companies. We appreciate their support.

ARCO E&P Technology

Mr. Mark Scheihing
2300 West Plano Parkway
Plano, Texas 75075-8427

Elf Aquitaine Production

Dr. Jean Christophe Navarre
Département de géologie sédimentaire
CSTJF avenue Larribau 64018
PAU cedex
France

Institut Français du Pétrole

Dr. Jean-Jacques Lacour
Communications Director
1 et 4, avenue de Bois-Préau
BP 311 - 92506 Rueil-Malmaison Cedex
France

KU International Studies

Prof. George Woodyard, Dean
The University of Kansas
Lawrence, Kansas

Kansas Geological Survey

Dr. Lee Gerhard, Director
The University of Kansas
1930 Constant Avenue - Campus West
Lawrence, Kansas 66047

Department of Geology

Dr. Anthony Walton, Chairman
The University of Kansas
Lindley Hall
Lawrence, Kansas 66045

Sponsors Supplying Computers for NES Workshop

Computers were loaned to us for this meeting from the following corporate sponsors at no cost.

Apple Computers
7100 College Boulevard
Overland Park, Kansas

MICROTECH Computers
4824 Quail Crest Place
Lawrence, KS 66049

Silicon Graphics
9393 West 110th St., Suite 533
Building Fifty-One
Overland Park, KS 66210

Sun Microsystems
6800 College Boulevard
Overland Park, Kansas

Acknowledgments

KU Astute Center - **Sue Nishikawa**, Director, contacts for computer equipment

KU Media Services -- projection equipment

Ian Rowell, Dept. of Geology, assistance with projectors and LCD panel

Center for Research, Inc. (CRINC) - **Barbara Armbrister**, Assoc. Director, for establishing workshop budget and invoicing/contracting

Computer Network, **Joe Ritt, Jr.**, Asst. Director, KGS, Technical Info. Services, **Pat Moore**, KGS, **Mike Neighbors**, KGS
Dana Adkins-Heljeson, KGS -- Web site manager, NES Home page, file translations and color printing, ftp site administration

Robert Sampson, KGS, Mathematical Geology Section, Unix machine setup

Melanie Cromwell, ERC -- meeting registration, housing, events manager

LeaAnn Davidson, KGS, Petroleum Research -- invitation mailings, formatting abstracts, production of abstract volume, support for breakout sessions

Logistical Support from Graduate Students --
event set up, audiovisual, posters, transportation

Scott Beatty, Geology/KGS, **Saibel Bhattacharya**, C&PE/KGS
Steve Franklin, Geology/KGS, **John Hopkins**, Geology/KGS

Tom Mettelle, manager, Digital Access Support Center (DASC)/KGS, access to cool color printer for abstracts volume

Nichols Hall staff - **Bob Walters**, Manager, coordination of workshop functions with his staff and access to building
Wes Ellison, Nichols Hall, computer network

Kathy Sheldon, KGS, vehicle support

Jennifer Sims, KGS, Publications & Public Affairs -- cover/graphics design/production

Student Housing Department, **Ken Stoner**, Director, providing a block of rooms in dormitory

Participants List

Numerical Experiments in Stratigraphy May 15-17, 1996, Lawrence, Kansas

Anderson, John, E., Mobil, US

Bez, Martine, Elf Aquitaine Production, France, with J.C. Navarre (see Navarre)

Bornholdt, Stefan, Institut fuer theoretische Physik, Kiel, Germany, with H. Westphal, "Optimization using genetic algorithms"

Boss, Stephen, North Carolina State University, US, "Empirical parameterization of an evolving carbonate cycle: The Holocene of Northern Great Bahama Bank"

Bosscher, Hemmo, and Mark Newall, Shell International Exploration and Production B.V., Research and Technical Services, The Netherlands, "Stratigraphic modelling in Shell - Examples and model comparison"

Bowman, Scott, Marco Polo Software, Inc., US, "PHILx stratigraphic simulators and PHLuxx hydrocarbon generation modeller: Using objects and relationships with nearest neighbors to model stratigraphy and fluid flow"

Buddemeier, Robert, Kansas Geological Survey, US, "CaCO₃ saturation state variations: Possible effects on coastal biogeomorphology and sediment budgets"

Coakley, Bernard, and Lincoln Pratson, Lamont-Doherty Geological Observatory, US, "A 'map view' model of turbidite transport and deposition"

Cowell, Peter, University of Sydney, Australia, "Simulation of coastal evolution using the shoreface translation model (STM)"

Cross, Tim, Colorado School of Mines, US (See M. Lessinger) (also see D. Edington)

Davis, John, Kansas Geological Survey, US

de Boer, Poppe L., University of Utrecht, Institute of Earth Sciences, The Netherlands (see Zijlstra)

den Bezemer, Taco, with H. Kooi, Y. Podladchikov, S. Cloetingh, Vrije Universiteit, The Netherlands, "Sediment facies associated with multiple thrust faults; Inferences from numerical modeling"

Doligez, Brigitte, with D. Granjeon, P. Joseph, R. Eschard, Institut Francais du Petrole, France, and H. Beucher, CG, "How can stratigraphic modeling help constrain geostatistical reservoir simulations?"

Edington, Dwaine, Colorado School of Mines, US, with T. Cross, "4D non-linear-dynamical fluvial modeling using deterministic equations and fuzzy logic"

Flemings, Peter, Pennsylvania State University, US, with Ruth Robinson, Andy Hoover, Roberta Hotinski, Steve Nelson, Chris Poulsen, and Glenn Spinelli, "Integrated approaches to advanced stratigraphy: Seismic interpretation and 'STRATA' modeling of the Neogene Baltimore Canyon Trough"

Flemings, Peter, with J. Carlson, "Transport and deposition of heterogeneous-sized sediment in a non-marine sedimentary basin"

Franseen, Evan, Kansas Geological Survey, US

Gerhard, Lee, Kansas Geological Survey, US

Gerlach, Paul, Kansas Geological Survey, US

Goldstein, Robert, University of Kansas, Department of Geology, US

Granjeon, Didier, Institut Francais du Petrole, France, with P. Joseph, "Concepts and applications on a 3D multilithological diffusive model"

Griffiths, Cedric, with Taizhong Duan and Andy Mitchell, University of Adelaide, Australia, "How to know when you get it right (formally and quantitatively)"

Harbaugh, John, Stanford University, US, "Stratigraphic modeling of cyclic and chaotic behavior on continental margins"

Harff, Jan, with W. Lemke, A. Mutzke, T. Seifert, and F. Tauber, Baltic Sea Research Institute, Rostock-Warnemünde, Germany, "Modeling of sediment distribution and currents in the Western Baltic Sea"

Haupt, B., Keil, Germany, with K. Statterger, "Data based modeling of the ocean-sediment system in large basins"

Holbrook, John, Southeast Missouri State University, US (see Ray)

Johnson, David, Exxon Production Research, US, "Modeling tectonic, climatic, and eustatic effects on orogen/foreland basin systems"

Joseph, Philippe, with D. Granjeon and M. Rabineau, Institut Francais du Petrole, France, "Estimation of modelling parameters from well logs and seismic data" (also see D. Granjeon)

Lerche, Ian, University of South Carolina, US, with E. Bagirov (senior author), "Probability and sensitivity analysis of 2D basin modeling results"

Lessenger, Margaret, Colorado School of Mines, US, with T. Cross, "CSM2D" model demonstration, "Construction and application of stratigraphic inverse models" and "Estimating accuracy and uncertainty of stratigraphic predictions from inverse numerical models"

Levine, Phillip, Mobil Technology Company, US

Lorenzetti, Elizabeth, Texaco, Exploration Production Technology, US

Matthews, Martin, Texaco, US, "Constraints on basin fluid flow modeling; combined sedimentary/structural models"

McCormick, David, Chevron Petroleum Technology Company, US

Merriam, Daniel, Kansas Geological Survey, US

Navarre, Jean-C., Elf Aquitaine Production, France, with M. Bez, "Accommodation: Sediment supply ratio (A/S) a key parameter for stratigraphic modeling"

Nordlund, Ulf, Uppsala University, Institute for Earth Sciences, Sweden, "FUZSIM, Replacing equations with common sense rules"

Paola, Christopher, University of Minnesota, US, "Experimental stratigraphy - bridging the gap between modern processes and long-term stratigraphic record"

Pelletier, Jon, Cornell University, US, with D. Turcotte, "Scale invariance in fluvial sedimentary basins"

Penn, Brian, University of Texas, El Paso, US, with John Harbaugh, "Phase plots, sedimentary cross sections, and bifurcation diagrams: Representing output from a dynamical sedimentary model"

Perlmutter, Martin, Argonne National Laboratory, US, with R. Plotnick, "The effect of the phase relationships of insolation, climate, sediment yield, and glacioeustatic cycles on stratigraphy"

Plotnick, Roy, University of Illinois at Chicago, US, "Ecological modeling in the context of stratigraphic modeling: Building the ecological stage"

Prather, Bradford, Shell International E&P, The Netherlands

Priddy, Gary, Texaco, Exploration Production Technology, US, "STRATSIM modeling"

Rankey, Eugene, University of Kansas, Department of Geology, US, "The roles of system-external and -internal mechanisms on lateral and vertical high-resolution stratigraphic predictability - A quantitative case study from the late Paleozoic, western U.S.A."; "Of the making of models there is no end..." -- an introduction to the NES Workshop (with Lynn Watney)

Ray, Timothy, with John Holbrook, Yuzhi Chi, and M. D. Raghunath, Southeast Missouri State University, US, "Stochastic modeling of Dakota Sandstone (Rocktown Channel Member) in central Kansas using architectural-element analysis"

Robinson, Ruth, Pennsylvania State University, US, with R. Slingerland, "Sediment transport in stratigraphic simulation models: getting it right"

Sampson, Robert, Kansas Geological Survey, US

Scheihing, Mark, ARCO E&P Technology, US

Slingerland Rudy, Pennsylvania State University, US (see R. Robinson)

Smart, Peter, University of Bristol, UK (see F. Whitaker)

Smith-Rouch, Linda, Mobil, US, "Testing different relative sea level curves on sedimentation in three basins using stratigraphic modeling: US Gulf of Mexico, Texas Offshore; Paradox Basin, SE Utah; and South Caspian Sea, Azerbaijan"

Statterger, Karl, University of Kiel, Geologish Palaeontolgy Inst., Germany (see B. Haupt)

Steckler, Mike, Lamont-Doherty Geological Observatory, US, "SEQUENCE - An interactive stratigraphic modeling tool"

Swift, Donald, Old Dominion University, US, with Y. Zhang, A. Niedoroda, C. Reed, J. Thorne, "Modeling facies with physics of sedimentation and building stratigraphy with the results: Toward an analytical theory of stratigraphy"

Syvitski, James, University of Colorado, Institute of Arctic and Alpine Research, US, "Predicting sediment delivery and stratigraphy on marginal slopes and shelf basins for the Navy"

Tetzlaff, Dan, Western Atlas Logging Services, Houston, US, with E. Rodriguez, "Probabilistic estimates from reservoir-scale sedimentation models"

Thorne, Julian, Chevron Petroleum Technology Company, US

van Balen, Ronald T., Vrije Universiteit, The Netherlands, "The effect of rift shoulder erosion on stratal patterns at rifted margin: Implications for sequence stratigraphy"

Walton, Anthony, University of Kansas, Department of Geology, US

Watney, Lynn, Kansas Geological Survey, US (with Gene Rankey), "Of the making of models there is no end..." -- an introduction to the NES Workshop; Model comparison summary; "KANMOD – A 2D carbonate modeling program demo" (with John French)

Weltje, Gert Jan, University of Utrecht, Institute for Earth Science, The Netherlands, "Controls on sediment provenance and dispersal from compositional data: Inverse modeling strategies for improved parameter estimation"

Wendebourg, Johannes, Institut Francais du Petrole, France, "Use of sedimentary process simulation in reservoir characterization"

Westphal, Hildegard, GEOMAR, Research Center for Marine Geosciences, Kiel, Germany, with S. Bornholdt, "Optimization using genetic algorithms"

Whitaker, Fiona, with Peter Smart, Department of Geography, University of Bistol, Bristol BS8 1SS, England, and Yvette Hague, David Waltham, and Daniel Bosence, Department of Geology, Royal Holloway University of London, Egham, Surrey TW20 OEX, England, "Development of a coupled 2-dimensional sedimentological-diagenetic model of carbonate platform evolution"

Wold, Christopher, National Center for Atmospheric Research, US, "Evaporite and bauxite proxy formation models forced by a global climate model"

Zhang, Yong, Old Dominion University, US, with D. Swift, A. Niedoroda, C. Reed, "Modeling event stratigraphy on the continental margin"

Zijlstra, J.J.P., University of Utrecht, Institute of Earth Sciences, The Netherlands, with P. de Boer, "Simulation of the genesis of wavy-bedded tempestite cycles in chalk"

DAY 1, Wednesday, May 15, 1996

NES Workshop, Lawrence, Kansas
Apollo Room, Nichols Hall, West Campus
The University of Kansas

Please note:

Item 1. For those who have indicated that they need a ride back to Kansas City Airport or vicinity on Friday afternoon, please confirm your schedule and destination at the NES information table with Melanie Cromwell. Also please check van schedule on Friday.

Item 2. Lunch is on your own. We will lead a group to the Burge Union located about 1/2 mile (0.8 km) east of Nichols Hall (see campus map). They serve relatively fast, inexpensive meals and have plenty of seating. They also have a campus bookstore. If you are driving a car, your parking passes will work in the yellow parking lot next to the union.

Item 3. Tonight's dinner will be a catered barbecue (Bum Steer Catering). It will be served on the south side of Nichols Hall outside of the atrium. This will permit you to stay and enjoy the posters and computer demonstrations.

Item 4. Men who were staying in Templin Hall Tuesday night must check out and move over to Lewis hall (across the street) by midnight tonight.

Item 5. If you have any questions or needs, please check with a convener or Melanie Cromwell at the NES information table located in the atrium of Nichols Hall.

Model Comparisons Oral Presentations

(Two 35-mm Kodak slide carousels and an overhead projector will be provided. Please load your 35-mm slides in slide trays located in the projection room before your early morning, late morning (after break), or afternoon session begins. Extra slide trays will be available. Also a color overhead LCD-SVGA tablet will be available for projecting computer output from Mac or pc. A Pentium desktop unit will have an X-window client linked to the workstations.)

Note the slightly modified schedule and that some of the presentations on first day have been shortened to 25 minutes.)

AM (Morning Session)

- | | |
|-----------|---|
| 8:00-8:10 | Welcome, Lee Gerhard, Director, Kansas Geological Survey, and Anthony Walton, Chairman, Department of Geology, The University of Kansas |
| 8:10-8:40 | L. Watney & E. Rankey, "Of the making of models there is no end..." -- an introduction to the NES Workshop and Model comparison summary |
| 8:40-8:50 | P. Smart, "Introduction to the Mallorca dataset" |

- 8:50-9:30 **M. Steckler**, "Introduction to Baltimore Canyon area & SEQUENCE - An interactive stratigraphic modeling tool"
- 9:30-10:00 **D. Granjeon & P. Joseph**, "Concepts and applications of the 3D multilithological diffusion model - Dionisos"
- 10:00-10:30 *BREAK*
- 10:30-10:55 **H. Bosscher and M. Newall**, "Stratigraphic modelling in Shell - examples and model comparison"
- 10:55-11:20 **S. Bowman**, "PHILx Stratigraphic Simulators and PHLuxx Hydrocarbon Generation Modeller: Using objects and relationships with nearest neighbors to model stratigraphy and fluid flow"
- 11:20-11:45 **P. Flemings**, with **S. Nelson, C. Poulsen, and G. Spinelli**, "Integrated approaches to advanced stratigraphy: Seismic interpretation and "STRATA" modeling of the Neogene Baltimore Canyon Trough"
- 11:45-12:10 **J. Wendebourg**, "Use of sedimentary process simulation in reservoir characterization"
- conveners: five-minute summary of posters
- 12:15-1:30 *LUNCH* (You can ride in a van over to the Burge Union cafeteria, if you like. They have a soup and salad line and a line for hot entrees.)

PM (Afternoon session). Wednesday, May 15, 1996

- 1:45-2:10 **D. Tetzlaff & E. Rodriguez**, "Probabilistic estimates from reservoir-scale sedimentation models"
- 2:10-2:35 **U. Nordlund**, "FUZSIM, Replacing equations with common sense rules"
- 2:35-3:00 **C. Griffiths**, "How do you know when you get it right?"
- 3:00-6:00 breakout sessions+posters
- 6:00-7:00 catered BBQ at Nichols Hall
- 6:00-9:00 computer demonstrations/posters

Posters, Wednesday, May 15, 1996

(Posters for Wednesday session can be set up anytime in the assigned areas in the atrium at Nichols Hall located outside of the Apollo Room. A map of assigned locations will be provided. Posters can remain up through the meeting. Please contact NES information table, if you need additional supplies. Please plan to be around the poster in the evening.

- T. den Bezemer, H. Kooi, Y. Podladchikov, and S. Cloetingh**
"Sediment facies associated with multiple thrust faults; Inferences from numerical modeling"
- B. Coakley**
"A 'map-view' model of turbidite transport and deposition"
- P. Cowell (also computer demonstration)**
"Simulation of coastal evolution using shoreface translation model (STM)"
- B. Doligez, D. Granjeon, P. Joseph, R. Eschard**
"How can stratigraphic modeling help constrain geostatistical reservoir simulations?"
- D. Johnson**
"Modeling tectonic, climatic, and eustatic effects on orogen/foreland basin systems"
- M. Matthews**
"Constraints on basin fluid flow modeling - combined sedimentologic/stratigraphic models"
- J.-C. Navarre, M. Bez**
"Accommodation: Sediment supply ratio (A/S) a key parameter for stratigraphic modeling"
- J. Pelletier and D. Turcotte**
"Scale invariance in fluvial sedimentary basins"
- G. Priddy, "STRATSIM" -- computer demonstration**
- T. Ray, J. Holbrook, C. Yuzhi, and M. D. Raghunath**
"Stochastic modeling of Dakota Sandstone (Rocktown Channel Member) in central Kansas using architectural-element analysis"
- L. Smith-Rouch**
"Testing different relative sea level curves on sedimentation in three basins using stratigraphic modeling: US Gulf of Mexico, Texas Offshore; Paradox Basin, SE Utah; and South Caspian Sea, Azerbaijan"
- J.J.P. Zijistra and P.L. de Boer**
"Simulation of the genesis of wavy-bedded tempestite cycles in chalk"
- J. Thorne**
"Numerical simulation of clastic stratigraphy: A regime approach to canyon formation and sediment gravity flow deposition" (work performed at ARCO during 1985-1989; currently with Chevron Petroleum Technology Company, US)

Computer Demonstrations (Wednesday and Thursday)

(Note: Computers and network will be installed on Monday and Tuesday, May 13 and 14 in the Apollo Room at Nichols Hall and hallways leading into auditorium. Someone will be available to assist you in setting up your computer on Tuesday afternoon. A floor plan shows assigned locations. Computer demonstrations will run Wednesday and Thursday. Silicon Graphics computers will be disassembled on early Friday morning before session begins. Other computers will be taken down except for a Pentium during the noon hour on Friday.)

Macintosh

M. Lessinger & T. Cross, CSM2D, Power Mac (own)

D. Edington & T. Cross, 4D nonlinear-dynamical fluvial modeling, Power Mac (own)

U. Nordlund, FUZSIM, Power Mac (own)

Pentiums

P. Cowell, STM - Shoreface Transition Model, Pentium (desktop #1)

J.J.P. Zijlstra and P.L. de Boer, Simulation of tempestite cycles, Pentium (desktop #2)

B. Haupt & K. Statterger, SEDLOB, PATLOB, Pentium (desktop #3)

J. French and L. Watney, KANMOD, Pentium laptop (own)
SEDPACK, Sun Sparc (x-term back to KGS Sparc10 on laptop of French/Watney)

Silicon Graphics

P. D. Granjeon and P. Joseph, IFP modeling, DIONISOS, loaded SGI (unit #1)

G. Priddy, Texaco, STRATSIM, SGI (unit #2)
Dan Tetzlaff, Western Atlas

S. Bowman, PHIL, share use of Silicon Graphics unit #2; also utilize X-windows client to SGI on a Pentium desktop

Sun Microsystems

F. Whitaker, Peter Smart, Y. Hague, D. Waltham, and D. Bosence, Coupled 2-dimensional sedimentological-diagenetic model of carbonate platform evolution, Sun Sparc 10 (unit #1)

D. Waltham & P. Smart, CARBPLAT, Sun Sparc (on machine with Whitaker)

P. Flemings, STRATA, SunSparc 10 (unit #2)

Day 2, Thursday, May 16, 1996

NES Workshop, Lawrence, Kansas

Please note:

Item 1. For those who have indicated that they need a ride back to Kansas City Airport or vicinity on Friday afternoon, please confirm your schedule and destination at the NES information table with Melanie Cromwell. Also please check van schedule on Friday.

Item 2. Lunch is on your own. We will lead a group to the Burge Union located about 1/2 mile (0.8 km) east of Nichols Hall (see campus map). They serve relatively fast, inexpensive meals and have plenty of seating. They also have a campus bookstore. If you are driving a car, your parking passes are valid in the yellow parking lot next to the union.

*Item 3. **Tonight** is the banquet at the Adams Alumni Center. The standard attire is a sport coat. We will serve a light snack in the atrium beginning at 5pm so that you can stay and a bus will depart at 7pm from the Nichols Hall parking lot for the Adams Alumni Center. The double-decker bus will make a short stop by Lewis Hall dorm to pick up people. The bus will depart the Adams Alumni Center at 9:30 pm making stops at Lewis Hall and Nichols Hall.*

Novel Outcomes

Oral Presentations

(Two 35-mm Kodak slide carousels and an overhead projector will be provided. Please load your 35-mm slides in slide trays located in the projection room before your early morning, late morning (after break), or afternoon session begins. Extra slide trays will be available. Also a color overhead LCD-SVGA tablet will be available for projecting computer output from Mac or pc. A Pentium desktop unit have an X-window client linked to the workstations.)

AM (Morning Session)

- | | |
|-------------|---|
| 8:00-9:00 | Topical Breakout Session Chairs -- statements from breakout sessions |
| 9:00-9:30 | J. Syvitski , "Predicting sediment delivery and stratigraphy on marginal slopes and shelf basins for the Navy" |
| 9:30-10:00 | K. Stattegger & B. Haupt , "Data based modeling of the ocean-sediment system in large basins" |
| 10:00-10:30 | BREAK |
| 10:30-11:00 | C. Wold , "Evaporite and bauxite proxy formation models forced by a global climate model" |
| 11:00-11:30 | R. Robinson & R. Slingerland , "Sediment transport in stratigraphic simulation models, getting it right" |

11:30-12:00 **R. Plotnick**, "Ecological modeling in the context of stratigraphic modeling: Building the ecological stage"

Conveners: five-minute summary of posters

12:00-1:30 **LUNCH** (You can ride in a van over to the Burge Union cafeteria in a van, if you like. They have a soup and salad line and a line for hot entrees.)

PM (Afternoon Session), Day Two, Thursday, May 16, 1996

1:30-2:00 **P. Joseph**, "Estimation of modelling parameters from well log and seismic data"

2:00-2:30 **S. Bornholdt & H. Westphal**, "Optimization using genetic algorithms"

2:30-3:00 **M. Perlmutter & R. Plotnick**, "The effects of the phase relationships of insolation, climate, sediment yield, and glacioeustatic cycles on stratigraphy"

3:00-5:00 breakout sessions and posters

5:00-7:00 Posters, demonstrations, w/snacks

7:00-9:30 Banquet, Adams Alumni Center

Posters

(Posters can be set up anytime on Thursday in assigned areas in the atrium of Nichols Hall located outside of the Apollo Room. A map of assigned locations will be provided. Posters can remain up until noon on Friday. Tables and chairs will be returned at 4pm on Friday. Please contact NES information table, if you need additional supplies. Please plan to be around the poster during the 5 to 7 pm session.)

S. Boss

"Empirical parameterization of an evolving carbonate cycle: The Holocene of Northern Great Bahama Bank"

R. Buddemeier

"CaCO₃ saturation state variation: Possible effects on coastal biogeomorphology and sediment budgets"

P. Flemings with J. Carlson

"Transport and deposition of heterogeneous-sized sediment in a non-marine sedimentary basin"

J. Harff with W. Lemke, A. Mutzke, T. Seifert, and F. Tauber

"Modeling of sediment distribution and currents in the Western Baltic Sea"

C. Paola

"Experimental stratigraphy - bridging the gap between modern processes and long-term stratigraphic record"

B. Penn and J. Harbaugh

"Phase plots, sedimentary cross-sections, and bifurcation diagrams: Representing output from a dynamical sedimentary model"

G. Rankey

"The roles of system-external and -internal mechanisms on lateral and vertical high-resolution stratigraphic predictability - A quantitative case study from the late Paleozoic, western U.S.A."

R. Van Balen

"The effect of rift shoulder erosion on stratal patterns at rifted margin: Implications for sequence stratigraphy"

Y. Zhang, with D. Swift, A. Niedoroda, C. Reed

"Modeling event stratigraphy on the continental margin"

Computer Demonstrations

(same modeling programs as previous day)

DAY 3, Friday, May 17, 1996

NES Workshop, Lawrence, Kansas

(A confirmation and schedule sheet for those needing a ride back to the Kansas City International Airport or vicinity on late Friday afternoon is available at the NES information table. Please check schedule on Friday.)

Inverse Methods/New Philosophies

Oral Presentations

(Two 35-mm Kodak slide carousels and an overhead projector will be provided. Please load your 35-mm slides in slide trays located in the projection room before your early morning, late morning (after break), or afternoon session begins. Extra slide trays will be available. Also a color overhead LCD-SVGA tablet will be available for projecting computer output from Mac or pc. A Pentium desktop unit have an X-window client linked to the workstations.)

AM (Morning Session)

- | | |
|-------------|--|
| 7:30-8:30 | Topical Breakout Session Chairs -- statements from breakout sessions |
| 8:30-9:00 | D. Swift with Y. Zhang, A. Niedoroda, C. Reed, J. Thorne, "Modeling facies with physics of sedimentation and building stratigraphy with the results: Toward an analytical theory of stratigraphy" |
| 9:00-9:30 | J. Harbaugh, "Stratigraphic modeling of cyclic and chaotic behavior on continental margins" |
| 9:30-10:00 | I. Lerche with E. Bagirov (senior author), "Probability and sensitivity analysis of 2D basin modeling results" |
| 10:00-10:30 | break |
| 10:30-11:00 | J. Pelletier, "Stochastic 2D model of interaction of flow with landscape and resulting deposition/erosion" |
| 11:00-11:30 | G. Weltje, "Controls on sediment provenance and dispersal from compositional data; inverse modeling strategies for improved parameter estimation" |
| 11:30-12:00 | M. Lessinger & T. Cross, "Construction and application of stratigraphic inverse models" |

PM (Afternoon Session), Day Three, Friday, May 17, 1996

- 12:00-1:30 *LUNCH* (You can ride in a van over to the Burge Union cafeteria, if you like. They have a soup and salad line and a line for hot entrees.)
- 1:30-2:00 **M. Lessinger & T. Cross**, "Estimating accuracy and uncertainty of stratigraphic predictions from inverse numerical models"
- 2:00-4:00 summaries+statements+discussion from topical breakout sessions

(Folding tables and chairs will be removed by University facilities and operations at 4 pm. Please have poster material removed. Thanks.)

Check with van schedule for departure times to KCI Airport and vicinity.

Have a safe trip home.

Topical Breakout Sessions, NES Workshop

A. Topics and Co-Chairs:

1. *Model Comparisons*
Co-Chairs -- Hemmo Bosscher, Shell International E&P B.V.,
Johannes Wendebourg, Intitut Francais du Petrole
2. *Model Optimization*
Co-Chairs -- John Harbaugh, Stanford University,
Scott Bowman, Marco Polo & Rice University
3. *Geologic Observation/Parameterization*
Co-Chairs -- Marty Perlmutter, Argonne National Laboratory,
P.L. deBoer, Institute of Earth Science., Univ. of Utrecht,
James Syvitski, Arctic and Alpine Research Center, University of Colorado
4. *Algorithms/Output*
Co-Chairs -- Dan Tetzlaff, Western Atlas,
Mike Steckler, Lamont-Doherty Geological Observatory
Peter Flemings, Penn State University
5. *Inverse Methods*
Co-Chairs -- Margaret Lessenger, Colorado School of Mines,
Ian Lerche, University of South Carolina

B. Goals of the Topical Breakout Sessions are to:

1. permit an exchange of ideas,
2. capture the major points of the discussions,
3. organize summaries presented during the workshop, and
4. develop "white papers" to be published with proceedings.

C. Charge for session leaders

1. Homework to prepare for breakout session -- define discussion topics.
2. Record proceedings of sessions and summarize for wrap-up.
3. Present or designate presenter on progress/findings to large group.

D. Logistics:

Locations of breakout sessions during the meeting:

TOPICAL SESSION ASSIGNED

1. Gemini Room, 2nd floor (20 people)

2. Mercury room, 2nd floor (15 people)

3. back of Apollo Room (15 people)

4. south side of atrium, 1st floor (10 people)

5. north side of atrium, 2nd floor (10 people)

Supplies/equipment/support for breakout sessions:

1. flip chart and easel
2. overhead projector
3. secretarial support (LeaAnn Davidson) for copying documents, making overheads
4. OTHER?

"Of the Making of Earth Science Models There is No End...."
Introduction to the NES Meeting

Eugene Rankey (*grank@kuhub.cc.ukans.edu*), *Department of Geology, Lindley Hall, The University of Kansas, Lawrence, KS 66045* and **Lynn Watney** (*lwatney@pcmail.kgs.ukans.edu*), *Kansas Geological Survey, The University of Kansas, Lawrence, KS 66047*

Introduction

Models have always represented an advanced state of understanding of the complex interactions of a number of processes. Newton, Einstein, Copernicus, and other scientists have developed and utilized models in some respect. For every model, there must be certain evolutionary steps and tests to confirm its robustness and utility. The purpose of the NES meeting is to isolate and evaluate the status of each of a number of steps in order to provide developers and users with a clearer understanding of the needs and directions of future modeling studies. The purpose of this presentation is to provide a conceptual framework for one approach to addressing these goals.

To characterize models and their evolution, a first important question is "What is a model?" In simplest form, models are "intellectual devices for making natural processes easier to understand" (Lehr 1990). Models "do not represent reality, they represent our thinking about reality" (Anderson and Crerar 1993) and thus are limited by our perceptions and understanding. One diagnostic feature of a model is that it be "a well-constrained, logical proposition, not necessarily mathematical, that has necessary and testable consequences" (Greenwood 1989). It is the testable aspects that make a model "essentially a new kind of theory" (Lehr 1990) and constitute the 'science' in modeling.

Given the descriptions, it is obvious that there are several aspects of 'making models.' The first is the actual physical or computational design of the model itself, which is in part a function of perceptions, knowledge, and understanding of the system being modeled. Model designs may have several substeps: (1) a puzzling stage; (2) a cartoon, or 'back of the envelope' stage; (3) an empirical descriptive stage; (4) the idea/deeper understanding stage; and (5) the weighing/testing stage (Figure 1) (Greenwood 1989). The second aspect of making models is deriving the input for utilization in model runs. These data are independent of the model itself, but are utilized for predicting "what should happen in a real situation on the basis of the numerical situation which we feed the [model]" (Lehr 1990). The third aspect of 'making models' is the testing component, where model predictions are compared with real-world or observational data. This facet leads directly to evaluating the 'ends' of models.

'Model ends' include comparing the model predictions with observed data to provide value-added insights. These comparisons may be considered to be model "acceptability, accuracy, analysis, assessment, calibration, certification, confidence, credibility, evaluation, performance, qualification, quality assurance, reliability testing, validation, or verification" (Knepell and Arango 1993) depending on the model purpose. Three levels of confidence should be applied explicitly to a given model: (1) learning tools for general understanding; (2) status calculations for answering a specific question, but ignoring any other results; and (3) simulations for answering a broad set of questions (cf. Brown 1992). Model results should be evaluated within the 'error bars' of the model structure and design, and users should not fall prey to the "fidelity fallacy," which "occurs when someone assumes that a model is useless unless it is "high fidelity," i.e. a perfectly faithful representation of the sight" (Brown 1992). Several sources of error may be present that may account for limited fidelity of model predictions: "(1) model bias or errors in model structure; (2) measurement error or uncertainty in model parameters; and (3) variability of natural [systems]....." (O'Neill and Gardner 1979). Each of the three error sources should be addressed explicitly for a each model run, but nonunique solutions, error propagation, complex natural systems, and limited understanding provide challenges for explicitly evaluating the role of each of the three.

This review provides a brief conceptual overview of some of the guiding concepts and the challenges facing modeling. The NES meeting aims to evaluate each challenge through talks, posters, demonstrations,

comparisons, and discussion sessions. Similar to the greats, however, we must remember that modeling is an iterative process, with no 'end' in sight. After all, Icarus had a model of the principle of flight, poor as it was; he was, however, the first person to try to fly. Fortunately, unlike Icarus who died for his shortcomings, we can just turn off our computers if we fail!

Making Models

A geologic model is a predictive synthesis of a geologic system expanding on descriptions by logical or mathematical relations. Model types include conceptual/analog (a geological interpretation or construct that is a qualitative description or concept), correlation (manual interpretation of spatial association of geologic units), interpolation (machine generated association of spatial data, visualization), forward simulations (machine-generation of geology based on input of processes), and inverse (machine derivation of process parameters from geologic data) (Watney, French, and Guy, 1996).

Geologic models may be classified by vehicle and direction. The direction of a geologic model may be either inverse or forward. Inverse methods in stratigraphy utilize numerical procedures to interpret sedimentary processes and related parameters such as accumulation rate (Kominz, et al., 1991), water depths and subsidence rates (van Hinte, 1978), influences of allogenic and autogenic forcing mechanisms (Rankey, this volume), climate signatures (Perlmutter and Plotnick, this volume), tectonic signatures (Johnson, this volume), recognition of sediment provenance and dispersal patterns (Weltje, this volume), and patterns of inferred eustacy/climate changes (Earth's orbital periodicity and changes in insolation, de Boer and Smith, 1994). Inverse methods also include the use of iterative forward simulation to compare realizations to observations in order to evaluate accuracy and uncertainty and to solve for sedimentation parameters (Lessenger and Cross, this volume).

In contrast, forward sedimentary/stratigraphic models examine the interaction of processes to produce a sedimentary response. Output from forward models includes many attributes such as stratal geometry (a host of authors in this volume), lithofacies, depth-dependent facies (carbonates), grain-size distributions (Wendebourg and Harbaugh, 1996), pseudo well logs and seismic profiles (Shuster and Aigner, 1994; Bosscher and Newall, this volume), petrophysical properties (Wendebourg, 1994), and biofacies (Plotnick, this volume). Model vehicles include analog and simulation.

Analog Models

An analog or conceptual model is a nonquantitative, static, verbal or graphic predictive synthesis of a geologic system. An example is sequence (genetic) stratigraphy, where stratigraphers infer processes from lithologic and geometric attributes and anticipate other lithologic or geometric relationships. Another example is the carbonate microfacies model of Wilson (1975). An analog/conceptual model is portable, but may involve subjective qualitative inferences about processes and their interactions. Analog models provide a framework within which observations can be placed, but may have limited use in testing hypotheses. Analog models also include physical models or scaled reproductions of actual geologic systems, (e.g., sediment flumes) which may provide sedimentary parameters (Meyer-Peter and Muller, 1948). Analog models continue to provide valuable insights on process and response relationships from geologic systems at various scales.

Simulation Models

Another vehicle for modeling is computer simulation, which is particularly well-suited for experimentation and sensitivity analysis because of powerful computers. Computer simulations use quantitative measurements, estimates, or inferences to construct a numerical representation of a system. Computer simulations can be subdivided further into deterministic and stochastic simulations. Deterministic simulations involve experiments that model the dynamic interaction of processes (e.g. input) to create known, defined responses. Model runs in a deterministic simulation repeated with the same input parameters always will produce the same results (Read et al., 1986; Jervey, 1988; Tezloff and Harbaugh, 1989; Lawrence, et al., 1990; host of authors in this volume). Deterministic simulations can be subdivided into stratigraphic-form simulations and sedimentary process simulations (Wendebourg and Harbaugh, 1996).

In contrast, stochastic simulations model the dynamic interaction of processes (e.g. input) to create a known or unknown response; that is a process may or may not result in the same response each time, depending

upon an element of "chance." Stochastic modeling also may include geostatistical procedures used to generate constrained random variation in two and three dimensions (Isaaks and Srivastava, 1989). Stochastic models include discrete or object-based simulators, which represent averaged shapes and properties for large sedimentary bodies and continuous simulators which represent continuous small-scale variation. Stochastic models can represent combinations of both discrete and continuous approaches (e.g., Pelletier and Turcotte, this volume). Stochastic simulations may also include aspects of: (1) random processes; e.g., autocyclic tidal flat migration (unconstrained, unconfined system) (Demicco and Spencer, 1989; Spencer and Demicco, 1989), (2) nonlinear dynamical systems (deterministic chaos) (constrained, but unconfined system) (Nicolas and Nicolas, 1991; Smith, 1994), (3) responses to triggers (Drummond and Wilkinson, 1993), thresholds, or feedback (Gaffin, 1992), (4) bifurcation, chaos, and fractals, (5) neural networks and fuzzy logic (Nordlund and Sifersparre, 1994; Nordlund, this volume), (6) deterministic simulations of event beds and stochastic bed preservation potential (Zhang, et al., this volume), (7) Monte Carlo simulations of stratal architectural elements (Ray et al., this volume), (8) self organized criticality (Edington and Cross, this volume), (9) coupled dynamical systems (Harbaugh, this volume; Penn and Harbaugh, this volume), and (10) stochastic cellular automaton (Plotnick, this volume).

Deterministic stratigraphic and geostatistical modeling are being combined now to accomplish multiscale realizations (Doligez et al., this volume). Deterministic modeling is evaluating measures of uncertainty (Priddy, this volume). Swift et al. (this volume) are capturing a combination of small scale-deterministic and chaotic-deterministic processes in their modeling of event beds. Boolean geostatistics using Monte Carlo and conditional simulation may be used with forward modeling to develop large- and small-scale realizations of petroleum reservoirs (Tetzlaff and Rodriguez, this volume).

Designing A Stratigraphic/Sedimentation Model

In simplest terms, models can be considered to consist of three components: input, "engine," and output. Every model must contain these three components, although their exact character differs among models depending on the philosophy and goals of the modeler(s), the geologic system (temporal and spatial scale) under consideration, and computing power.

Input

Input parameters are constrained by geologic observation or interpretation. Sources for input data include forward or inverse models (including sensitivity analysis), studies of modern analogs, empirical observations, restraints imposed by physical laws ("first principles"), and mass balance/conservation (see Franseen et al., 1991; Table 1). Modern and Neogene analogs with well-constrained process information and geologic data provide valuable process data and process and response relationships. Accordingly, such studies and data reduce assumptions, inferences, and judgement in modeling (e.g., western Baltic, Harff et al., this volume; ocean-sediment system, Haupt and Statterger, this volume, slopes and shelf basins in project STRATAFORM, Syvitski, this volume) and subsequently have been used for the NES data set -- (a) Miocene carbonate platform in Mallorca (Bosence et al., 1994; (b) Neogene of Baltimore Canyon (Miller and Mountain, et al., 1996). Measured sections (outcrops, well cores), petrographic descriptions, paleontologic interpretations (biostratigraphy, paleoecology), wireline logs, seismic sections, geochemical signatures (including spectral gamma ray, rock magnetic stratigraphy, reversal stratigraphy), isopachous/facies maps, and geohistory diagrams/backstripping data can and should be used as input. Initial (boundary) conditions such as profile geometry or 3-D configuration of sedimentary body and sediment parameters are also important.

"Engine" -- Computational manipulation of model input parameters

The first step in the transformation from input to "engine" is assignment of input parameters to variables utilized by algorithms. One variable may utilize several input parameters for its definition.

The engine operates on various independent and dependent parameters. An example of an independent variable (a value that is a function of nothing but itself) is crustal age. An example of a dependent variable (a value that is calculated from the character of several other parameters) is water depth (Figure 2). In its simplest form, water depth at a given place and time is a function of (a) eustatic fluctuations, (b) tectonics, and (c) accumulation or erosion. In a model, all three parameters interact to produce water depth. Furthermore, each of

these parameters might be defined by two or more inputs. For example, tectonics (in the model and real world) might be a function of sediment and water loading, compaction, thermal subsidence, flexural loading, etc, which, in turn, might be defined further by the interaction of several other parameters (i.e. flexural rigidity, lithospheric thickness, mantle density, etc.). Thus, several input parameters might be used to define one variable, water depth (Figure 2a).

Models utilize "first principles" or approximate the results of these principles, depending upon the philosophy of the programmer, goal of the study, and the spatial and temporal scales being addressed. Models operate with various levels of real data, assumptions, and inferences. As fewer assumptions and inferences utilized, the accuracy of the model becomes more easily measured and the confirmation of the model becomes easier (Figure 2b). Accordingly, the added value provided by the model increases.

Model algorithm classes and some examples of models in these classes include:

1. *Diffusion algorithm.* Fick's Second Law (the diffusion equation) relates the time rate of change of some property (e.g., sediment distribution) to spatial gradients (e.g., slope or fluid velocity) affecting that property. For computer models, the rate of change is in time or space, the gradients are in space. The diffusion equation has been utilized to approximate sedimentary processes (e.g., siliciclastic sediment transport and deposition, Rivenaes, et al., 1992; Kaufman et al., 1991; advective diffusion model, Swift et al., this volume; 3-D multilithological diffusion model, Granjeon and Joseph, this volume; carbonate production and light penetration, Boscence, et al., 1994; Einstein's sediment transport equation, Flemings and Carlson, this volume).
2. *Fluid flow algorithm.* In SEDSIM, Tezloff and Harbaugh (1989) model the erosion, transport, and deposition of clastic sediment by running water. In their simulation, the user defines a topographic grid and fluid and sediment parameters. Sediment-water relations are described by the Navier-Stokes equations in two-horizontal dimensions, using the marker-in-cell technique. Current modules in SEDSIM also handle fluvial and wave processes, eustatic sealevel change, isostatic compensation, tectonic uplift, and subsidence, compaction, and submarine slope failure (Martinez and Harbaugh, 1993; Wendebourg et al., 1993, Wendebourg and Harbaugh, 1996). STRATSIM incorporates fluid flow with controlled and modulated by eustatic, tectonic, and climatic variations (Priddy, this volume).
3. *Geometry-controlled deposition algorithms.* This class of models uses geometric approximations of sediment transport processes to deposit, transport or erode sediment. They approximate the gross-scale results of sedimentation as geometries which, in turn, create a stratigraphic framework. These models usually use empirical or observational data to approximate processes (e.g., SEDPAK, Strobel et al., 1989; STRATAGEM, Bosscher and Newall, this volume; Dunn, 1990).
4. *A priori numerical approximation algorithm.* Models which use this algorithm use a predefined relation to describe the sedimentary response to a process or condition (e.g. water depth), independent of any gradient or geometry (e.g., KANMOD, French and Watney, 1990). The sediment may respond to a gradient, however, as in the situation of oversteepening and bypassing, but the process is not driven by the gradient itself (there is no dh/dx relation, for example, that controls sedimentation). These models usually use empirical or observational data to approximate processes.
5. *Tectonic modifications of sediment transport algorithms.* Models also incorporate structural algorithms that led to deformation of the sedimentation. Many forward stratigraphic/sedimentologic models include some aspect of structural deformation (SEDPACK, PHIL, SEDSIM, SEQUENCE, STRATAGEN, STRATA, and DIONISOS). New approaches to structural modeling include composite kinematic platform modeling applied to orogen/foreland basins (Johnson, this volume and 1995), and refinements in rifted passive margin structural modeling (van Balen, this volume).
6. *Hybrid (multicomponent) algorithms.* A broad landscape-stratigraphic model is being developed through extended collaborative investigations. The project is termed STRATAFORM sponsored by U.S. Office of Naval Research. The model addresses many processes at many scales (Syvitski, this volume).
7. *Stochastic numerical generating algorithms.* This is a relatively new development in forward modeling. Geostatistical models are being used to fill in volumes that are below the resolution of forward model

Is There an End?

The following are some excerpts directly from Oreskes et al. (1994) who provide a critical review of numerical models in the earth sciences. They make a challenge to define explicitly comparisons and tests for models and to clearly state what a model can and can not do. This advice is good for the science and the discipline.

The challenge of modeling complex, open natural systems is significant. Such models can not be verified, i.e., establish the truth. The truth may be there, but it is not realistically obtainable. Input parameters are incompletely known. Nonlinearity is the rule, if not characteristic. Scaling-up of nonadditive properties to construct a model leads to more uncertainty. Errors in assumptions, inferences, and input parameters can cancel out each other out and not be recognized (right for the wrong reasons). Small errors in input lead to large deviations for large time frames. There is no guarantee that future conditions will be similar, e.g., dynamic, unanticipated changes. Models results always are underdetermined by available information and results are nonunique. Models may be "empirically equivalent" if they produce the same result, but in itself does not verify the models. What defines the best model? The decision usually is based on simplicity and elegance, but perhaps personal, political, or metaphysical preference (Oreskes, et al., 1994).

To evaluate a model, we usually compare its output with real-world observations. Both output and observations are only the end product. Even if the ends are the same, it does not necessitate that the paths to that point are the same (i.e., input, parameters, assumptions). Evaluating a model takes on parallel paths: 1) model to model comparisons to verify a model, 2) model to real-world comparisons to calibrate a model, and 3) comparing the inner workings of a model to validate the model. A useful framework for model evaluation is presented in Figure 3 (after Sargent, 1987).

Model Validation and Reliability

Validation involves an analysis of the internal components of a model. Models can be validated or legitimized if they do not contain detectable flaws and are internally consistent. Checks can be made of the accuracy of hypotheses and assumptions that go into the model. Even if a model is internally consistent, it may not accurately or reliably represent physical reality.

Verification of a Numerical Solution -- Algorithm testing

Verification involves substantiation of the algorithm(s) and numerical solutions generated by a model. "Bench marking" involves the comparison of a model run to an analytical solution to demonstrate a match over a particular range of conditions. Congruence of the two approaches does not indicate either is related to reality. Extending solutions beyond range of known values (time, space, parameter distribution) lead to nonverified solutions (Oreskes et al., 1994).

Calibration on Numerical Models

Manipulation of the independent variable to obtain a match is calibration. Distribution of a dependent variable is usually the most well known aspect whereas the independent variable is the least well known (e.g., sediment supply and climate/tectonic regime). Examples of dependent and independent variables related to subsidence were presented earlier (Figures 2a and 2b). The use of dependent variables is accompanied by assumptions and approximations. The later must be presented in explicit form for a model to be most useful and from which improvements can be made.

Value-Added (i.e. is model worthwhile)

Hypotheses are corroborated by offering evidence to support them or weakened by negative evidence. Models elucidate discrepancies. Sensitivity analysis and "what if" testing of a model helps to determine where study is needed and what empirical data need to be collected. Modeling can guide a study, but can not prove the resultant interpretation. Modeling provides the definition for logical outcomes providing an assessment of the relative amounts of observation and measurements of accessible phenomenon, informed judgement, and convenience that go into knowledge of a system. Thus, the model provides a heuristic understanding of a

realizations (Tetzlaff and Rodriguez, this volume). Biotic species interaction is defined by stochastic cellular automaton with percolation and kinetic growth models (Plotnick, this volume).

Model Output

Several types of data may be provided by models as output, including: (1) Space-space diagrams (1D stratigraphic columns, or 2D cross sections) of facies (water depth, sediment type), sequences, possibly including sequence boundaries, condensed sections, etc., chronostratigraphic relations, geometries, and porosity-permeability cross-plots; (2) Time-space (Wheeler) diagrams; (3) Parameter history (e.g. sea-level, water depth, sediment surface, etc.); (4) Fischer plots; (5) Simulated gamma-ray logs; (6) Simulated seismic sections; (7) Pseudo-3D (2 1/2 D); (8) Bedforms; (9) Contour maps (real 3D; and (10) rates and magnitude of parameters vs. time.

Specific types of model output are used for different types of questions. Three levels of questions or hypotheses may be addressed: 1) general conceptual understanding of a system; 2) specific evaluation of one question; 3) development and understanding of an entire system (Brown, 1992). The precision of input data and the amount of detail of output increase with each level of questioning. Output can never prove a model wrong, just as it can never prove it correct.

At a large scale, societal/institutional needs are increasingly sophisticated and requires our geologic assessments to become more refined. Careful choices/design of model output can provide effective realizations that can demonstrate relevancy to tasks and addressing problems.

Model Testing

The wealth of output and the flexibility of computer systems facilitates systematic testing, but many studies utilizing simulations have failed to include possible tests. As outlined earlier, a model can be described as a prediction or synthesis of a geologic system expanding on descriptions by logic or mathematical relations. Model evaluation should involve testing not only the variables and algorithm, but also testing the validity of model applications. The degree to which a model run approximates a real geologic process-response system depends upon the validity of both the original input parameters and the way in which the model algorithm manipulates these parameters.

The influence and validity of variables on a simulation run can be examined through qualitative comparisons, sensitivity and error analyses. Qualitative analysis may include visual comparison of model runs with observed geology (as represented in any data form). Sensitivity analysis involves systematic variation of parameter(s) to assess their interaction and expected value or range of possible values (Lerche, 1990 a, 1990 b; Cao and Lerche, 1992; Lawrence, 1994). Error analysis utilizes quantitative comparison of model results with observed geology. For example, one may compare the deviation of simulated output (e.g., sediment type and thickness, well log or seismic response) with the measured or observed geology (Bosence et al., 1994; Schuster and Aigner, 1994). Optimization of the model also can be sought using genetic algorithms (Bornholdt and Westphal, this volume).

Evaluating variables is only one component of model testing. Examining the validity of algorithm(s) is also necessary to see that models are good approximations to the geologic systems that they are designed to simulate. Explicit comparison of algorithms may not be possible because not all models can work with all sedimentary systems and because all models have bounds and differing degrees of complexity, approximation, scale, and computer power. Comparisons can be made between different simulators using the same boundary conditions, parameters, and parameter history. This test is a primary goal of the NES meeting.

Simulations result in nonunique solutions due to inherent approximations of the geology and limitations in data type and quantity (Burton et al., 1987; Kendall et al. 1988, 1992), but simulators permit ongoing experimentation as data quality and understanding of processes improves. Systematic experimentation provides a rational path toward more improved constrained solutions (Schuster and Aigner, 1994). The results can serve as guides for data collection and hypothesis formulation including resource exploration and exploitation.

Simulation output may generate nonintuitive results. Critical examination of these results and their implications can lead to better interpretation and conceptual understanding of processes and process interaction. Better conceptual understanding in turn leads to improved algorithms and focused studies to validate realizations. Nonintuitive results also can enhance prediction and exploitation of resulting realizations, i.e., proving their existence through focused data collection.

geologic system, i.e., a integrated linkage of concept, data, process, and results, that can be built upon with new insight, data, and applications leading to increases in sophistication until the next shift in the knowledge paradigm, e.g., sequence stratigraphy.

Modeling is useful to access phenomenon not directly observable in either time or space. However, models should be applied to the appropriate temporal and spatial conditions known for the system. For example, reservoir simulators model fluid flow in petroleum reservoirs utilizing observed data, assumptions, and inferences. In these simulators, fluid flow is not modeled at the scale of a pore, but in larger volumes because Darcy's Law is not applicable at these small scales and yet the results are interpreted in terms of aggregate pore volume. Similarly, there are limits of appropriate application to sedimentary modeling.

Unlike chemists who can repeat an experiment, geologists are forced to infer processes that can not be observed. Forward models are valuable in that they provide the opportunity to integrate data, to evaluate systematically the influence of each parameter, and to estimate the rates, durations, and magnitudes of the various processes and their interactions through time and space. Modeling is valuable in that it: (1) affords a way to quantitatively test interpretations of the roles of eustasy, tectonics, sediment accumulation and their interactions to produce sedimentary packages and geometries; (2) encourages accuracy and precision in data collection and process interpretation through establishing formal quantified assertions in logical terms (Slingerland et al., 1994); (3) provides new perspectives on data and assists in integrating available information; (4) stimulates interdisciplinary cooperation and verification of data and interpretations; and (5) focuses problem-oriented research, data collection, and interpretation.

Problems/Challenges

The exponential growth of computer applications in sedimentology and stratigraphy have allowed rapid advances in our understanding of these systems. Nevertheless, much remains to be done. General issues in simulation modeling include 2D vs 3D, resolution (spatial and temporal), graphic display, calibration, first principles vs. empirical relationships, and use of deterministic, stochastic, or combined approaches (Harbaugh, 1992). We present here a few specific ideas on where modeling is going and where it might be improved or enhanced.

Input

Geologic data collection -- Quality, quantified data will aid in model development; likewise, models can guide data collection. Present needs for computer applications include:

- * evaluation and quantification of lateral continuity of strata (Halderson and Damsleth, 1993; Kerans and Fitchen, 1995; Rankey, 1996);
- * understanding and quantification of lag delays (internal inertia), quasi-equilibrium oscillatory behavior and trigger mechanisms;
- * documentation of detailed facies relations that can show associations between differential compaction and inherited paleotopography and subsequent sedimentation patterns (Hunt et al., in press; 1995);
- * quantification of relative changes in sealevel (e.g., tracing subaerial exposure surfaces down paleoslope), short-term patterns of subsidence, and timing of compaction (Goldstein and Franseen, 1995; Rankey and Lehman, in press);
- * derivation of a relation showing the interaction of rate of sealevel change, water depth, and carbonate productivity (e.g., nonequilibrium conditions);
- * integration of scales (regional, local) and types (visual, geophysical, geochemical) of observation;
- * real-time management of large and diverse four-dimensional data sets;
- * incorporation of climate data, linked to ice, ocean, atmospheric information;
- * establishing allogenic and autogenic process links between time equivalent marine and nonmarine strata.

Geologic data interpretation -- Many input parameters represent interpretations of geologic data. How geologists capture the essence of the system and interpret it is therefore of utmost importance in modeling. Recent advances that seem especially promising include:

- * the gamma method (Bond and Kominz 1993) which utilizes an inverse technique to try to estimate relative accumulation rates and sedimentary system periodicity;

- * variations of time-series analysis, e.g., wavelet theory;
- * recognition and analysis of nonlinear dynamical systems, e.g., fractals, neural networks, fuzzy sets (Nordlund and Silfversparre, 1994; Smith, 1994); and
- * 2- and 3-D seismic/petrophysical modeling to enhance understanding of rock volumes (Biddle et al., 1992).
- * evaluation and quantification of allogenic and autogenic influences on sedimentation to better predict real world variability and realistic "error bars" on model runs.

Engine

- * Comparing types and scales of modeling, e.g. 1st-principles/sedimentation [grain transport and accumulation], stochastic [internal oscillation], and stratigraphic [geometric accumulation/accommodation] models. This approach can provide a test of the errors associated with approximations of "first principles," evaluation of the practicality and limits of various types of models (Figure 3);
- * Recognizing and accommodating the realization that sedimentation is inherently stochastic at some temporal and spatial scale, and that our understanding is limited by data quality and quantity and by knowledge of processes;
- * Explicitly comparing models and algorithms as at NES;
- * Accommodating nonintuitive responses. Both external and internal forcing may induce unanticipated and nonintuitive changes (triggers and feedbacks, or linked variables) to the depositional system. The traditional process and response relationships, dominated by external forcing, that drives current models should be coupled with analysis of the nonlinear dynamics of each system. "Complexity might be an intrinsic property generated by the nonlinear character of the system's dynamics." (Nicolis and Nicolis, 1991; Harbaugh, this volume; Penn and Harbaugh, this volume).

Output

- * quantitatively compare and contrast model run with real data to determine "goodness-of- fit";
- * develop standard testing protocols to compare model performance;
- * evaluate systems and processes for which models do not work and analyze why;
- * develop and integrate inverse modeling techniques to obtain more comprehensive quantitative information for input into the forward models. Modeling should be interactive and iterative, including integration of forward and inverse techniques. For example, use model runs as both forward and inverse models, then use the inverse model to reconstruct the input parameters of the forward model and vice-versa. How close are the original inputs or outputs to those determined by the inverse or forward model?
- * utilize statistics, probability, and error analysis procedures to measure consistency;
- * incorporation of available standard graphics protocols for display to make it easier to modify algorithms and engines and to make application more portable between types of computers; and
- * development of output controls that make it easier to tailor model to specific situations (temporal, spatial, depositional system).

Summary

1. This paper provides an overview for the NES Workshop presenting the purpose, concepts and definitions related to modeling, particularly those of model testing and evaluation. The purpose of the workshop is to isolate and evaluate the status of several steps in model development and to establish the needs and directions of future modeling studies within these areas.
2. Models evolve through stages of physical or computational design that utilize perceptions, knowledge and understanding of the system. The design stage includes several substeps including puzzling, cartoon, empirical descriptive, idea, and testing. Deriving the input for utilization in model runs is another stage followed by testing the model with real-world and observational data (i.e., evaluating the ends of the model). Model ends or products include predictions with observed system, usually with value added insights about the

geologic system. Recognition of these steps in an evolving model are pertinent to effectively evaluate and to ascertain the appropriateness of model applications to specific geologic situations.

3. Levels of confidence to modeling evolve from their use as learning tools to addressing status calculations and finally providing answers to broad questions. The fidelity fallacy is the assumption that a model is useless unless it is "high fidelity." Sources of error include model bias, measurement error and uncertainty in model parameters, and variability in nature. Confidence in modeling is a subjective entity, but must and can be categorized and effectively addressed in order for modeling to proceed and to be productively utilized in solving important geologic problems.

4. Geologic models can be divided into conceptual/analog, correlation, interpolation, forward/simulations, and inverse. Models can be classified by direction as forward or inverse and by vehicle as analog or simulation. Simulations can be categorized further as deterministic, stochastic, or combined. Stochastic simulations include stratigraphic form and sedimentary process simulations. The classifications aid in identifying ways that models can be analyzed and compared.

5. Stratigraphic/sedimentologic models are separated into three basic components - input, engine, and output. The input includes modern analogs, empirical observations, restraints of physical laws, and mass balance/conservation. The engine involves the assignment of input to variables used by the algorithms including dependent and independent parameters. The algorithm can be based on "first principles" or an approximation of these principles derived according to the philosophy, goals, and scale of time and space being modeled. Many forms of output are now available, increasingly focused on direct simulation of observed data types, e.g. well logs and seismic profiles. These steps will continue to facilitate comparisons and improve model testing.

6. Evaluating models involves analysis of (1) input variables (comparison, sensitivity, and error analysis) and statements of assumptions, judgement, and convenience measures, (2) algorithm comparison; and (3) "goodness-of-fit" output to observed geology and with other models. Each of these are parallel paths in the evaluation process. A framework for model evaluation is presented in Figure 3 (Sargent, 1987). Stratigraphic/sedimentologic simulation models must be compared in this manner in order for advancements to take place in an orderly and systematic manner. Even if the end result of two models is the same, the paths of the models can be different. A model can be verified by comparing it with other models. Models can not be verified by comparing results to natural geologic systems because the path may not accurately reflect the true processes and steps followed by nature. Similarly, models can not be used to prove some geologic situation, but can confirm a hypothesis or theory. Nevertheless, models can be calibrated with the real world. The calibration is accomplished by manipulating the independent variables. Models can be validated by comparing their input parameters, assumptions, and algorithms.

7. Value-added results of modeling can take many forms. Sensitivity analysis and what-if testing helps to define future studies for improving input data and to refine general understanding. Improved input, engine, and algorithms reduce assumptions and judgement and increases the number of independent variables to make the model more robust and reflective of the geologic processes and responses. Models can be use tailored to appropriate situations with important problems to increase the value of the model. Many challenges face the geologic community including responding more precisely and accurately to the needs of society, government, and institutions. An important step in that direction is to actively build a quantitative knowledge base of natural systems that can be incrementally improved by efficiently capturing new understanding as it becomes available. Stratigraphic/sedimentology modeling provides an important pathway towards this end. The formal quantified assertions in logical terms provided by models (Slingerland et al., 1994) provides an effective vehicle to incorporate new data and new thinking.

Questions?

1. Can models be tested and confirmed?
2. What are we testing?
3. How do models work?
4. What are challenges and opportunities that face modelers?

Acknowledgments

We appreciate the review and comments of Dan Merriam.

Figure captions

Figure 1. Model designs (after Greenwood, 1989).

Figure 2. Example of independent and dependent parameters.

Figure 3. Framework for model evaluation (after Sargent, 1987).

Figure 4. Temporal succession in development of forward stratigraphic simulation models. All three phases continue to be viable, valuable avenues of research today.

Table 1. Sources of information used as input in stratigraphic simulation models.

References Cited

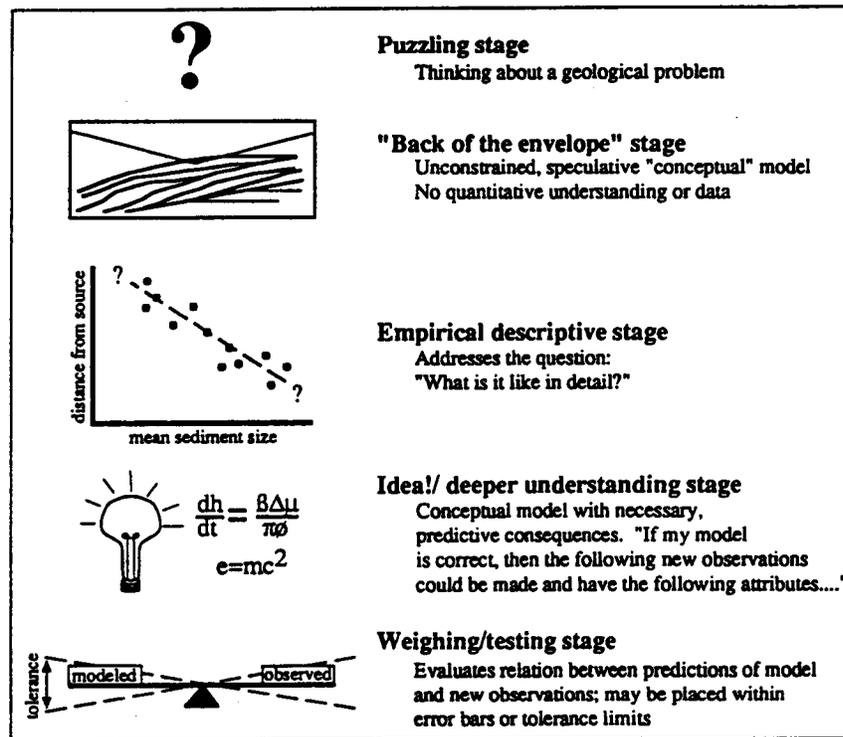
- Biddle, K., Schlager, W., Rudolph, K.W., and Bush, T.L., 1992, Seismic model of a progradational carbonate platform, Picco do Vallandro, the Dolomites, northern Italy: AAPG Bulletin, v. 76, p. 14-30.
- Bond, G.C., Devlin, W.J., Kominz, M.A., Bevan, J., and Manus, J., 1993, Evidence of astronomical forcing of the earth's climate in Cretaceous and Cambrian times: Tectonophysics, v. 222, p. 295-315.
- Bond, G.C., and M.A. Kominz, 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup, and crustal thinning: Geological Society of America Bulletin, v. 95, p. 155-173.
- Bosence, D., and D. Waltham, 1990, Computer modeling the internal architecture of carbonate platforms: Geology, v. 18, p. 26-30.
- Bosence, D., and D. Waltham, 1990, Computer modeling the internal architecture of carbonate platforms: Computers and Geosciences, v. 10, p. 10-20.
- Bosence, D.W.J., Pomar, L., Waltham, D.A., and Lankester, T.H.G., 1994, Computer modeling a Miocene carbonate platform, Mallorca, Spain: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 247-266.
- Bosscher, H. and W. Schlager, 1992, Computer simulation of reef growth: Sedimentology, v. 39, p. 503-512.
- Brown, D.M., 1992, The fidelity fallacy: Groundwater, v. 30, p. 482-483.
- Burton, R., Kendall, C.G.St.C. Lerche, I., 1987, Out of our depth: on the impossibility of fathoming eustasy from the stratigraphic record: Earth Science Reviews, v. 24, p. 237-277.
- Cant, D.J., 1991, Geometric modeling of facies migration: theoretical development of facies successions and local unconformities: Basin Research, v. 3, 51-62.
- Cao, S. and I. Lerche, 1992, Basin modelling: Applications of sensitivity analysis: Journal of Petroleum Science and Engineering, v. 4, p. 83-104.
- Davis, R.A., and H.E. Clifton, 1987, Sea-level change and the preservation potential of wave-dominated and tidal-dominated coastal sequences: in, Nummedal, D., O.H. Pilkey, and J.D. Howard, eds., Sea-level Fluctuation and Coastal Evolution, Society of Economic Paleontologists and Mineralogists, Special Publication No. 41, p. 167-178.
- de Boer, P.L., and Smith, D.G., 1994, Orbital forcing and cyclic sequences, *in*, de Boer, P.L., and Smith, D.G., eds., Orbital Forcing and Cyclic Sequences, International Association of Sedimentologists Special Publications No. 19, Blackwell Scientific Publications, Boston, p. 1-14
- Demico, R.V., and R.J. Spencer, 1989, MAPS - A BASIC program to model accumulation of platform sediments: Computers and Geology, v. 15, p. 95-105.
- Drummond, C.N. and B.H. Wilkinson, 1993, Carbonate cycle stacking patterns and hierarchies of orbitally forced sea-level change: Journal of Sedimentary Petrology, v. 63, p. 369-377.

- Dunn, P.A., 1990, Diagenesis and cyclostratigraphy -- an example from the Middle Triassic Latemar platform, Dolomites Mountains, northern Italy, [unpublished Ph.D. dissertation], John Hopkins University, Baltimore, Maryland, 791 p..
- Enos, P., 1991, Sedimentary parameters for computer modeling: *in* Franseen, E.K., Watney, W.L., Kendall, C.G.St.C., and Ross, W., Sedimentary modeling: Computer simulations and methods for improved parameter definition: Kansas Geological Survey Bulletin 233, p. 63-99.
- Franseen, E.K., R.H. Goldstein, and T.E. Whitsell, 1993, Sequence stratigraphy of Miocene carbonate complexes, Las Negras area, southeastern Spain: Implications for quantification of changes in relative sea-level: *in* Loucks, R.G., and J.F. Sarg, eds., Carbonate Sequence Stratigraphy: American Association of Petroleum Geologists Memoir 57, p. 409-434
- Franseen, E.K., W.L. Watney, C.G.St.C. Kendall, and W. Ross, 1991, Sedimentary modeling: Computer simulations and methods for improved parameter definition: Kansas Geological Survey Bulletin 233, 524 p.
- French, J.A., and W.L. Watney, 1990, Computer modeling of midcontinent cyclothem: Application to the prediction of hydrocarbon reservoirs: [abst.] American Association of Petroleum Geologists Bulletin, v. 74, p. 657.
- Gaffin, S.R., and K.A. Maasch, 1991, Anomalous cyclicity in climate and stratigraphy and modeling nonlinear oscillations: Journal of Geophysical Research, v. 6701-6712.
- Gaffin, S.R., 1992, Unforced oscillations in a freeboard and basin model: Analog to glacial/climate oscillators?: Journal of Geology, v. 100, p. 717-729.
- Goldhammer, R.K., P.A. Dunn, and L.A. Hardie, 1987, High-frequency glacio-eustatic sea level oscillations with Milankovitch characteristics recorded in Middle Triassic platform carbonates in northern Italy: American Journal of Science, v. 287, p. 853-892.
- Goldstein, R.H., and E.K. Franseen, 1995, Pinning points: a method providing quantitative constraints on relative sea-level history: Sedimentary Geology, v. 95, p. 1-10.
- Greenwood, H.S., 1989, On models and modeling: Canadian Mineralogist, v. 23, p. 1-14.
- Halderson, H.H., and Damsleth, E., 1993, Challenges in reservoir characterization: American Association of Petroleum Geologists Bulletin, v. 77, p. 541-551.
- Harbaugh J.W., and G. Bonham-Carter, 1970, Computer Simulation in Geology: Wiley Interscience, New York, 575 p.
- Hay, W.W., C.A. Shaw, and C.N. Wold, 1989, Mass-balanced paleogeographic reconstructions: Geologische Rundschau, v. 78, p. 207-242.
- Hay, W.W., C.N. Wold, and J.M. Herzog, 1992, Preliminary mass-balanced 3-D reconstructions of the Alps and surrounding areas during the Miocene: *in* Pflug, R., and J.W. Harbaugh, eds., Computer Graphics in Geology, Lecture Notes in The Earth Sciences, v. 41, Springer-Verlag, Berlin, p. 100-110.
- Helland-Hansen, W., C.G.St.C. Kendall, I. Lerche, K. Nakayama, 1988, A simulation of continental basin margin sedimentation in response to crustal movements, eustatic sea-level changes, and sediment accumulation rates: Mathematical Geology, v. 20, p. 777-802.
- Helland-Hansen, W., and J.G. Gjelberg, 1994, Conceptual basis and variability in sequence stratigraphy: a different perspective: Sedimentary Geology: v. 92, p. 31-52.
- Isaaks, E.H., and Srivastava, R.M., 1989, An introduction to applied geostatistics: Oxford University Press, New York, 561 p.
- Hunt, D., Fitchen, W.M., Swarbrich, R.E., and Allsop, T., 1995, Differential compaction as a primary control of sequence architecture and development in the Permian Basin: Geological significance and potential as a hydrocarbon exploration model, *in*, Garber, R.A., and Lindsay, R.F., eds., Wolfcampian-Leonardian shelf margin facies of the Sierra Diablo: Seismic scale models for subsurface exploration: West Texas Geological Society Guidebook, Publication 95-97, p. 83-104.
- Hunt, D., Allsop, T., and Swrbrich, R.E., in press, Differential compaction and sequence stratigraphy over the margins of the carbonate platforms and buildups, Geology.
- Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression: *in* Wilgus, C.K., et al., Sea-level changes: An integrated approach: SEPM Special Publication v. 42, p. 47-68.

- Kaufmann, P., J.P. Grotzinger, and D.S. McCormick, 1991, Depth-dependent diffusion algorithm for simulation of sedimentation in shallow marine depositional systems: *in* Franseen, E.K., W.L. Watney., C.G.St.C. Kendall, and W. Ross, 1991, Sedimentary modeling: Computer simulations and methods for improved parameter definition: Kansas Geological Survey Bulletin 233, p. 489-508.
- Kendall, C.G.St.C., and I. Lerche, 1988, The rise and fall of eustasy: *in* Wilgus, et al., eds., Sea-level changes: An Integrated Approach, SEPM Special Publication 42, p. 3-17.
- Kendall, C.G.St.C., Moore, P., Whittle, G., and Cannon, R., 1992, A challenge: Is it possible to determine eustasy and does it matter? *in* Dott, R.H., ed., Eustasy: The ups and downs of an historical concept: Geological Society of America Memoir 180, p. 93-107.
- Kerans, C., and Fitchen, W.M., 1995, Sequence stratigraphy and facies architecture of a carbonate ramp system: San Andres Formation of Algeria Escarpment and western Guadalupe Mountains, West Texas and New Mexico: Bureau of Economic Geology, University of Texas-Austin, Report of Investigations, No. 235, 86p.
- Knepell, P.L., and Arangno, D.C., 1993, Simulation validation: A confidence assessment methodology: IEEE Computer Society Press, 1-1 to R-2 p.
- Kominz, M.A., Beavan, J., Bond, G.C., McManus, J., 1991, Are cyclic sediments periodic? Gamma analysis and spectral analysis on Newark Supergroup lacustrine strata, *in*, Franseen, E.K., Watney, W.L., Kendall, C.G.St.C., Ross, W., eds., Sedimentary Modeling: Computer Simulations and Methods for Improved Parameter Definition: Kansas Geological Survey, Bulletin 233, p. 293-317.
- Koerschner, W.F., III, and Read, J.F., 1989, Field and modeling studies of Cambrian carbonate cycles: Journal of Sedimentary Petrology, v. 59, p. 654-687.
- Larue, D.K., and P.A. Martinez, 1989, Use of bed-form climb models to analyze geometry and preservation potential of clastic facies and erosional surfaces: American Association of Petroleum Geologists, Bulletin, v., 73, p. 40-53.
- Lawrence, D.T., M. Doyle, and T. Aigner,, 1990, Stratigraphic simulation of sedimentary basins -concepts and calibration: American Association of Petroleum Geologists Bulletin, v. 74, p. 273-295.
- Lawrence, D.T., 1994, Evaluation of eustasy, subsidence, and sediment input as controls on depositional sequence geometries, and the synchronicity of sequence boundaries: *in*, Weimer, P., and H. Posamentier, eds., Siliciclastic Sequence Stratigraphy -- Recent Developments and Applications, AAPG Memoir 58, p. 337-368.
- Lehr, J.H., 1990, The scientific process, Part II: Can we learn it?: Groundwater, v. 28, p. 850-855.
- Lerche, I., 1990, Basin Analysis: Quantitative Analysis, Volumes 1 & 2: Academic Press, San Diego, CA. 570 p.
- Lerche, I., 1990, Philosophies and strategies of model building: *in* Cross, T.A., ed., Quantitative Dynamic Stratigraphy, p. 21-44.
- Lessenger, M.A., and T.A. Cross, submitted, Sediment volume partitioning: Rationale for stratigraphic model evaluation and high-resolution stratigraphic correlation: Journal of Sedimentary Petrology, 19 p. 12 figures.
- Lessenger, M., 1993, Forward and inverse simulation models of stratal architecture and facies distributions in marine shelf to coastal plain environments: unpublished doctoral dissertation, Colorado School of Mines, 182 p.
- Mackey, S.D., and Bridge, J.S., 1995, Three-dimensional model of alluvial stratigraphy: theory and applications: Journal of Sedimentary Research v. B65, p. 7-31.
- Martinez, P.A., and Harbaugh, J.W., 1993, Simulating nearshore environments: Pergamon Press, Oxford, 265 p.
- Meyer-Peter, E., and R. Muller, 1948, Formulas for bed-load transport: Proceedings of the 2nd International Association of Hydraulic Structures Research Conference, Stockholm. Appendix 2, p. 39-64.
- Miller, K.G., Mountain, G.S., the Leg 150 Shipboard Party, and Members of the New Jersey Coastal Plain Drilling Project, 1996, Science, v. 271, p. 1092-1095.
- Nicolis, G., and C. Nicolis, 1991, Nonlinear dynamic systems in the geosciences: *in* Franseen, E.K., W.L. Watney, C.G.St.C. Kendall, and W. Ross, 1991, Sedimentary modeling: Computer simulations and methods for improved parameter definition: Kansas Geological Survey Bulletin 233, p. 33-42.
- Nordlund, U. and M. Sifversparre, 1994, Fuzzy logic -- A means for incorporating qualitative data in dynamic stratigraphic modeling, International Association of Mathematical Geology Annual Conference, Papers and Extended Abstracts for Technical Programs, p. 265-266.

- O'Neill, Z.V. and Gardner, R.H., 1979, Sources of uncertainty in ecological models, *in*, Zeigler, B.P., et al., eds, *Methodology in systems modeling and simulation*: North Holland Publishing Company, p. 447-463.
- Oreskes, N., Shrader-Frechette, K., and Belitz, K., 1994, Verification, validation, and confirmation of numerical models in the earth sciences: *Science*, v. 263, p. 641-646.
- Pflug, R., and J.W. Harbaugh, eds., 1992, *Computer Graphics in Geology -- Three-Dimensional Computer Graphics in Modeling Geologic Structures and Simulating Geologic Processes*, Lecture Notes in Earth Sciences #41, Springer-Verlag, New York, 298 p.
- Rankey, E.C., and W.L. Watney, 1994a, Data_Sim: A relational database for analysis of stratigraphic/sedimentologic computer models: American Association of Petroleum Geologists Annual Meeting Program p. 241.
- Rankey, E.C., and W.L. Watney, 1994b, Analysis of stratigraphic/sedimentologic computer models: International Association of Mathematical Geology Annual Conference, Papers and Extended Abstracts for Technical Program, p. 293-298.
- Rankey, E.C., 1996, *in prep.*, Isolating controls on sedimentation: Late Paleozoic, western USA. [unpublished Ph.D. dissertation].
- Rankey, E.C., and Lehrmann, D.J., *in press*, Anatomy and origin of toplap in a mixed carbonate-clastic system, Seven Rivers Formation (Permian, Guadalupian), Guadalupe Mountains, New Mexico, USA, *Sedimentology*.
- Reynolds, D.J., M.S. Steckler, and B.J. Coakley, 1991, The role of sediment load in sequence stratigraphy: The influence of flexural isostasy and compaction: *Journal of Geophysical Research*, v. 96, p. 6931-6949.
- Rivenaes, J.C., 1992, Application of a dual lithology, depth-dependent diffusion equation in stratigraphic simulation: *Basin Research*, v. 4, p. 133-146.
- Rivenaes, J.C., 1993, A computer simulation model for siliciclastic basin stratigraphy: [unpublished Ph.D. dissertation] University of Trondheim, 133 p. and 7 color plates.
- Ross, W.C., 1990, Modeling base-level dynamics as a control on basin-fill geometries and facies distribution-a conceptual framework: *in* Cross, T.A., *Quantitative Dynamic Stratigraphy*: Prentice-Hall, Englewood Cliffs, NJ, p. 387-399.
- Sargent, R.G., 1987, An overview of verification and validation of simulation models: *Proceedings, 1987, Winter Simulation Conference, Society of Computer Simulation*.
- Schwarzacher, W., 1975, Sedimentation models and Quantitative Stratigraphy: *Developments in Sedimentology* 19, Elsevier, Amsterdam, 382 p.
- Shuster, M.W., and Aigner, T., 1994, Two-dimensional synthetic seismic and log cross sections from stratigraphic forward models: *American Association of Petroleum Geologists Bulletin*, v., 78, p. 409-431.
- Slingerland, R., J.W. Harbaugh, and K.P. Furlong, 1994, *Simulating Clastic Sedimentary Basins*: Englewood Cliffs, NJ, Prentice-Hall, 220 p. and one disc.
- Spencer, R.J., and R.V. Demicco, 1989, Computer models of carbonate platform cycles driven by subsidence and eustasy: *Geology*, v. 17, p. 165-168.
- Stam, J.M.T., 1994, Process-based modeling of eolian bedforms: [unpublished Ph.D. dissertation] Technische Universiteit Delft, 170 p.
- Strobel, J., Soewito, F., Kendall, C.G., Biswas, G., Bezedk, J., and Cannon, R., 1989, Interactive (SEDPACK) simulation of clastics and carbonate sediments in shelf to basin settings: *Computers and Geosciences*, v. 15, p. 1279-1290.
- Swift, D.J.P., 1975, Barrier-island genesis: evidence from the central Atlantic shelf, Eastern U.S.A., *Sedimentary Geology*, v. 14, 1-43.
- Syvitski, J.P.M., and J.M. Alcott, *in press*, RIVER3: Simulation of water and sediment river discharge from climate and drainage basin variables: *Computers and Geosciences*.
- Syvitski, J.P.M., and S. Daughney, 1992, DELTA2: delta progradation and basin filling: *Computers and Geosciences*, v. 18, p. 839-897.
- Tezloff, D.M., and J.W. Harbaugh, 1989, *Simulating Clastic Sedimentation*: Van Nostrand Reinhold, 202 p. and 16 color plates.
- Turcotte, D.L., and G. Schubert, 1982, *Geodynamics - Applications of Continuum Physics to Geological Problems*: New York, John Wiley and Sons, 450 p.

- Vail, P.R., R.M. Mitchum Jr., R.G. Todd, J.M. Widmier, S. Thompson, III, J.B. Sandgree, J.N. Bubb, and W.G. Hatelid, 1977, Seismic stratigraphy and global changes in sea-level: in Payton, C.E., ed., *Seismic Stratigraphy - Applications to Hydrocarbon Exploration: AAPG Memoir 26*, p. 49-212.
- Van Hinte, J.E., 1978, Application of micropaleontology in exploration geology: *American Association of Petroleum Geology Bulletin*, v., 62, p. 201-222.
- Watney, W.L., French, J.A., and Guy, W.J., 1996, Modeling petroleum reservoirs in Pennsylvanian strata of the Midcontinent USA, *in*, Forster, A., and Merriam, D.F., *Geologic Modeling and Mapping*, Plenum Press, New York, p. 43-77.
- Watney, W.L., J.A. French, J.A. Doveton, W.J. Guy, and J.C. Youle, 1994, Architecture of Pennsylvanian carbonate shelf, Midcontinent, U.S.A. -- Cycle hierarchy and reservoir development: [abst.] *American Association of Petroleum Geologists Annual Convention Program*, p. 279.
- Wendebourg, J., 1994, *Simulating hydrocarbon migration and stratigraphic traps: unpubl. doctoral dissertation, Stanford University*, 258 p.
- Wendebourg, J., and Harbaugh, J.W., 1996, Sedimentary process simulation: A new approach for describing petrophysical properties in three dimensions for subsurface flow simulations: *in*, Forster, A., and Merriam, D.F., *Geologic Modeling and Mapping*, Plenum Press, New York, p. 1-25.
- Wilson, J.L., 1975, *Carbonate Facies in Geologic History: Springer-Verlag*, 471 p.
- Wold, C.N., and W.W. Hay, 1990, Estimating ancient sediment fluxes: *American Journal of Science*, v. 290, p. 1069-1089.



modified from Greenwood (1989)

Figure 1. Model designs (after Greenwood, 1989).

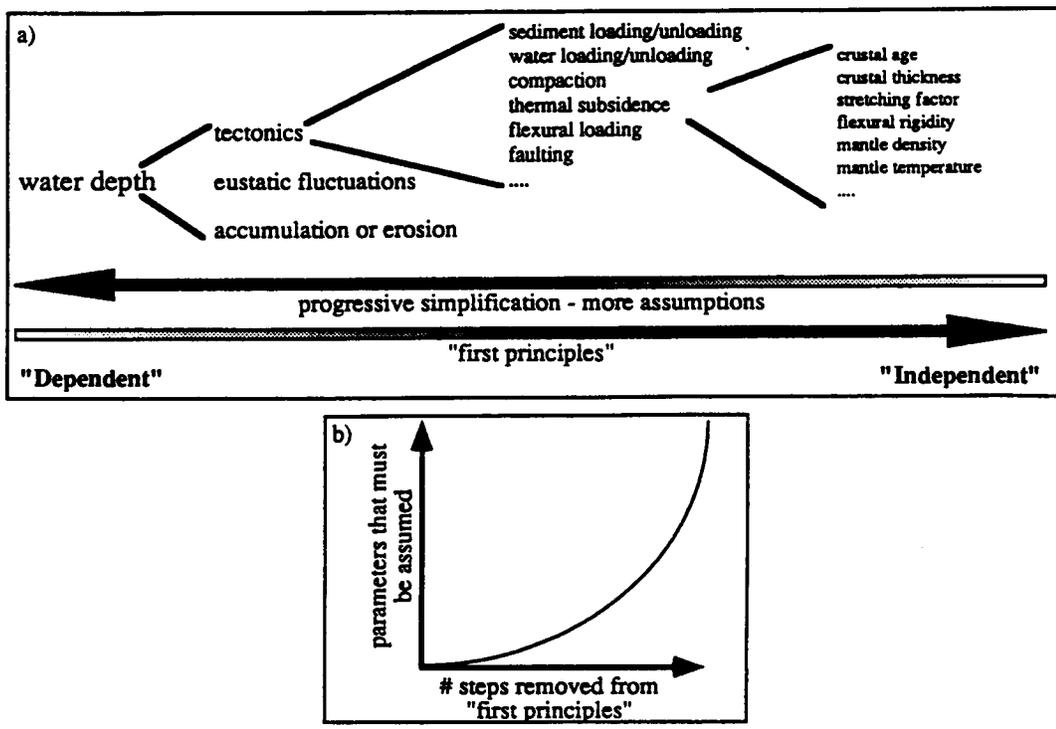


Figure 2. Example of independent and dependent parameters.

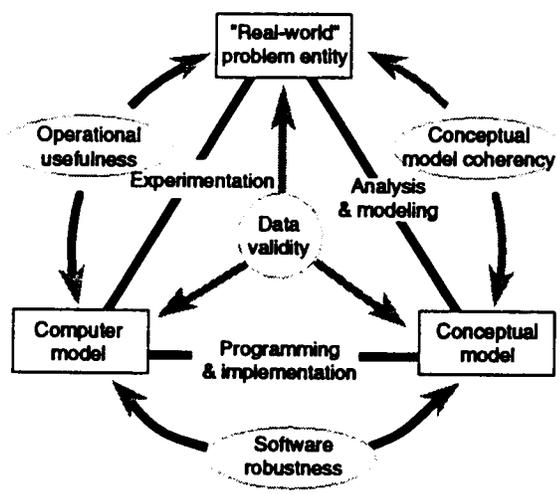


Figure 3. Framework for model evaluation (after Sargent, 1987).

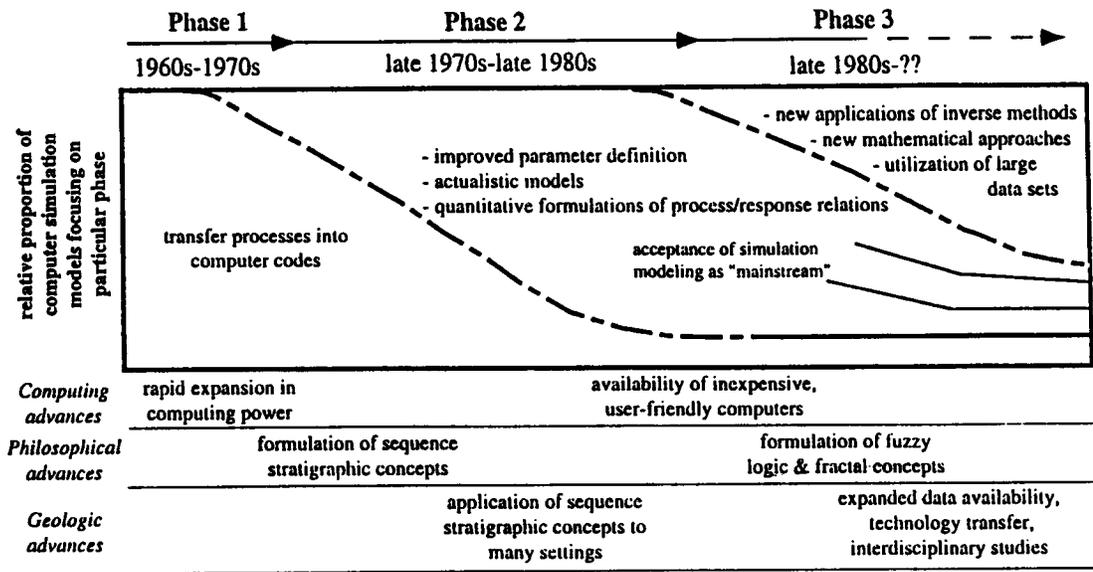


Figure 4. Temporal succession in development of forward stratigraphic simulation models. All three phases continue to be viable, valuable avenues of research today.

	Forward/inverse models	Empirical observations	Physical laws/theory	Mass balance	Modern analogs
Sea-level history	a) Koerschner and Read (1989) utilized Fisher plots to derive a relative sea-level history; b) Watney et al. (1994) used Fourier analysis of Th/U ratios to constrain stacking patterns and define relative sea-level history.	Franseen et al. (1993) and Goldstein and Franseen (1995) traced subaerial exposure surfaces down paleoslope to obtain a quantified value for minimum falls in relative sea-level for Miocene carbonates in Spain.	No examples, save Milankovitch hypothesis	Several models (for example, French and Watney 1990) utilize Pleistocene oxygen isotope curves as proxies for ice volume (and thus sea-level).	Bosence et al. (1994) utilized facies and geometries in Miocene carbonates that were similar to Pleistocene examples to estimate relative sea-level changes. By observing lateral and vertical patterns, they were able to derive a sea-level history.
Tectonics	The Quantitative Stratigraphy Model of Ross et al. (in review) extracts subsidence and sediment supply data from backstripping across a basin.	Many authors utilize the observations of Bond and Kominz (1984) to describe subsidence patterns on passive margins.	Many studies cite the work of Turcotte and Schubert (1982) to describe the deflection of the lithosphere due to a sediment or thrust load.		Most models assume that short-term tectonics are insignificant in driving sedimentation patterns. Neotectonics can be a significant influence on sensitive sedimentary systems (e.g. alluvial plains).
Compaction	Reynolds et al. (1991) executed a series of sensitivity analysis to describe (theoretically) the influences of flexural rigidity and compaction on sedimentation patterns.	Rivenaes (1993) used pre-existing well-core porosity data and the empirical curves of Baldwin and Butler (1983) to estimate compaction with burial.			
Sediment erosion/accumulation	a) Bosence et al. (1994) performed several sensitivity procedures and compared results with observed geometries to evaluate possible depositional scenarios and constrain parameters. b) Bosscher and Schlager (1992) used sensitivity analysis to estimate the influence of several growth parameters on growth rates c) Bond et al. (1993) utilize the "gamma method" to estimate sediment accumulation rates, calibrated using comparison of resulting time-series analysis of successions of sedimentary cycles.	a) Enos (1991) tabulated 1000s of studies of sediment accumulation rates in modern and ancient settings in various environments b) Flemings and Jordan (1989) tabulated sediment transport coefficients for siliciclastics in various environments; They also considered the fill rates of several well-studied foreland basins.	Tezloff and Harbaugh (1989) describe sediment-fluid relations in terms of the Navier-Stokes equation. All sediment dynamics are controlled by this equation (and the 2nd Law of Thermodynamics)	a) Hay et al. (1989; 1992) used the inverse of erosion equations and estimates of sediment volumes to reconstruct the Miocene Alps and the Late Pliocene/Pleistocene Rocky Mountains. b) Wold and Hay (1990) estimated global sediment fluxes through the Phanerozoic.	a) Bosscher and Schlager (1992) evaluated Holocene depth-production pairs to arrive at estimates of carbonate accumulation rate changes with depth. b) Slingerland et al. (1994) use charts of data showing suspended sediment yield vs. mean annual precipitation and mean basin elevation, and denudation rate vs. mean local relief and amount of uplift.
Initial depositional profile		French and Watney (1990) utilized regional isopach maps and facies patterns to estimate original depositional profiles in the Pennsylvanina of the midcontinent U.S.A.	Ross et al. (1995) utilized the concept of a "graded profile of equilibrium" to define shelf profiles at run starts and throughout model runs		

Table 1. Sources of information used as input in stratigraphic simulation models.

NES Workshop Overview

General Statement

This is a workshop and all that it implies.

Stratigraphic and sedimentologic computer modeling has the potential to be a primary vehicle in advancing our understanding of the interaction of geologic processes that created the stratigraphic record. Because computer simulations require acquisition, utilization, and integration of all available data, they serve a valuable role in conceptual and practical understanding of stratigraphic and sedimentologic systems.

Modeling has advanced to a new threshold of usefulness and successes have established the potential for wider application. With this comes the need for better understanding of how models operate. How can models be tested and confirmed? What aspect of the model construction causes differences, what are the advantages and disadvantages of the various types of models given various types of problems? How do models perform? What areas of modeling show new promise?

Experts in quantitative modeling and simulation of the stratigraphic record and those working on deriving such data suited for these models are assembled to pursue several meeting objectives:

Objectives

1. To characterize, demonstrate, and compare various approaches to both inverse and forward stratigraphic computer modeling;
2. To explicitly compare models utilizing common data sets;
3. To define trends and promising areas of research;
4. To focus discussions of results, philosophies, and applications of computer simulation modeling;
5. To encourage discussion and interaction.

Anticipated Results

1. Enhanced understanding of similarities and differences between models and modeling philosophies;
2. Increased communication among different modeling groups;
3. Critical evaluation of applications where models have and have not been successful and an assessment of how they might be better utilized;
4. Improved and refined techniques for describing model input and output, including field-, lab-, and computer-based data.

Overview of Workshop

The meeting assembles a unique, broad spectrum group of modeling experts. Disciplines include:

1. Basin (passive margin and foreland basin) research;
2. Petroleum reservoir characterization;
3. Oceanography of coastal, shelf, and deep sea regions;
4. Bedform modeling;
5. Structural, stratigraphic, sedimentologic, paleontologic and climatological modeling;
6. Modern/Neogene and ancient stratal modeling and analog development;
7. Deterministic, stochastic, and nonlinear modeling;
8. Inverse and forward modeling;
9. Uncertainty estimating;
10. Improved empirical data sets and analog "test beds" for better model confirmation.

Meeting Schedule

A. Model Comparisons, Wednesday, May 15, 1996 -- 11 talks, 9 posters, 15 computer demonstrations, 5 breakout sessions, informal discussions

B. Novel Outcomes, Thursday, May 16, 1996, 8 talks, 9 posters, computer demonstrations (continued), 5 breakout sessions, informal discussions

C. Inverse Methods, New Philosophies, Friday, May 16, 1996 -- 7 talks, 2-4 meeting summary led by breakout session findings

The workshop is designed to provide opportunities to present, listen, see, demonstrate, and discuss latest developments in numerical modeling. Focused comments are encouraged via *Topical Breakout Sessions* --

1. Model Comparisons;
2. Model Optimization;
3. Geologic Observation/Parameterization;
4. Algorithms/Output;
5. Inverse Methods.

Goals of the *Topical Breakout Sessions* include

1. Encourage an exchange of ideas and focused discussion;
2. Capture the major points of the discussions;
3. Organize summaries presented during the workshop; and
4. Develop "white papers" to be published with proceedings.

Break Session Titles and Co-Chairs:

1. Model Comparisons
Co-Chairs -- **Hemmo Bosscher**, Shell International E&P B.V.
Johannes Wendebourg, Intitut Francais du Petrole
2. Model Optimization
Co-Chairs -- **John Harbaugh**, Stanford University
Scott Bowman, Marco Polo & Rice Univ.
3. Geologic Observation/Parameterization
Co-Chairs -- **Marty Perlmutter**, Argonne National Laboratory
P.L. deBoer, Institute of Earth Science., Univ. of Utrecht
James Syvitski, Arctic and Alpine Research Center, University of Colorado
4. Algorithms/Output
Co-Chairs -- **Dan Tetzlaff**, Western Atlas
Mike Steckler, Lamont-Doherty Geological Observatory
5. Inverse Methods
Co-Chairs -- **Margaret Lessenger**, Colorado School of Mines
Ian Lerche, University of South Carolina

Publication?

An majority of participants at this workshop are interested in publishing in a proceedings of this meeting. This will be discussed.

May 15-17, 1996 - Meeting

Summer 1996 - Collate "white papers," summarize findings, update NES home page, prepare for published volume, obtain publisher

Fall/Winter 1996 - Submit manuscripts

Winter/Spring - Review and revise manuscripts

Spring 1996 - Edit volume

Summer/Fall 1997 - Publish hard copy volume with accompanying CD-ROM



Modeling Parameters for Siliciclastic Model Comparison -- Baltimore Canyon

Overview

A "real world" example from Baltimore Canyon offshore, USA was selected for model comparison. This Neogene siliciclastic shelf-to-basin transect contains sediment deposited in shallow marine/coastal plain, deltaic, and deep slope settings. This model comparison dataset is focused on a long dip-oriented seismic line, Ewing 1003. This line and supporting data were generously provided by the Lamont research group (Greg Mountain, Mike Steckler, Nick Christie-Blick, and Ken Miller). A large-scale, unmarked copy of the Ewing 1003 and a black-line print containing tracings of the major sequence boundaries are enclosed. Other supporting data necessary for modeling are also enclosed and are available on the FTP server as described below.

The setting for this comparative modeling exercise has some of the best, well constrained information that are publicly available including good age models, facies, and stratal geometry. Subsidence is essentially linear through the period of the Neogene increasing steadily across the shelf, minimizing its impact on sedimentation. The Baltimore Canyon area continues to be of interest to industry, academia and large government-sponsored research programs such as the Ocean Drilling Program due to the quality of the data and uniqueness of the setting. Prospects appear to be very good of acquisition of new information in this area and along this seismic line (see enclosed memo by Mountain and others).

Input parameters are supplied on attached tables and are available to download via an FTP server at the Kansas Geological Survey at the address *crude2.kgs.ukans.edu*. You will need to log in as *anonymous* and use your *e-mail address* as the password. Files are located in directory */pub/outgoing/*. The files include comma delimited (.csv), Excel (.xls), and text (.txt) formats:

- 1) this document ([silicicl.txt](#)),
- 2) comma delimited file with elevations of key sequence boundaries ([datums3.xls](#) and [datums3.csv](#)),
- 3) sea-level history (Haq curve fit adjusted to time scale described by Mountain and others, [haqsl2.xls](#), [haqsl2.csv](#)),
- 4) subsidence rates ([subside.xls](#), [subside.csv](#)),
- 5) original picks on the seismic section in two-way travel time ([picks.xls](#), [picks.csv](#)).

Output specifications are provided below. Please follow these specifications as closely as possible to facilitate comparisons. Also, please send your output directly to the attention of Lynn Watney in Lawrence by **May 1st**, if possible, in order for us to compile and summarize the results before the meeting. The FTP server in directory */pub/incoming/* can be used to report results (text and graphics files). We need to know the file name and format. We can read and convert most graphics formats, if you tell us what the original format is, e.g., SGI rgb format, tifs, gifs, etc.

DEADLINE FOR MODEL RESULTS: May 1

NOTE: If you are going to make a presentation on your model in the comparison session on day 1 of the meeting, we would suggest that it be focused on why your model is different, important parameters, algorithms used, major assumptions (explicit, implicit), and an example of a successful/optimal model of the "real world."

THE SILICICLASTIC DATA SET -- Baltimore Canyon

Input Parameters

The primary data set for the Baltimore Canyon consists of a dip-oriented seismic profile (Ewing Line 1003) and an age model provided by the Lamont group (See enclosures). Additional references on the area include papers by Greenlee and others. (1988), Greenlee and others (1992), Schroeder and Greenlee (1993), and Miller and others (1996). The complete references follow.

An Exxon seismic section and chronostratigraphic diagram was modeled by Schroeder and Greenlee (1993). This Exxon section is only several hundred meters from Ewing Line 1003. Lithology, biostratigraphy, depositional facies, stratigraphic ages, and ages ranges of sequence boundaries were previously developed using nearby well control. Nine depositional sequences are recognized in the Miocene (see memorandum and enclosures by Mountain and others, and copy of paper by Miller and others, 1996). Several sequences exhibit onlapping in a landward direction and downlapping in a seaward direction, defining a series of shelf edges. Four middle Miocene sequences show pronounced progradation.

Two Middle Miocene sequences are chosen for model comparison, delimited by the boundaries m5(Green), m4(Pink-2), and m3(Blue). These sequences span an age range of 18 Ma (million years) to 13 Ma. These sequence boundaries as well as others are identified as traces on the cross section that accompanies the unmarked Ewing 1003 seismic section. These correlations were made by Mountain and others (see enclosed note). The m5(Green) seismic surface is also the initial depositional surface for the modeling exercise. If you have a high resolution, 2-D siliciclastic model to test, please use the lower sequence between m5 and m4 sequence boundaries.

Elevations of Sequence Boundaries

The modeling information includes elevations in meters of sequence boundaries extracted from the seismic sections including the base of the interval to be modeled (m5[Green] seismic marker). These datum elevations are part of the file called datums3.csv and datums3.xls. The former is a comma delimited file and the later is an Excel spreadsheet. The files are on the FTP server as described above. A copy of the tabular data is enclosed. The original picks made from the seismic section in two-way travel time are provided on enclosed table called Picks and on similarly titled files picks.csv and picks.xls.

The time-to-depth conversion is based on the following table supplied by Greg Mountain.

2-way time	depth
below seafloor	below seafloor
milliseconds	meters

100	72
-----	----

200	165
300	255
400	345
500	434
600	526
700	619
800	715
900	816
1000	923
1100	1035
1200	1155
1300	1284
1400	1422
1500	1571

Sea Level History

The Haq and others (1987) sea-level curve is provided for the time interval to be modeled in file [haqsl2.csv](#) ([haqsl2.xls](#)). The curve is adjusted to the time scale established by Mountain and others (see attached). Please make your own adjustments of sea level and shelf elevation.

Subsidence

The subsidence rate is adapted from Schroeder and Greenlee (1993) and is found in a file called [subside.csv](#) ([subside.xls](#)).

Model Output for Baltimore Canyon Comparison Data Set

Please provide the following output by **May 1st** in a form as close as possible to that defined here. You can use the FTP server to place text and graphic files. Please supply the file names and file types by separate e-mail. If there are questions, please contact Lynn Watney at lwatney@pcmail.kgs.ukans.edu.

1. Depth cross section or 3-D view showing --
 - a. depositional facies,
 - b. depositional sequences,
 - c. ages of major sequence boundaries at points of maximum regression,
 - d. point of maximum onlap,
 - d. locations of 1-million year incremental time lines (19, 18, ...12 Ma).

2. Chronostratigraphic diagram including --
 - a. six depositional facies:
 - depth based: >0 m above sea level
 - 0-10 m
 - 10-20 m
 - 20-50 m
 - 50--200 m
 - 200+m

- b. location of depositional shelf edge.
- 3. Stratigraphic columns at 40 km, 60 km, and 78 km:
 - a. depositional sequence boundaries and their range in age,
 - b. depositional facies (see above),
 - c. 1 m.y. incremental time lines.

Selected References

Greenlee, S.M., and Moore, T.C., 1989, Recognition and interpretation of depositional sequences and calculation of sea-level changes from stratigraphic data - offshore New Jersey and Alabama Tertiary: *in*, Wilgus, C.K., eds., *Sea-Level Changes: An Integrated Approach*, Society of Economic Paleontologists and Mineralogists, Special Publication No. 42, Tulsa, p. 329-353.

Greenlee, S.M., Schroeder, F.W., and Vail, P.R., 1988, Seismic stratigraphic and geohistory analysis of Tertiary strata from the continental shelf off New Jersey; Calculation of eustatic fluctuations from stratigraphic data: *in*, *The Geology of North America*, Vol. I-2, *The Atlantic Continental Margin: U.S.*, The Geological Society of America, Boulder, p. 437-444.

Greenlee, S.M., Devlin, W.J., Miller, K.G., Mountain, G.S., and Flemings, P.B., 1992, Integrated sequence stratigraphy of Neogene deposits, New Jersey continental shelf and slope: Comparison with the Exxon model: *Geological Society of America, Bulletin*, v. 104, p. 1403-1411.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, The chronology of fluctuating sea level since the Triassic: *Science*, v. 235, p. 1156-1167.

Miller, K.G., and Mountain, G.S., 1994, 2. Global sea-level change and the New Jersey margin: *in*, Mountain, G.S., Miller, K.G., Blum, P., et al., *Proceedings of the Ocean Drilling Program, Initial Reports*, v. 150, p. 11-20.

Miller, K.G., Mountain, G.S., the Leg 150 Shipboard Party, and Members of the New Jersey Coastal Plain Drilling Project, 1996, *Science*, v. 271, p. 1092-1095.

Schroeder, F.W. and Greenlee, S.M., 1993, Testing eustatic curves based on Baltimore Canyon Neogene stratigraphy: An example application of basin-fill simulation: *American Association of Petroleum Geologists, Bulletin*, v. 77, No. 4, p. 638-656.

Acknowledgement

Our thanks to Greg Mountain, Mike Steckler, Nick Christie-Blick, and Ken Miller for sharing the seismic data and supporting information.

Lamont-Doherty Earth Observatory | Palisades, NY 10964
of Columbia University

Telephone: (914) 365-8540
Internet: mountain@ldeo.columbia.edu

Fax: (914) 365-3181

Modellers:

Tracings are based upon our best efforts at first identifying mappable reflectors on the slope that could be correlated to Leg 150 drillsites, and then tracing each up onto the shelf and across the grid of Ew9009 lines to line 1003. Several sites proposed for ODP drilling (MAT1 through 7A) on the enclosed map lie along this line 1003; it coincides with Greenlee's line 6 to within a few hundred meters.

In most cases and without too much finagling, we found that these major slope surfaces matched reflectors on the shelf that had the geometry to be able to be properly called sequence boundaries. We show 8 reflectors on the tracing provided to you that have been correlated this way to Leg 150 drillsites, and which also match to the best of our ability sequence boundaries of Greenlee et al., 1992 (GSA 104:1403-1411). The tentative ages provided by the latter were based on commercial well cuttings on the shelf; these have been improved by Miller et al., 1996 (Science 271[5252]:1092-1095). These tentative sequence boundaries have been traced on the enclosed profile to the limits of where we are most confident they meet the need of the modelers; more work is required to extend these to the ends of this profile.

The enclosed table (from Miller et al., 1996) provide ages of these surfaces and shows how far out onto a limb we're willing to go by matching them to surfaces drilled onshore in Leg 150X. The Haq curve, both on this table and on the accompanying drawing, is simply taken from the 1987 publication and adjusted to the time scale we've used (as described in the footnote on the table.)

Of all the time intervals worth devoting effort to, we recommend that between m3 and m5; age control is adequate and geometries of the clinoforms are pretty good, and if line 1003 is ever drilled, these sediments will be sampled extensively.

Good luck!

Greg Mountain
Mike Steckler
Nick Christie-Blick
Ken Miller

77°

76°

75°

74°

73°

72°W

41°N

MID-ATLANTIC TRANSECT

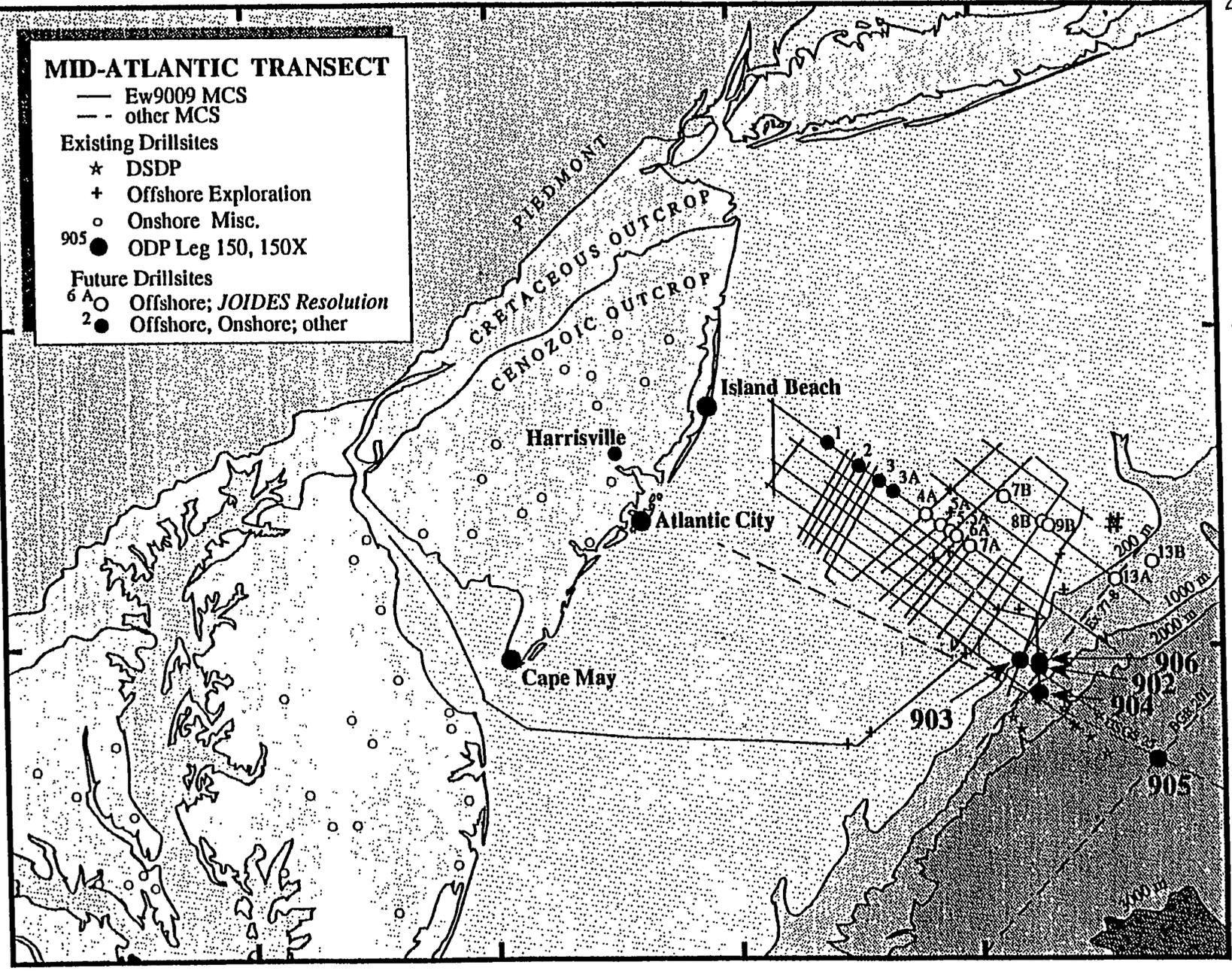
- Ew9009 MCS
- - other MCS

Existing Drillsites

- ★ DSDP
- + Offshore Exploration
- Onshore Misc.
- 905 ● ODP Leg 150, 150X

Future Drillsites

- 6 A ○ Offshore; JOIDES Resolution
- 2 ● Offshore, Onshore; other



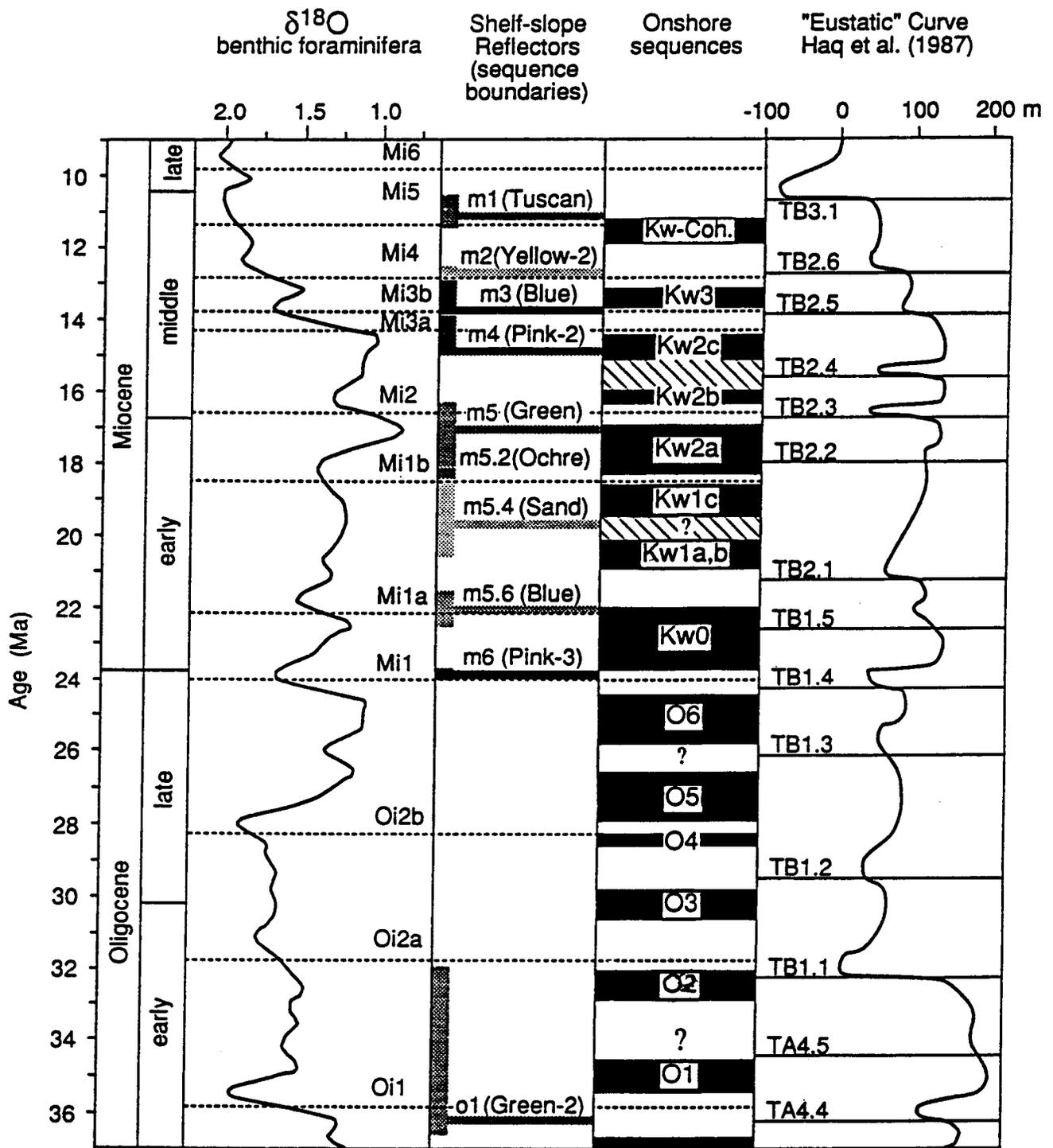
44

40°

39°

38°





Miller et al. Figure 2

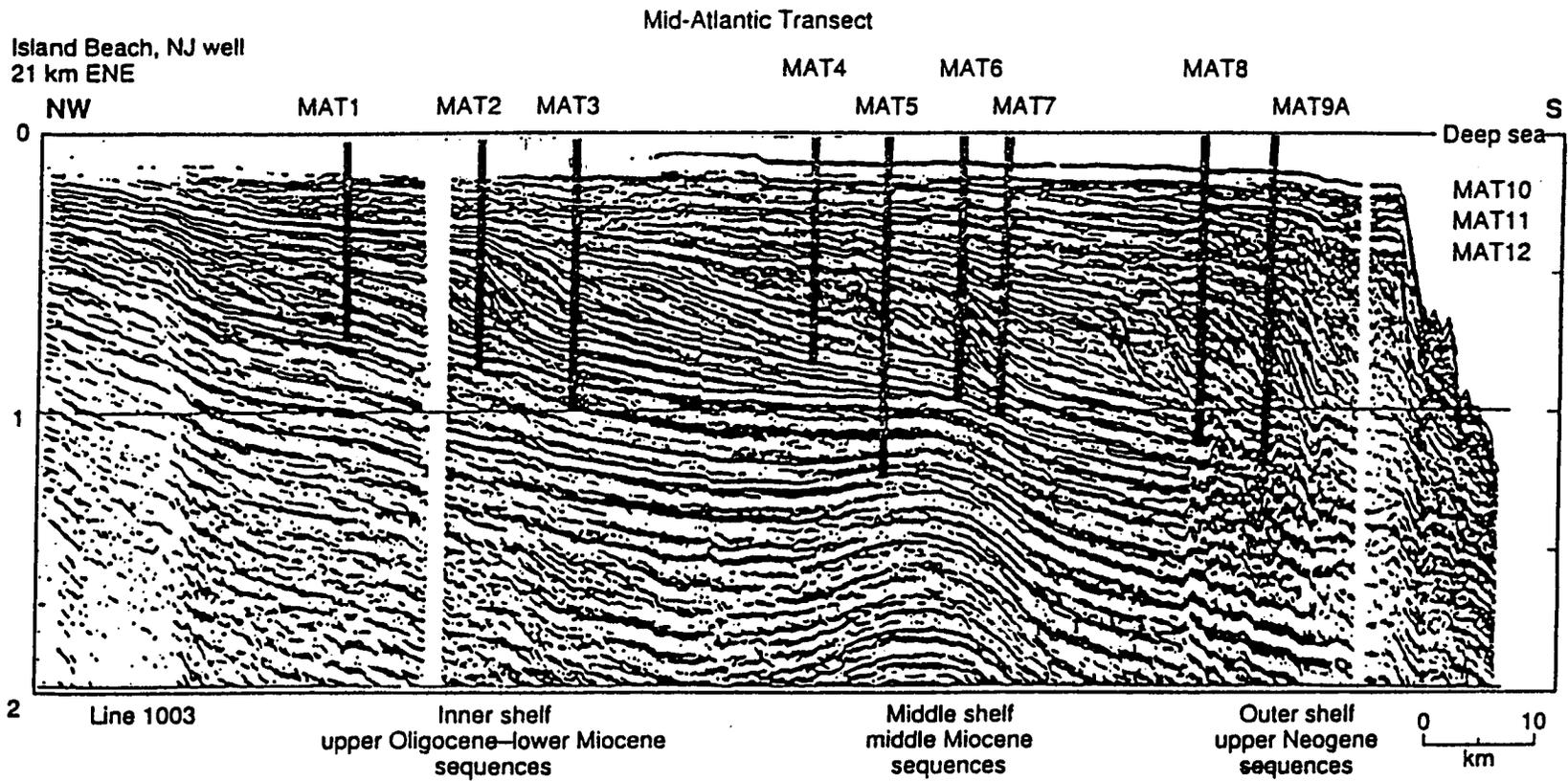


Figure 4. The Mid-Atlantic Transect. Compressed Cruise Ew9009 Line 1003 showing locations of shelf sequences and proposed shelf boreholes MAT1-9.

Table 1. Comparison of Sr-isotope based age estimates of Oligocene-middle Miocene seismic reflectors, New Jersey continental slope with onshore sequences^(26,28), oxygen isotopic increases^(12,16), and the sequences of Haq et al.⁽⁶⁾.

Slope reflector	Age estimate, Ma		Onshore	$\delta^{18}\text{O}$		Haq et al.	
	best (error)	BKSA95		Zone	Max. inflection	Sequence	Age/Corr. age
m1 (Tuscan)	~11 (10.5-11.3)	~11.5	--	Mi5	11.3-11.4	TB3.1	10.5
m2 (Yellow-2)	12.5 (12.5-12.6)	12.7	Kw-Coh?	Mi4	12.6-12.8	TB2.6	12.5
m3 (Blue)	13.6 (12.8-13.6)	13.6	Kw3	Mi3b	13.5-13.6	TB2.5	13.8
m4 (Pink-2)	14.8 (13.8-15.0)	14.7	Kw2c	Mi3a	14.1-14.4*	TB2.4	15.5
m5 (Green)	~16.9 (16.3-18.0)	~16.6	Kw2b	Mi2	16.1-16.3	TB2.3	16.5
m5.2 (Ochre)	18.2 (18.0-18.4)	17.7	Kw2a	Mi1b	18.1-18.5	TB2.2	17.5
m5.4 (Sand)	19-20 (18.4-20.6)	18.8-19.8	Kw1c	?minor	?20.6-21.1*	TB2.1	21.0
m5.6 (True blue)	~22 (21.5-22.5)	21.8	Kw1a,b	Mi1a	21.8-22.4	TB1.5	22.0
m6 (Pink-3)	23.8 (23.6-24.0)	23.8	Kw0	Mi1	23.5-23.8	TB1.4	25.5/24.2
			O6	?minor	26.0-26.2*	TB1.3	26.5/26.3
			O5	Oi2b	28.0/28.2	TB1.2	28.4/29.4
			O4	?minor	?	--	--
			O3	Oi2a	31.5-32.0	TB1.1	30.0/32.2
			O2	?minor	?	TB4.5	33.0/34.4
o1 (Green)	35.8-36.7 (32-36.7)		Oi1	--	35.8-36.0	TA4.4	36.0/35.9

* not a formal isotopic zone.

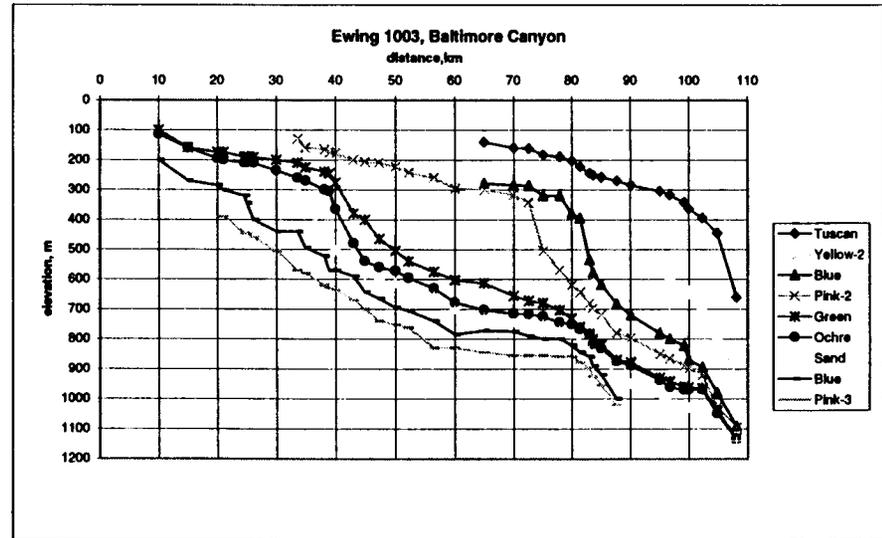
BKSA95 column provides the ages of sequences using the Berggren et al. (in press⁽¹⁴⁾). Corrected ages of Haq et al.⁽⁶⁾ were obtained by linearly interpolating ages between TB1.4 corrected for time scale differences (24.2 vs. 25.5 Ma), the revised age of the TB1.1 sequence of 32.2 Ma⁽³²⁾, and the revised age of TA4.4 of 35.9 Ma⁽³²⁾. Differences were obtained by subtracting the best estimates of New Jersey slope reflectors or the timing of the inflections in the oxygen isotope record from the Haq et al. sequence ages.

datums3.xls

**Baltimore Canyon
Ewing 1003 seismic section**

Distance from left kilometers	Sequence Boundaries										
	m1 Tuscan meters	m2 Yellow-2 meters	m3 Blue meters	m4 Pink-2 meters	(top datum)	(initial [lower] datum)	m5 Green meters	m5.2 Ochre meters	m5.4 Sand meters	m5.6 Blue meters	m6 Pink-3 meters
10							100	115		200	
15							160	160		270	
20							175	195		285	
21.05							175	200		302	390
24.6							190	210		320	445
25							192	210		345	447
26.16							192	211		400	460
30							200	235		440	505
33.6				129			210	260	292	440	570
34.9				158			225	270	332	495	580
38.08				165			240	300	460	522	620
38.9				175			245	305	480	570	630
40				178			276	365	503	570	635
43				200			380	480	565	590	670
44.9				208			400	540	590	642	700
47.3				210			465	560	600	665	740
50				223			503	572	612	695	752
52.2				243			540	595	635	705	762
56.5				260			575	630	655	740	830
60				295			603	678	700	785	830
65	140		278	300			613	703	724	772	845
70	160		285	318			655	715	745	775	855
72.6	162		286	343			672	717	750	790	855
75	183		320	503			680	725	748	800	855
77.9	190		320	568			703	745	770	800	858
80	203		380	618			730	750	785	821	858
81.4	223		395	642			760	767	805	845	878
83	245		535	681			782	786	835	860	898
83.6	250		578	698			801	818	850	890	925
85	258		618	722			818	832	868	920	955
87.7	270		682	780			870	875	918	1000	1020
90.1	285		720	795			878	890	950		
95	305		780	850			930	938	995		
96.8	318	590	800	865			942	962	1005		
99.2	343	638	823	890			960	970	1042		
100	363	650	870	898			962	970	1030		
102.3	395	695	895	920			965	970	1065		
104.8	445	800	980	1030			1040	1050	1080		
108.1	660	920	1092	1095			1130	1135	1140		

48



PICKS

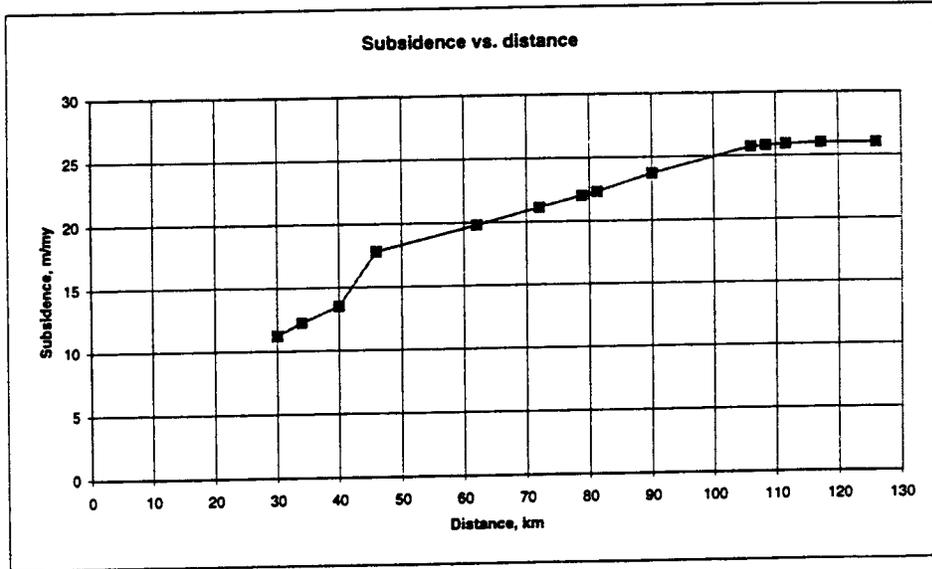
Baltimore Canyon, picks.csv and picks.xls
Ewing 1003

km from left	zero to seafloor	two-way travel time								
		m1 Tuscan	m2 Yellow-2	m3 Blue	m4 Pink-2	m5 Green	m5.2 Ochre	m5.4 Sand	m5.6 Blue	m6 Pink-3
10	0.08					0.205	0.22		0.315	
15	0.08					0.25	0.27		0.395	
20	0.08					0.2855	0.31		0.415	
21.05	0.08					0.285	0.315		0.43	0.53
24.6	0.08					0.295	0.33		0.45	0.59
25	0.08					0.3	0.33		0.48	0.595
26.16	0.08					0.305	0.34		0.535	0.61
30	0.08					0.32	0.355		0.585	0.66
33.6	0.08				0.24	0.325	0.38	0.41	0.585	0.725
34.9	0.08				0.265	0.345	0.395	0.465	0.645	0.735
38.08	0.08				0.275	0.365	0.43	0.6	0.675	0.78
38.9	0.08				0.285	0.37	0.435	0.625	0.725	0.79
40	0.08				0.29	0.4	0.5	0.655	0.725	0.795
43	0.08				0.315	0.49	0.635	0.72	0.75	0.83
44.9	0.08				0.325	0.535	0.69	0.75	0.805	0.86
47.3	0.08				0.33	0.615	0.713	0.76	0.83	0.9
50	0.082				0.345	0.655	0.73	0.775	0.86	0.915
52.2	0.085				0.37	0.695	0.76	0.798	0.875	0.943
56.5	0.085				0.385	0.735	0.795	0.82	0.905	0.995
60	0.082				0.42	0.765	0.84	0.865	0.95	0.98
65	0.097	0.27		0.395	0.445	0.805	0.88	0.905	0.95	1.02
70	0.105	0.3		0.44	0.47	0.84	0.905	0.93	0.96	1.04
72.6	0.108	0.305		0.445	0.503	0.86	0.91	0.94	0.98	1.04
75	0.109	0.33		0.49	0.685	0.87	0.92	0.94	0.99	1.04
77.9	0.109	0.335		0.5	0.75	0.9	0.935	0.96	0.99	1.045
80	0.109	0.35		0.525	0.8	0.925	0.942	0.978	1.01	1.045
81.4	0.109	0.37		0.56	0.83	0.95	0.963	1	1.025	1.067
83	0.109	0.397		0.712	0.87	0.975	0.985	1.025	1.05	1.085
83.6	0.11	0.4		0.761	0.89	0.995	1.01	1.04	1.08	1.105
85	0.115	0.413		0.808	0.92	1.015	1.03	1.063	1.11	1.14
87.7	0.117	0.43		0.885	0.98	1.065	1.07	1.11	1.18	1.2
90.1	0.118	0.45		0.925	0.995	1.075	1.085	1.14		
95	0.118	0.475		0.98	1.045	1.12	1.13	1.18		
96.8	0.119	0.485	0.785	1	1.065	1.138	1.155	1.19		
99.2	0.118	0.515	0.83	1.04	1.085	1.15	1.16	1.22		
100	0.12	0.54	0.85	1.065	1.095	1.155	1.215	1.215		
102.3	0.128	0.585	0.905	1.1	1.125	1.165	1.167	1.25		
104.8	0.13	0.64	1.01	1.185	1.225	1.24	1.25	1.265		
108.1	0.135	0.875	1.13	1.265	1.266	1.315	1.316	1.32		

SUBSIDE.XLS

Baltimore Canyon, subside.xls

control point (km)	subsidence rate (m/my)
30	11.2
34	12.2
40	13.5
46	17.8
62	19.8
72	21.1
78.8	22
81.2	22.3
90	23.7
106	25.7
108.4	25.8
111.6	25.9
117.2	26
126	26

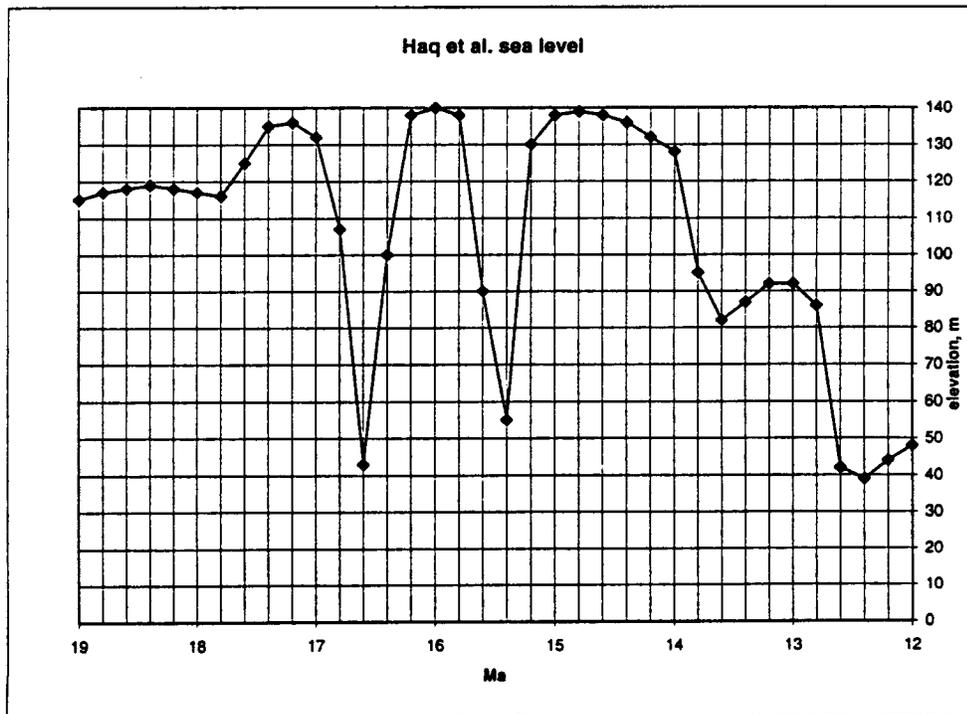


HAQSL2.XLS

Baltimore Canyon, haqsl2.xls

Haq et al. sea level
Ma m

12	48
12.2	44
12.4	39
12.6	42
12.8	86
13	92
13.2	92
13.4	87
13.6	82
13.8	95
14	128
14.2	132
14.4	136
14.6	138
14.8	139
15	138
15.2	130
15.4	55
15.6	90
15.8	138
16	140
16.2	138
16.4	100
16.6	43
16.8	107
17	132
17.2	136
17.4	135
17.6	125
17.8	116
18	117
18.2	118
18.4	119
18.6	118
18.8	117
19	115



Modeling Parameters for Carbonate Model Comparison -- Mallorca, Spain

Overview

This text file, carbon.txt, and the comma-delimited data files that accompany this are available via an FTP server at the Kansas Geological Survey at the address *crude2.kgs.ukans.edu*. You will need to log in as *anonymous* and use your *e-mail address* as the password. Files are located in directory */pub/outgoing/*.

Please generate any or all of the output as specified. We would like to compile this output before the meeting. Another FTP directory, */pub/incoming/*, is available to submit output. We can read most graphic files. Just specify in an e-mail to Lynn Watney the file names and types that have been sent. Our deadline for receiving this output has been extended to **May 1st**.

The "real world" carbonate example comes from the Miocene Carbonate Platform, Mallorca, Spain (Bosence et al., 1994). The stratigraphic sections utilized are well exposed along cliff sections of reef-rimmed progradational carbonate platform. Facies include reef-core, overlying lagoonal, and underlying reef-slope and open-shelf deposits. Strontium isotope age dates confirm that the reef is upper Tortonian or lower Messinian (approximately 6-7 Ma) (Waltham, personal communication). The reef complex is 150 m thick and progrades over 20 km (Llucmajor Platform). Six kilometers are well exposed in vertical sea cliffs up to 90 m high (Bosence et al. 1994). A copy of the paper by Bosence et al. (1994) is attached to provide both background material to the geology and their computer simulation.

Four orders of sea-level cyclicity are interpreted at higher resolution than the 3rd-order global cycles of Haq et al. (1987). The coral morphology and distribution of coralline algae were used to derive water depth and permitted accurate and precise reconstruction of the amplitude of high-frequency relative changes in sea-level. The durations and magnitudes of these orders of cyclicity are shown in Table 1.

Table 1. Orders of Cyclicity

Order of Cyclicity	Est. Time Period	Erosional Bounding Surface Units	Rock
3rd order	millions of years	-	Llucmajor Platform
4th order	hundreds of k.y.	-	sets of sigmoid cosets
5th order	hundreds of k.y.	A	sigmoid cosets
6th order	tens of k.y.	B	sigmoid sets
7th order	one-tens of k.y.	C	sigmoids

(adapted from Table 1. Bosence et al., 1994)

Sigmoids are interpreted as the result of accretion during highest frequency relative rise or highstand of sea-level which is usually followed by erosional truncation during subsequent fall of sea-level. Sigmoids are stacked into sigmoid sets also bounded by unconformities. Sets of sigmoids form sigmoid cosets that are also bounded by unconformities. Pomar (1991) suggests that these depositional sequences are hierarchically integrated within the 3rd-order TB 3.2 cycle of Haq et al. (1987) with an estimated duration

of 1.9 m.y. Alternatively, the inferred accommodation may have been caused by basin margin subsidence. Pomar (1991) also suggests that a correlation exists between the 5th-order cycles and the 100-k.y. Pleistocene eccentricity cycles. The frequency is obtained assuming this correlation.

Input Parameters

Input parameters used by Bosence et al. (1994) to model these strata were selected as the common dataset for the carbonate model comparison.

Initial Depositional Surface

Initial Depositional Surface is provided in a comma-delimited ASCII file. Distance is in km and elevation above present day sea level is in meters. The elevation of the surface is held constant through the model run, i.e., there is no subsidence.

The file name is **profile.csv**. This and other files are available via an FTP server at the Kansas Geological Survey at the address *crude2.kgs.ukans.edu*. You will need to log in as *anonymous* and use your *e-mail address* as the password. Files are located in directory */pub/outgoing/*. I will supply a diskette if needed. A listing of the file is attached.

Sea-Level Curve

The sea-level curve used in this model comparison is that presented by Bosence et al. (1994). A comma-delimited file, **sealevc.csv**, contains the sea-level data (time in k.y. vs elevation in m). The time step is 1 k.y. and the duration of the model run is 130 k.y. This file can be found at same FTP site on crude2. A listing of sealevc.csv is attached.

Carbonate Sediment Production Rates

Bosence and Waltham (1990) established carbonate production rates for Caribbean and Pacific reefs which was utilized in their modeling. Carbonate production rates range from a negative rate (erosional) for intertidal to a maximum of 4 m/k.y. between 1 and 10 m of water depth and then is reduced linearly to a value of 0.1 m/k.y. at 60 m depth (Figure 5, Bosence et al., 1994). A file of these production rates called **product.csv** is also on the FTP site on crude2. A listing of product.csv is attached.

Erosion and Redeposition

Please incorporate these parameters as best that you can in your model.

A. Redistribution of sediments downslope. Bosence et al. (1994) utilize a diffusion coefficient to smooth topography at a rate determined by the slope, transport rate, and grain density. The diffusion coefficient used is 0.1 m²/yr based on recent data of Hubbard et al. (1990), calculated from an average slope of 20 degrees, bed-load transport of 38 kg/m of shelf edge per year, and grain density of 1900 kg/m².

B. Bank top erosion. The bank top is eroded at a rate of 2 m/k.y. down to zero at wave base (average of 5 m). Eroded sediment diffuses out from the bank top and is assumed to settle out with an exponential decrease away from the platform edge.

C. Subaerial erosion. Subaerial erosion is accounted for by negative carbonate production for elevations above sea level. This carbonate is assumed to be dissolved.

Output Specifications

Model Output for Mallorca Comparison Data Set

Please provide the following output by **May 1st** in a form as close as possible to that defined here. If there are questions, please contact Lynn Watney.

1. *Depth cross section* view showing --
 - a. depositional facies/water depth:
 - <4 m above sea level
 - 4-10 m
 - 10-20 m
 - 20-30 m
 - >30 m,
 - b. depositional sequences,
 - c. ages of major sequence boundaries at points of maximum regression,
 - d. locations of 50 k.y. time lines.

2. *Chronostratigraphic (Wheeler) diagram* including --
 - a. 5 depositional facies:
 - depth based (5 categories as listed above)
 - b. location of depositional shelf edge.

3. *Stratigraphic columns* at 4 km, 4.5 km, and 5.8 km from landward side:
 - a. depositional sequence boundaries and age span,
 - b. depositional facies/water depth,
 - c. 50 k.y. time lines.

References Cited

- Bosence, D.W.J., and Waltham, D.A., 1990, Computer modeling in internal architecture of carbonate platforms: *Geology*, v. 18, 26-30.
- Bosence, D.W.J., Pomar, L., Waltham, D.A., and Lankester, T.H.G., 1994, Computer modeling a Miocene carbonate platform, Mallorca, Spain: *American Association of Petroleum Geologists Bulletin*, v. 78, no. 2, p. 247-266.
- Haq, B.U., Hardenbol, J., Vail, P., 1987, Chronology of fluctuating sea levels since the Triassic: *Science*, v. 235, p. 1156-1167.
- Hubbard, D.K., Miller, A.I., Scaturro, D., 1990, Production and cycling of calcium carbonate in a shelf edge reef system (St. Croix, U.S. Virgin Is.): application to the nature of reef systems in the fossil record: *Journal of Sedimentary Petrology*, v. 60, p. 335-360.
- Pomar, L., 1991, Reef geometries, erosion surfaces and high frequency sea level changes, Upper Miocene Reef Complexes, Mallorca, Spain: *Sedimentology*, v. 28, p. 243-269.

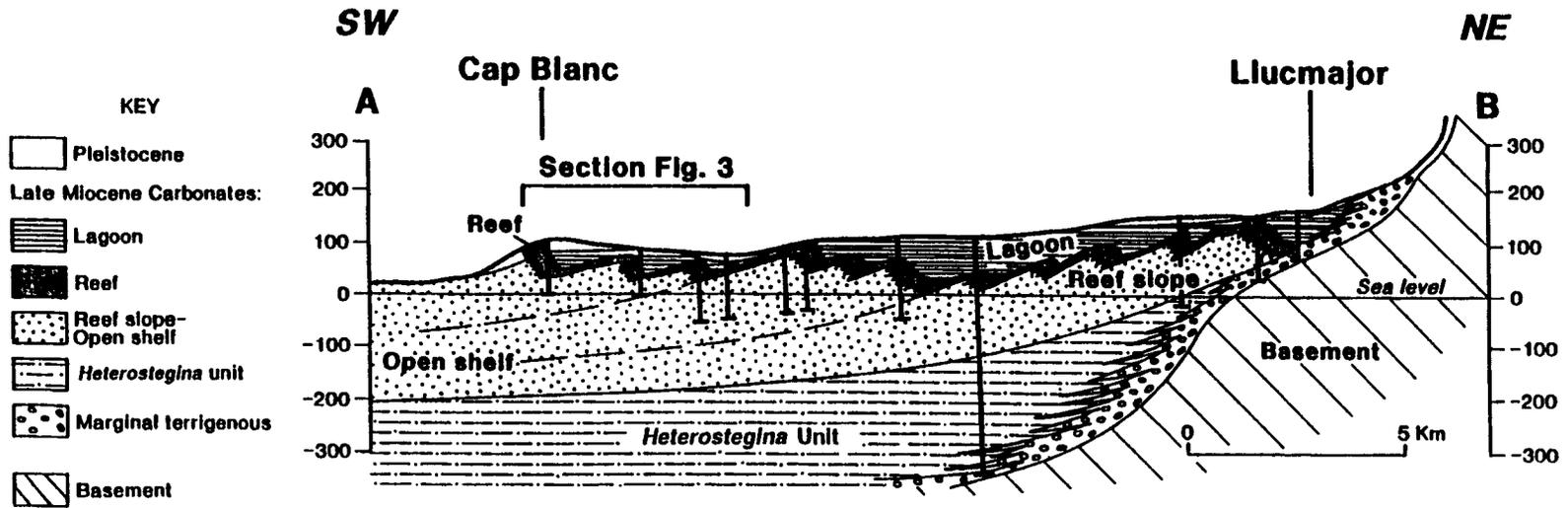
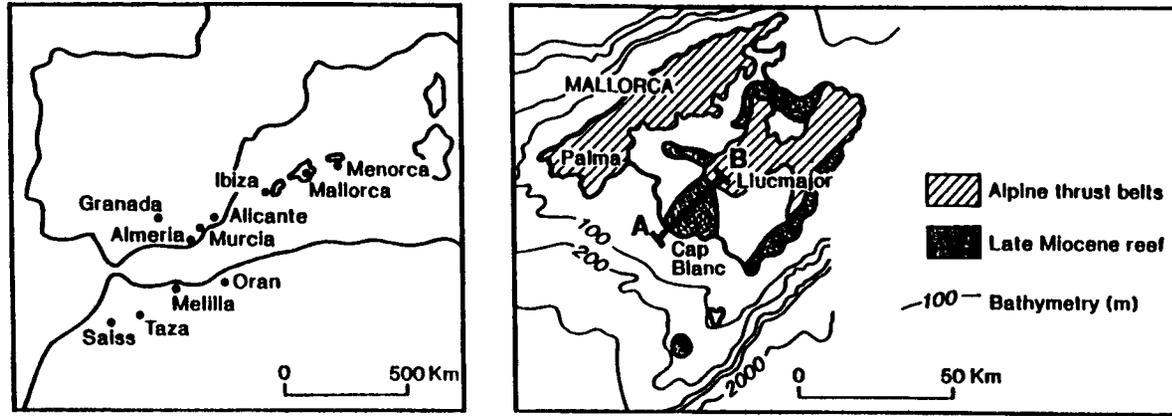


Figure 1—The Lluçmajor Platform of Mallorca, its location, stratigraphic setting, and morphology. Note the section near Cap Blanc contains a projected section compiled from locations and borcholes from Cap Blanc to the Palma basin.

Computer Modeling

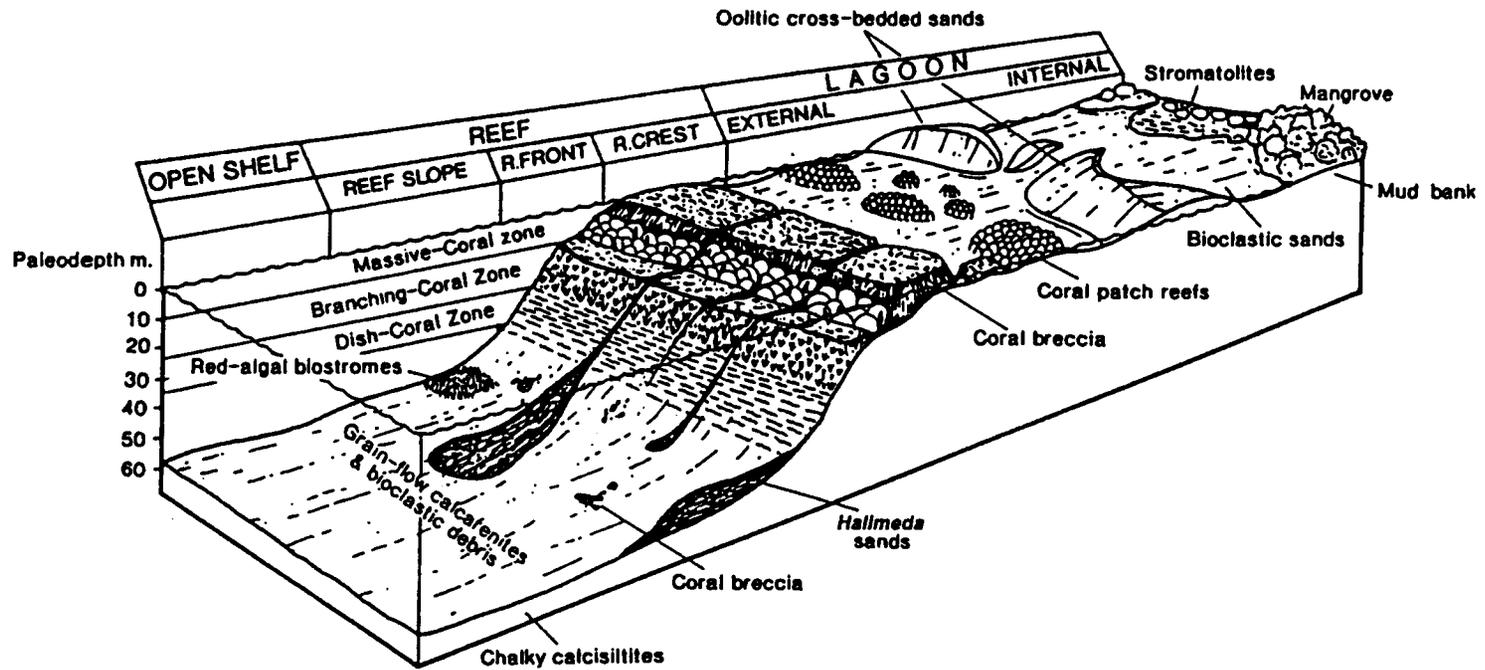
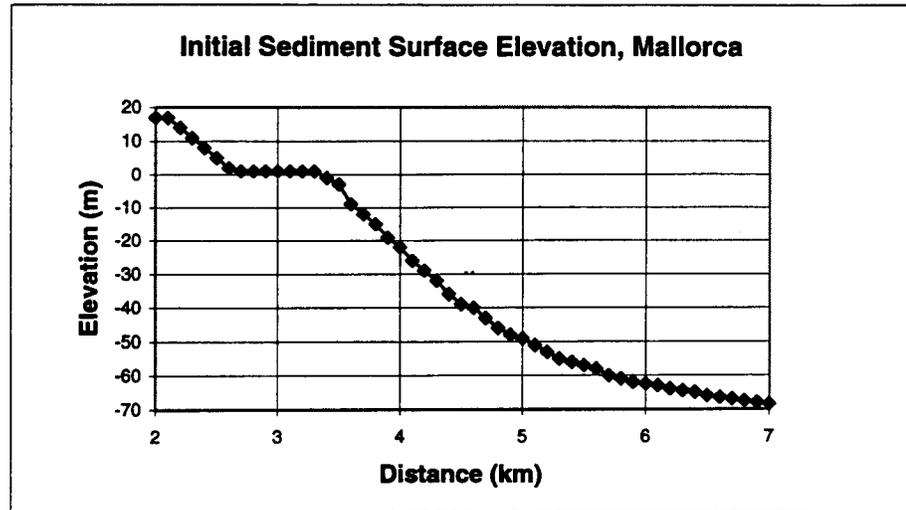


Figure 2—Facies model for reef-rimmed Cap Blanc Platform, Mallorca (after Pomar, 1991).

Miocene Carbonate Platform, Mallorca, Spain

Initial sediment surface elevation

Distance (km)	Elevation (m)
2	17
2.1	17
2.2	14
2.3	11
2.4	8
2.5	5
2.6	2
2.7	1
2.8	1
2.9	1
3	1
3.1	1
3.2	1
3.3	1
3.4	-1
3.5	-3
3.6	-9
3.7	-12
3.8	-15
3.9	-19
4	-22
4.1	-26
4.2	-29
4.3	-32
4.4	-36
4.5	-39
4.6	-40
4.7	-43
4.8	-46
4.9	-48
5	-49
5.1	-51
5.2	-53
5.3	-55
5.4	-56
5.5	-57
5.6	-58
5.7	-60
5.8	-61
5.9	-62
6	-62.5
6.1	-63
6.2	-64
6.3	-64.5
6.4	-65
6.5	-66
6.6	-66.5
6.7	-67
6.8	-67.5
6.9	-68
7	-68.5

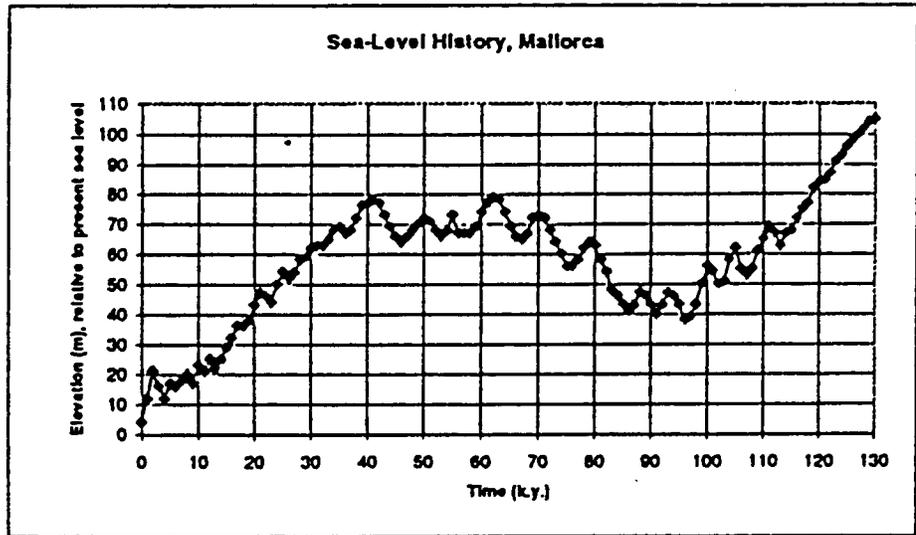


SEALEVC.XLS

Miocene Carbonate Platform, Mallorca, Spain

Sea Level History, with respect to present sea level

Time (k.y.)	Elevation (m)
0	4
1	12
2	21
3	16
4	12
5	17
6	16
7	18
8	20
9	17
10	23
11	21
12	25
13	22
14	25
15	29
16	32
17	36
18	36
19	38
20	43
21	47
22	46
23	44
24	50
25	54
26	52
27	54
28	58
29	59
30	62
31	63
32	63
33	65
34	68
35	69
36	67
37	68
38	72
39	76
40	77
41	78
42	77
43	73
44	69
45	66
46	64
47	66
48	68
49	70
50	72
51	71
52	68
53	66
54	68
55	73
56	67
57	67
58	67
59	69
60	74
61	77

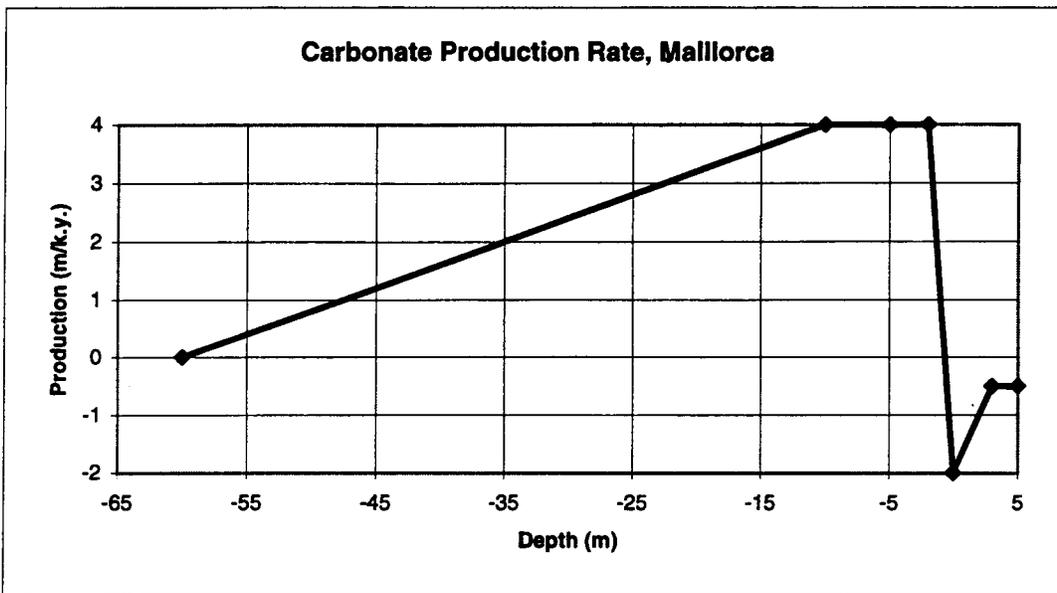


Time (k.y.)	Elevation (m)						
62	79	82	54	102	50	122	87
63	78	83	48	103	51	123	91
64	74	84	46	104	58	124	93
65	69	85	43	105	62	125	96
66	66	86	41	106	55	126	96
67	65	87	43	107	53	127	100
68	67	88	47	108	55	128	102
69	72	89	46	109	61	129	104
70	73	90	43	110	65	130	105
71	72	91	40	111	69		
72	68	92	43	112	67		
73	64	93	47	113	63		
74	60	94	46	114	67		
75	56	95	43	115	68		
76	56	96	38	116	72		
77	58	97	39	117	75		
78	62	98	43	118	77		
79	64	99	50	119	82		
80	63	100	56	120	84		
81	58	101	54	121	85		

Miocene Carbonate Platform, Mallorca, Spain

Carbonate Production Rate (m/k.y.)

Depth (m)	Production (m/k.y.)
5	-0.5
3	-0.5
0	-2
-2	4
-5	4
-10	4
-60	0



Probability and Sensitivity Analysis of 2D Basin Modeling Results

E. Bagirov, *Geologic Institute, Azerbaijan Academy of Sciences, Baku, Azerbaijan and*
I. Lerche, *Department of Geological Sciences, University of South Carolina, Columbia, SC*
29208

A procedure is provided for determining the relative importance of uncertainties in input information and in multiple parameter estimation to all outputs from 2D basin modeling codes. The procedure does not rely on Monte Carlo methods but, instead, upon some simple properties of the cumulative probability distribution of output variations related to uncertainties. As a consequence, only a couple of computer trials are needed to evaluate the relationship of the variability of outputs to input uncertainties.

Application of the procedure is given to a two-dimensional cross-section, with evolution of the section with time. Attention is focused first on mainly geologic input uncertainties, and then on uncertainties of thermal factors and of hydrocarbon kinetic factors, each group initially taken separately; and then all three groups of uncertainties are combined and used simultaneously. The influence is explored of each group of uncertainties on a range of different outputs from the basin model at different times across the evolving section. The relative sensitivity of the uncertainty in a specified output to each group of input uncertainties is examined at each time-step, as is the relative importance of the uncertainty in a specified input to the suite of all outputs at each time-step. In addition, the global relative importance (GRI) of input uncertainties to output variabilities is looked at, where the GRI provides a measure of output uncertainty effects, no matter where and when they occur, as a consequence of input uncertainties.

The importance of this work is that it enables an assessment to be made of which inputs need to be more tightly constrained, and also determines by how large a factor they need to be better constrained, if the uncertainties on a suite of specified outputs are to remain within given tolerance limits.

The advantage of having available this rapid procedure is that one can more quickly focus on those factors of dominance in controlling, say, overpressure development or hydrocarbon charge in a basin, without having to spend an inordinate amount of time, effort, personnel or financial resources on providing narrower limits of uncertainty on input factors which provide but little change in output uncertainties.



Optimization Using Genetic Algorithms

Stefan Bornholdt (*bornholdt@theo-physik.uni-kiel.de*), *Institut für Theoretische Physik, Universität Kiel, Leibnizstr. 15, 24098 Kiel, Germany* and **Hildegard Westphal** (*hwestphal@geomar.de*), *GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany*

Model building in the Earth Sciences often encounters problems of high dimensional data fitting and parameter estimation. Whenever such problems occur, optimization procedures can help in finding and improving possible solutions.

A powerful tool for nonlinear optimization problems is the genetic algorithm (Mitchell 1996). As opposed to local optimization techniques (hill climbing, gradient techniques), it optimizes with respect to a global performance measure of the model. This avoids the danger of getting stuck in sub-optimal parameter regions as is often the case for local search techniques. In addition, it does not require any knowledge of partial derivatives of the objective function. The basic principle of a genetic algorithm is inspired by biological evolution: A "population" of randomly chosen models struggles for the survival of the fittest. In a selection step, the models with the lowest performance are removed from the population. Successful ones are reproduced and generate new solutions via processes of mutation and crossover, inspired by the biological analogues for producing new trial individuals. This procedure is iterated until a satisfactory solution is found.

During the past years, the genetic algorithm entered a wide variety of applications in the fields of operations research, manufacturing, and information sciences with applications like optimizing timetables, computer chip wiring, or computer programs. In Earth Sciences applications, genetic algorithms appeared only recently. Some current applications include seismic waveform inversion and seismic data processing, earthquake hypocenter location, and well log interpretation.

Here, an application of genetic algorithms to stratigraphic modeling is introduced. In stratigraphic modeling, matching a model to physical data can be viewed as an optimization procedure. The parameters specifying the model (geometries, sea level, subsidence, etc.) have to be adjusted in order to achieve a model that reproduces available geological data. In the genetic algorithm approach, the model parameters are changed in the process of a guided search. The "fitness" of a specific model is determined by comparison with the geological data: The results of a complete model run can be compared with well log or seismic data, etc. The deviation of the model from the desired data is summarized in an overall root mean square error as a global performance measure. No gradient information is needed to compute this measure, and an arbitrarily large testing data set can be used. The cycle of optimizing stratigraphic models in a genetic algorithm is schematically shown in the figure. Starting with a randomly chosen initial population, the models are evaluated by comparison with real data, the best are selected, and copies of them are altered in order to create new models on the basis of the best models so far.



Empirical Parameterization of an Evolving Carbonate Cycle: The Holocene of Northern Great Bahama Bank

Stephen K. Boss (*boss@meavax.nrrc.ncsu.edu*), Dept. of Marine & Atmospheric Sciences, P.O. Box 8208, North Carolina State University, Raleigh, NC 27695-8208

Computer models which attempt to explore interactions among dynamic parameters believed to influence the development of "cyclic" carbonate platform sequences have been popularized over the past few years. These models typically utilize vectors for subsidence (constant) and cyclical eustatic sea-level changes as input parameters to create "accommodation space" which is filled by sedimentation (depth-dependent rates) following an appropriate "lag-time" (non-depositional episode during initial platform flooding). Though many of these models are intended to reflect general principles of cyclic carbonate deposition on basin-scales, it is instructive to test their predictive utility by comparing typical model outputs with an actively evolving depositional cycle on a modern carbonate platform where rates of subsidence, eustatic sea-level rise and relations among accommodation and sediment accumulation are either known or calculable. Carbonate deposits resulting from the Holocene transgression of northern Great Bahama Bank provide such a "test-platform" for model-data comparisons.

On Great Bahama Bank, formation of accommodation space depends on eustatic sea-level rise because tectonic subsidence is very slow ($<20 \text{ mm ky}^{-1}$). Contrary to typical model input parameters, however, the rate of formation of accommodation space varies irregularly across the bank-top because irregular bank-top topography (produced by subaerial erosional and constructional processes; Fig. 1a) results in differential flooding of the platform surface.

The interaction of platform-top relief with rising sea-level does not produce uniform, meter-scale "layers" but instead complex, localized patterns of net sediment transport or accretion which are difficult to predict (Fig. 1b). Calculated Holocene sediment accumulation rates are not depth-dependent ($r^2=0.002$; Fig. 1c). Therefore, Holocene sediment thickness and accommodation space are uncorrelated ($r^2=0.03$; Fig. 1d) and Holocene sediment thickness (i.e. cycle thickness) is not proportional to depositional interval (i.e. cycle duration; Fig. 1e). Lag depth (i.e. depth interval of non-deposition following platform flooding) and lag time (i.e. time interval of non-deposition following platform flooding) vary as functions of sea-level rise rate, position across the irregular bank-top surface and tidal flow across the bank-top. As a result, both parameters are broadly variable and difficult to define (Fig. 1f).

Results of this study indicate that typical computer-model input variables (subsidence, sea-level, sedimentation rates, "lag-time" or "lag depth") and output depositional geometries (uniform meter-scale layers) are poorly correlated with real depositional patterns across an actual carbonate platform (Great Bahama Bank) and may not be the principal determinants of cycle geometry. Since other modern carbonate platforms and ancient carbonate successions display similarly complex stratigraphies, it is suggested that computer models must evolve to include consideration of realistic, three-dimensional platform relief and fluid dynamical relations in order to improve their predictive value for cyclostratigraphic interpretations.

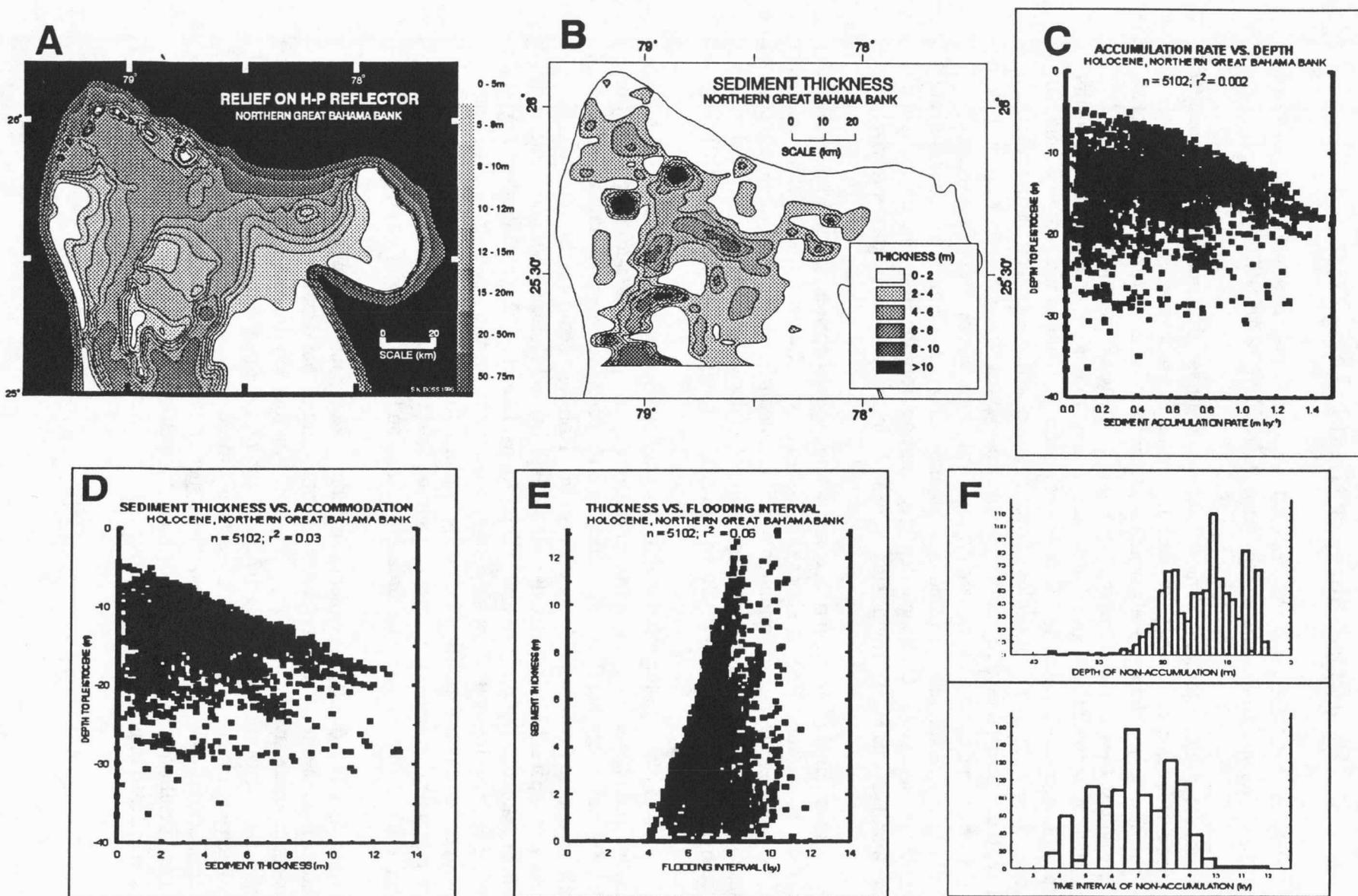


Fig. 1. **A**) Relief on Holocene-Pleistocene Unconformity (H-P Reflector) determined from network of single channel, high-resolution seismic profiles. **B**) Isopach map of Holocene sediment thickness determined from seismic data. Note irregular distribution of sediments across platform-top. **C**) Scatter plot showing average Holocene sediment accumulation rate vs. depth (*i.e.* depth-to-Pleistocene). **D**) Scatter plot of Holocene sediment thickness vs. accommodation (*i.e.* depth-to-Pleistocene). **E**) Scatter plot of Holocene sediment thickness vs. flooding interval (*i.e.* cycle duration). **F**) Histograms of observed depth of non-accumulation (*i.e.* lag depth) and observed time-interval of non-accumulation (*i.e.* lag time).

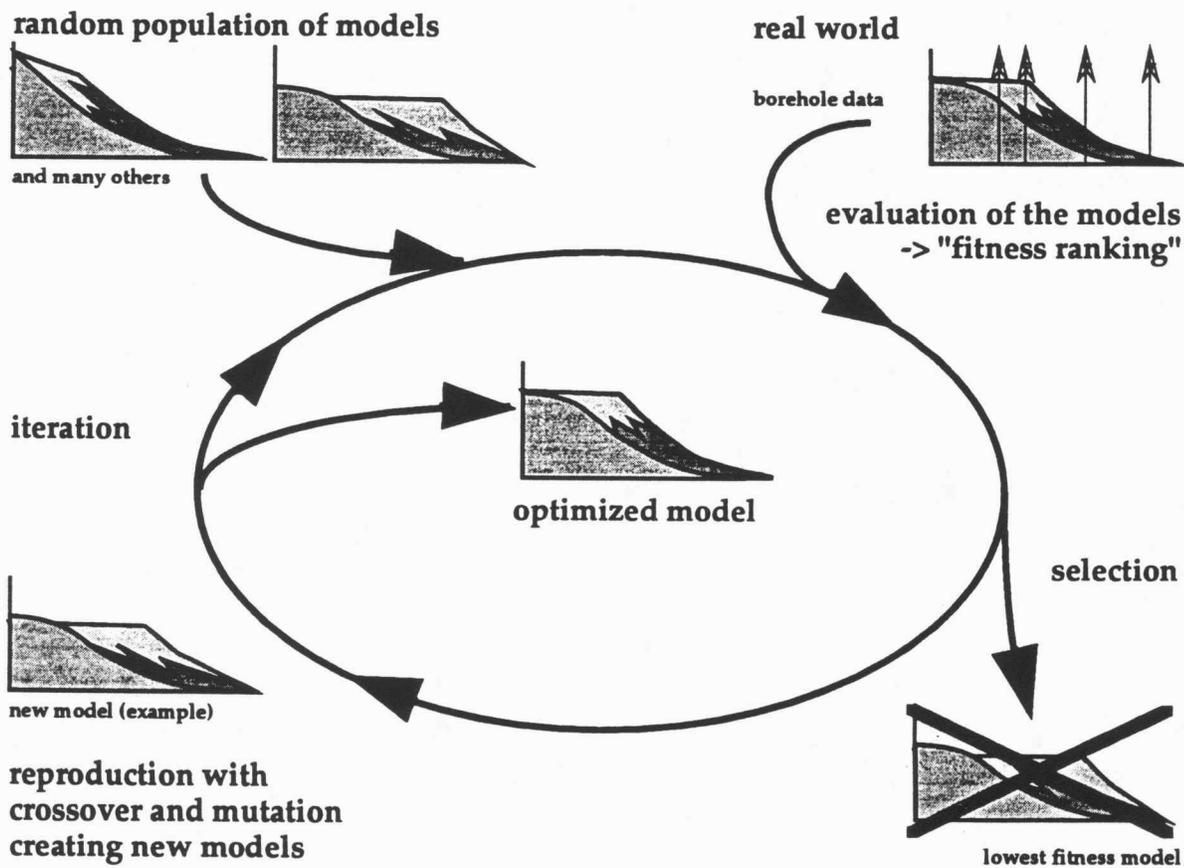
This procedure has been successfully tested for two stratigraphic modeling tasks (Westphal & Bornholdt 1996). The implementation was done on the basis of the modeling program Fuzzim (Nordlund & Silfversparre 1995) combined with a standard genetic algorithm. First, an artificial toy model with exact knowledge of all parameters has been recovered correctly by a genetic algorithm from pseudo well data of the final model output alone. A second task was the optimization of a stratigraphic model for the Eocene to Miocene of the Bavarian Molasse Basin.

References

Mitchell M., 1996, An Introduction to Genetic Algorithms, MIT Press, Boston.

Nordlund U., and Silfversparre, M., 1995, Fuzzim, Version 1.2, Uppsala University.

Westphal H., and Bornholdt, S., 1996, Automation of stratigraphic simulations - quasi-backward modeling by genetic algorithms: Geological Society Special Publication, London. Forthcoming.



The cycle of optimizing a stratigraphic model using a genetic algorithm.



Stratigraphic Modelling in Shell - Examples and Model Comparison

Hemmo Bosscher (*bosscherh@ksepl.nl*) and **Mark Newall**, *Shell International Exploration and Production B.V., Research and Technical Services, Volmerlaan 8, P.O. Box 60, 2280 AB Rijswijk, The Netherlands.*

Shell has been active in developing and applying forward stratigraphic modelling software in exploration for over 10 years. The latest Shell stratigraphic modelling program STRATAGEM, uses a geometric/deterministic approach and follows overall modelling procedures similar to its predecessor BASMOD. It is now installed at several operating companies and Shell Research and Technical Services, where it is mainly used for evaluating geological models on an exploration scale.

Development of the program focused on building the program in a modular way to allow implementation of several algorithms for the same geological process and data import. A lot of input data required for stratigraphic modelling (subsidence, geometries etc.) can be generated by other basin modelling programs. Therefore, the program is linked to a variety of structural/geological/ basin modelling/geochemical software applications. Comparison with seismic data, the main source of input, is enabled by the ability to import seismic lines into the program and create synthetic seismic sections from simulation results. Import of basic well logs and creation of synthetic wells is also possible.

Stratigraphic modelling programs are an extremely powerful tool for the definition of fundamental controls on basin fill architecture and testing of multiple geological scenarios. The quantification of these controls allows construction of models that are consistent with the available geological data and thus enables assessment of the effect of changing other, unconstrained parameters.

The program has proven to be a valuable aid in establishing and refining geological models based on seismic interpretation:

During a bidding round for exploration in the Porcupine Basin (offshore Ireland) the program was used to assess the overall prospectivity of the early Tertiary deposits and predict favourable locations for the deposition of deep water sands.

As part of the evaluation of a farm-in offer offshore Vietnam STRATAGEM was used to help distinguish between different sea-level scenarios to evaluate the probability of low stand deposits. Using stratigraphic modelling 'reasonable' doubt was established on the viability of the proposed prospect.

In mature areas such as the Niger Delta the program has been applied to test the overall geological model and establish new play concepts in areas beyond current well calibration.

Stratigraphic modelling is now an accepted means of evaluating geological models in both frontier and mature basins.



PHILx Stratigraphic Simulators and PHLuxx Hydrocarbon Generation Modeller: Using Objects and Relationships with Nearest Neighbors to Model Stratigraphy and Fluid Flow

Scott A. Bowman (*terraobjx@aol.com*), *Marco Polo Software, Inc., 12410 Meadow Lake Dr., Houston, Texas 77077*

PHIL is an interactive object-oriented program that allows you to backstrip 2-D cross sections, simulate the stratigraphy between known horizons, automatically refine the model based on observations, automatically build incremental models between end members, determine a statistical value for closeness of fit, compare geologic observations with model results, and model hydrocarbon generation and migration within a basin.

Our modeling philosophy emphasizes matching detailed observations regarding the behavior of the stratigraphic system while sacrificing mathematical complexity when available. The system is governed by physical laws that define the relationship between neighbors. We try to keep it simple because rocks are rarely as clever or predictable as humans, but often much more non-linear. All processes are independent and can be activated or removed with the flick of a switch, allowing easy testing of different algorithms.

PHIL integrates a multiply-sourced sedimentation model with a detailed tectonic, water level, and sediment-supply history to simulate the depositional history of a dip-section through a basin. PHIL allows the user to model stratal patterns in many tectonic settings. Passive margins, foreland basins, and strike-slip basins are modeled by varying the distribution of subsidence/uplift rates over time and space of with respect to the source of the sediment supply. You can test the effect of changing sediment volume and type, erosion rates, pre-existing bathymetry; slopes of stability for many depositional interfaces; gravity-flow deposition parameters, timing, and geometry, flexural loading parameters, compaction rates, and many other factors. The size of the model is limited only by the memory on your computer and your patience.

A siliciclastic sediment supply can be introduced simultaneously with a depth-dependent "carbonate factory" that is reduced by siliciclastic poisoning. Siliciclastic sediments are transported by traction and suspension processes. Traction processes are modeled with an equilibrium profile, defined by slopes of the fluvial plain, coastal plain, shoreface and marine depositional slope. Suspended sediments are dispersed by a dispersion process within the marine environment. The width of coastal plain and depth of fairweather wavebase also control the equilibrium profile and distribution of suspension deposits. Unstable sediment packages are bypassed into the basin by slumping and mass wasting processes. They are redeposited as slumps, basin-floor fans and slope fans. PHIL uses an algorithm for gravity-flow sedimentation based on conservation of potential and kinetic energy and observations of modern turbidite events. The effects of headward erosion, surface beveling, channel incision, and marine currents can be introduced.

PHIL employs four depth-dependent carbonate production functions including:

- 1) laterally unrestricted shelf production,
- 2) restricted shelf-margin production,
- 3) suspended mud produced on the platform, and
- 4) pelagic sediment.

After production sediment is redistributed by erosion, traction, and suspension processes.

PHIL employs an algorithm above a homogeneous elastic plate to account for lithospheric flexure due to sediment loading. A compaction algorithm compacts sediments as a function of burial depth. A compacting substrate can be defined. A post-depositional history of subsidence, burial, compaction, uplift and erosion can be defined.

Graphical presentations include Depth Sections, Chronostratigraphic Sections, Stratigraphic Columns, Relative Changes of Sea Level Analysis. Variables that are plotted include absolute age, stratigraphic age, sequence age, depth, paleobathymetry, depositional environments, lithofacies, systems tract, sequence, porosity, density, grainsize, sedimentation rate, permeability, pressures, and others.

A 100 layer 200 column (20000 cell) model with flexural loading and compaction is completed as follows:

SGI Indigo Extreme 200 Mhz 40 seconds
Macintosh 604 PPC 120 Mhz 50 seconds
Sun SPARC 20 Model 71 60 seconds
Intel Pentium 166 Mhz 70 seconds

Current development focuses on faulting and three dimensions.

CaCO₃ Saturation State Variations: Possible Effects on Coastal Biogeomorphology and Sediment Budgets

Robert W. Buddemeier (*bobb_buddemeier@msmail.kgs.ukans.edu*), *Kansas Geological Survey, 1930 Constant Avenue - Campus West, The University of Kansas, Lawrence, Kansas*

Although saturation state is generally recognized as a control on the inorganic precipitation of CaCO₃, there has been little systematic attention given to its influence on the formation of biogenic carbonates. However, on geologic time scales it has been suggested that the shift away from calcite-dominated carbonate sediments and the emergence of new taxa of organisms with aragonite or high-magnesian calcite skeletons in the Mesozoic might be attributed to increases in the degree of carbonate saturation in the oceans at that time. Such geochemical adaptation may not be irreversible, as there is also evidence that some skeletal anthozoans descended from scleractinian corals. Experimental work has shown that at least three genera of reef-building corals and one calcareous alga exhibit calcification rates that correlate with the degree of CaCO₃ supersaturation.

Evidence for systematic variations in the distribution of saturation in the ocean also continues to grow. Long-term variations in the depth of the lysocline and carbonate compensation depth have been recognized for some time. More recently, both theoretical and empirical evidence for glacial-interglacial variations in the oceanic carbonate budget has been recognized. Climate-related fluctuations in surface ocean pCO₂ as mediated by atmospheric composition are also beginning to be more clearly understood.

Chemical controls, interacting with sea level and climate factors, may affect coastal zone sedimentation patterns in at least three ways. First, there can be changes in the total amount, mineralogy, and spatial distribution of the carbonate sediments deposited and/or preserved. Second, there may be variations in the degree to which post-depositional cementation stabilizes and preserves sediment structures. Third, local sedimentary regimes may be influenced to different degrees by distant biogeomorphic structures.

Variations in sedimentation rate, in sediment composition, or in postdepositional alteration all leave evidence within the sediments themselves. The effects of biogenic structures at some distance from the locus of sedimentation, however, can only be inferred and are easily confused with other environmental factors. An estuary behind an offshore barrier reef, for example, is a very different sedimentary regime than that same estuary in the absence of the reef -- and the effects of reef growth or erosion may be mistaken for changes in sea level, or in the regional (as opposed to local) wind and wave regime. Our improved understanding of the dynamic nature of carbonate sedimentary cycles suggests that interpretation of sedimentary regimes that involve -- or might interact with -- carbonate systems should be approached with caution.

A "Map-View" Model of Turbidite Transport and Deposition

Bernard Coakley and Lincoln Pratson (*bjc@ldeo.columbia.edu*), *Lamont-Doherty Earth Observatory, 107 Oceanography, Palisades, New York 10964*

In many sedimentary environments, studies of repetitive events have built a thorough understanding of primary processes and their variation through time. Rivers, deltas and beaches are amenable to study because there are significant variations in activity at historical time scales. Intermittently active systems present challenges to interpretation. Events are rarely observed. Processes and rates must be inferred from the stratigraphic record. The "normal" behavior of a system and its' progressive evolution over time are only partially characterized or understood.

Basin modeling offers some solutions to these dilemmas. To date the bulk of these models have concentrated on reproduction of stratal geometries in two dimensions. Crucial to the credibility of these models is the assumption that the aggregate system achieves "grade" at a time scale that is short compared to the time scale of the dated horizons. Reproduction of the observed stratal discontinuities is taken as confirming the model itself and the inputs or forcings applied during the model run.

Profile models utilize geometry as a proxy for the dynamic processes that act to develop stratigraphy. The physics of sediment transport, or its qualitative approximates, offer another constraint. To properly consider heterogeneous behavior, it is necessary to develop 3-D or "map-view" models that do not arbitrarily restrict activity to the plane of "observation." In a map-view model lateral process gradients also act to dictate the results of the stratigraphic experiment.

In an effort to examine the delivery of sediments from the slope to the rise we developed a simple, rule-based model that operates in map view. The primary aim of this work was to construct and test a slope-based model of mass wasting linked to turbidite flow and deposition. The model has been constructed and satisfactorily reproduces some of the qualitative aspects of turbidite dispersal and accumulation. The advantage of this approach is that we can consider the effects of flow concentration or expansion, which cannot be considered in two-dimensional (profile) numerical models of turbidite behavior. The disadvantage of this approach is that we cannot explicitly comment on various hydrodynamic aspects of these processes. Both the advantages and disadvantages are evident in the model output.

The model develops long, continuous sediment conduits of constant (graded) slope, which extend across the sediment prism, bypassing the proximal prism to deliver sediments to distal areas. Autocyclic behavior, perhaps analogous to lobe switching, can be seen in the periodic reorganization of these conduits. A serious deficiency of the model is that the sediment prism grows primarily by lateral accretion, not by aggradation as is observed in many modern settings and suggested by ancient stratigraphy. Because the model considers only the relative magnitude of slopes and the continuity necessary to sustain flow, estimates of flow velocity and flow thickness cannot be derived from model output. Inertial effects are ignored. This

deficiency can only be addressed by a more explicit formulation of the model in terms of physics of density driven flow.

While the physically-based, map-view models have the potential to reproduce some of the behavior expected of complex sedimentary systems, validation remains a challenge. Physical principles provide a strong constraint but testing quantitative models by comparison to our expectations could merely provide confirmation of our opinions rather than explanation of geological observations. As these techniques evolve over the next few years, it will be necessary to develop means to extract summary or statistical information from the stratigraphic record to compare to similar measures extracted from model outputs.

Simulation of Coastal Evolution Using the Shoreface Translation Model

Peter Cowell (*cowell@extro.ucc.su.oz.au*), Coastal Studies Unit, University of Sydney, Institute Building H03, NSW 2006, Australia, **Peter Roy**, New South Wales Geological Survey, and **Poppe de Boer** (*pde.Boer@earth.ruu.nl*), Institute of Earth Sciences, P.O. Box 20.021, University of Utrecht, WL 3508 TA Utrecht, The Netherlands

The Shoreface Translation Model (STM) is designed to permit numerical experimentation on the evolution of coastal morphology and stratigraphy under conditions of: a) changing sea level; b) variations in morphological length scales related to sedimentation and erosion processes; and/or c) variations in external sediment budgets. The model simulates coastal change based only on principles of sand-mass conservation and geometric rules for shoreface and barrier morphology (Cowell *et al.*, 1995). The geometric rules are represented in terms of bulk parameters based on process studies; empirical, analytical and/or numerical (de Vriend, 1991). Solutions can be constrained further through assimilation of real-world data from stratigraphic and surface-morphology, with experimentation then proceeding via manipulation of the unknown variables.

The model simulates lateral and vertical translation of the cross-shore profile over the pre-existing coastal substrate which undergoes reworking as a consequence. This produces changes in position of the coastline as well as erosion and deposition, which in turn generates backshore and inner-continental shelf geomorphology and stratigraphy. The model can be applied at a wide range of scales in space (tens of meters to tens of kilometers) and time (days to millennia) depending on experimental designs. In principle, the model can simulate basin fill resulting from multiple cycles of sea-level transgression and regression (Fig. 1). However, since the model provides a rigorous albeit highly-generalized representation of coastal morphodynamics, work to date has capitalised on this strength by focussing on the simulation of transgressive and regressive evolutionary sequences during the late Pleistocene, exemplified by computer experiments on the coasts of Cape Cod (Fig. 2a) and The Netherlands (Fig. 2b). Interplay between variations in the rate of sea-level rise and the rate of sediment supply govern the simulated coastal behavior, although shoreface dimension also prove to be important in obtaining agreement between simulated and measured morphostratigraphy.

References

- Cowell, P.J., Roy, P.S., and Jones, R.A., 1995, Simulation of large-scale coastal change using a morphological behavior model: *Marine Geology*, 126, p. 45-61.
- Vriend, H.J. de, 1991, Modelling in marine morphodynamics, *in*, Computer Modelling in Ocean Engineering '91, ed. Arcilla, A.S., Pastor, M., Zienkiewicz, O.C., and Schrefler, B.A., Rotterdam: Balkema, p. 247-260.

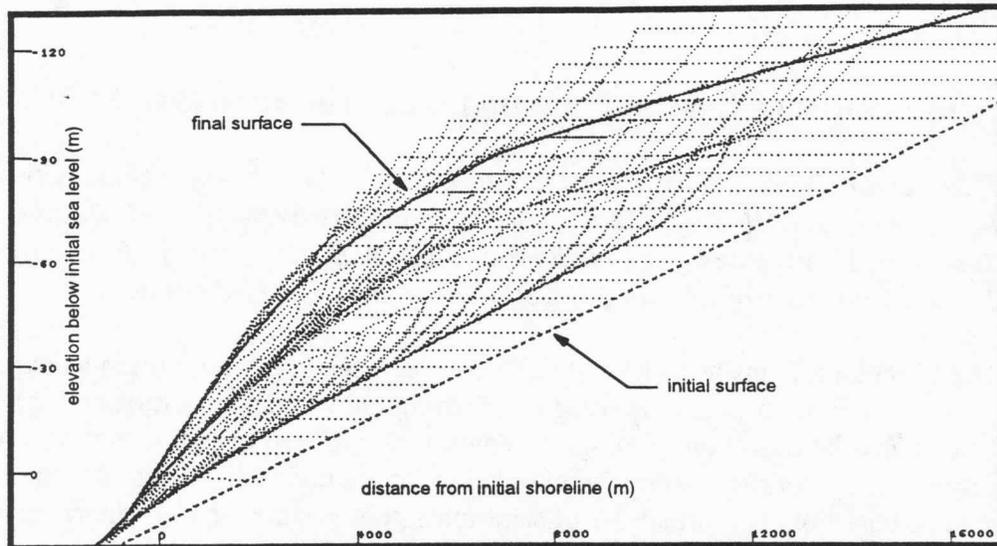


Figure 1. Simple simulation of three cycles of transgression and regression of a marine shoreface over an initial, linear surface of 0.4° slope. The fine dotted lines are former surfaces at 90 different time steps (each step separated by a 5 metre sea-level increment). (No distinction is made between erosional and depositional surfaces.)

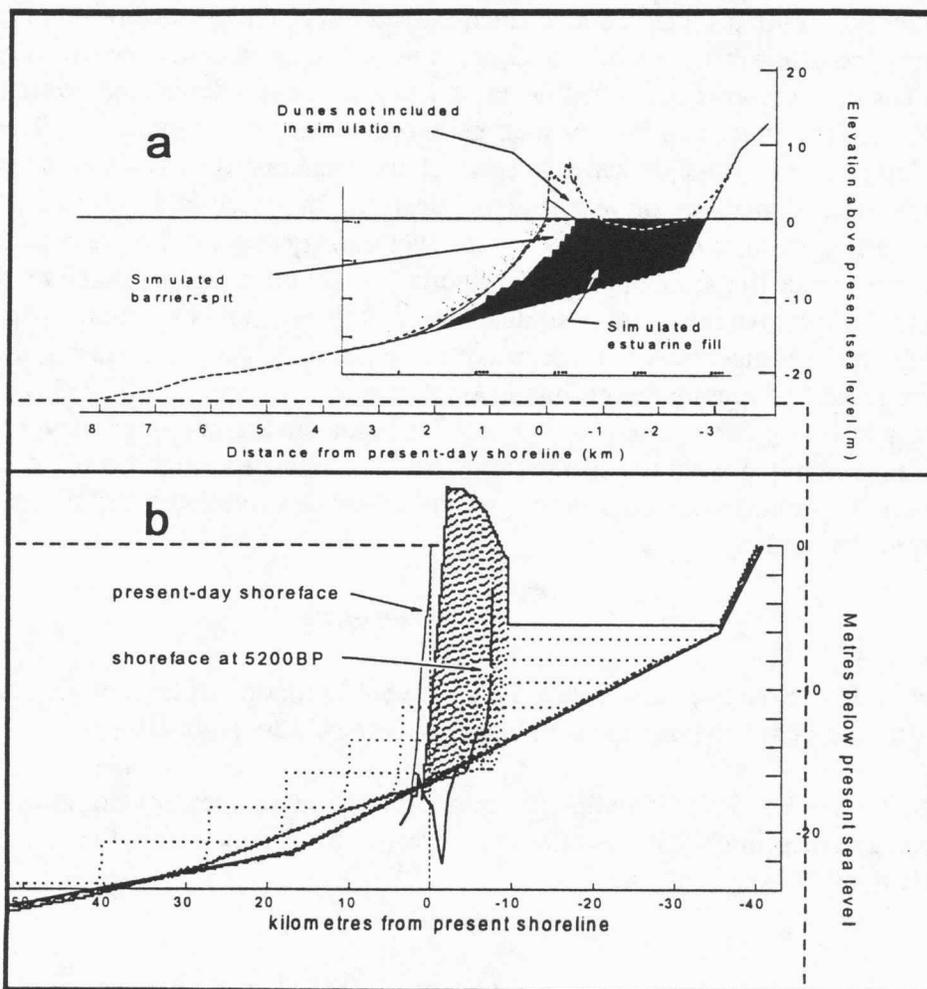


Figure 2. Simulations of coastal evolution with measured morphologies overlaid for: a) Sandy Neck spit, Cape Cod, and b) the central Netherlands coast.

SEDIMENT FACIES ASSOCIATED WITH MULTIPLE THRUST FAULTS; INFERENCES FROM NUMERICAL MODELING

T. den Bezemer, Vrije Universiteit, Amsterdam, The Netherlands

H. Kooi, Vrije Universiteit, Amsterdam, The Netherlands

Y. Podladchikov, Vrije Universiteit, Amsterdam, The Netherlands

S. Cloetingh, Vrije Universiteit, Amsterdam, The Netherlands

A kinematic model describing fault-bend folding combined with a dual-lithology diffusion model simulating sedimentation and erosion is developed to investigate the effects of fault geometry, changes in displacement-rate and sequence of fault activation on contemporaneous sedimentation. Deformation is prescribed by advecting basement and sediment in a velocity field consisting of domains separated by kinkaxes (Fig 1). Each domain is characterized by one velocity vector that is parallel to the underlying fault segment and whose magnitude is given by the imposed displacement velocity along the fault. Kinkaxes occur at each change in fault dip and are fixed to the footwall. The sediment model assumes that sediment transport is proportional to local gradient, sediment type (e.g. sand, shale) and the fraction of each sediment type in a thin boundary layer. The composition of the boundary layer dynamically adjusts itself to current substrate and transport conditions thereby simulating armouring. Constant elevation boundary conditions are used which act as sediment sinks and simulate local baselevels of erosion.

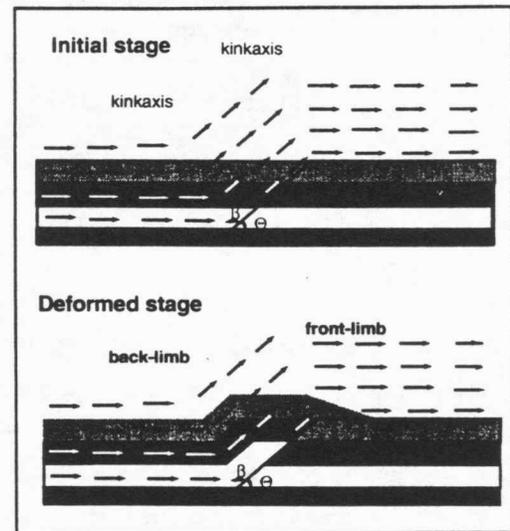


Figure 1

Figure 2 illustrates the characteristic features predicted for a single fault-bend fold. Back-limb : unconformity and concentric facies pattern. Front-limb: onlap with coarse sediments at the base and a coarse to fine zonation. The concentric facies pattern at the backlimb is caused by continuous erosion close to the fold causing finer grained sediments to be

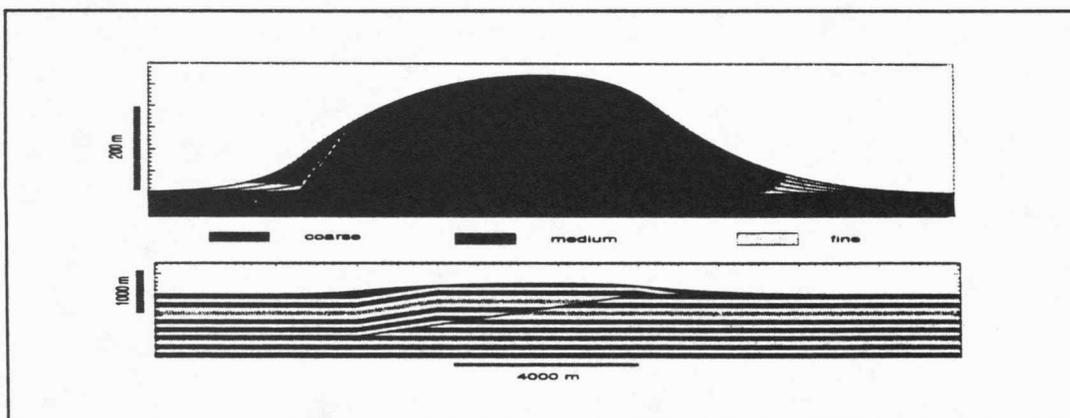


Figure 2

exposed there. The front-limb, however, is a site of ongoing sedimentation resulting in progressively progressively buried, coarse proximal facies (purple colours in Fig. 2). The effects of variation in displacement rate along a fault with a simple step in decollement are shown in figure 3. The instantaneous drop in displacement rate causes an expansion of the back-limb unconformity away from the fault-bend fold and the development of an unconformity at the front-limb. On both sides of the fold this is accompanied by outbuilding of coarse sediments. This response reflects a transition to a more erosion-dominated state when the advection decreases and sediments are cannibalized. The subsequent onset of deformation causes a drastic onlap towards the fault-bend fold at both sides and a

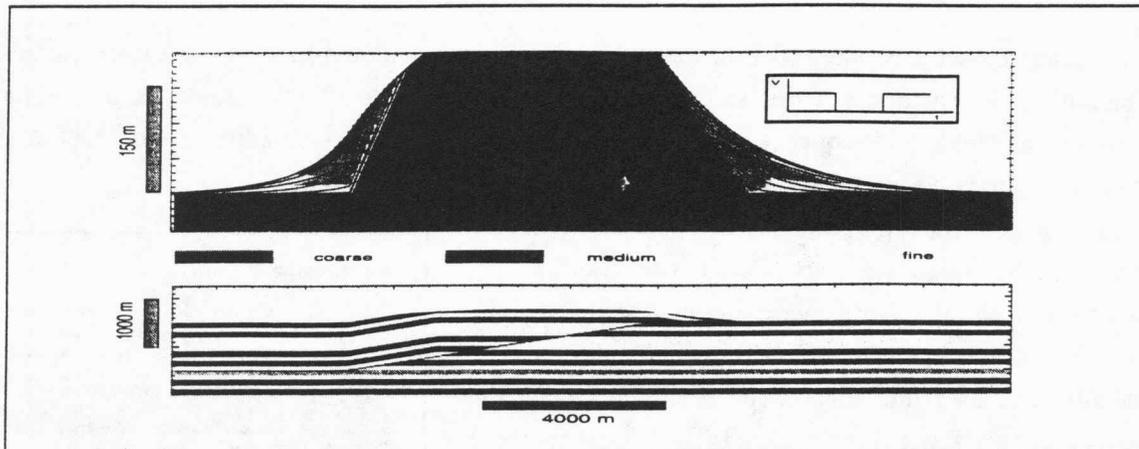


Figure 3

return to the initial basic sequence stratigraphic and facies geometries. A very pronounced feature of the predicted geometry is the buried basement step at the front-limb. Recognition of these basic geometries proved very useful in interpreting the sedimentary record for experiments with multiple faults. Predicted patterns for piggy-back thrusting and out-of-sequence thrusting are very different and may be used as a guide in the interpretation of the sedimentary record associated with multiple thrust-faults.

How Can Stratigraphic Modeling Help To Constrain Geostatistical Reservoir Simulations?

B. Doligez (*brigitte.doligez@ifp.fr*), **D. Granjeon**, **P. Joseph**, **R. Eschard**, *Institut Français du Pétrol, 1 et 4, avenue de, Bois-Préau, BP 311 - 92506 Rueil-Malmaison Cedex, France,* and **H. Beucher**, *CG*

Geostatistical reservoir simulations are now common tools used in intensive exploration and reservoir appraisal. However at this stage, significant uncertainty still exists, due to the limited amount of hard data.

A way to better constrain these stochastic simulations could be to integrate information coming from a stratigraphic modeling approach: On one hand, stratigraphic models give information about geometry, continuity, position, and dimensions of the main depositional sequences in a studied area, using input data as eustasy, subsidence, and sediment supply. On the other hand, geostatistical models aim to generate equiprobable images of the reservoirs inside these main sequences, which honour the well data, and which variability can be linked to the variability computed from the data.

The uncertainty associated to this type of stochastic simulations may be reduced at least at two levels by the coupling with a stratigraphic model. First, the geometry and architecture of the simulation units may be directly given by the stratigraphic model. Second, the relative percentage of facies (or sand-shale ratio) computed between two time-lines as a result of the stratigraphic modeling approach may be used as an additional constraint in the stochastic simulation.

This approach has been validated on an outcrop case study in the Campanian of the San Juan basin in Colorado. The IFP stratigraphic model DIONISOS has been used to introduce quantitative sedimentological knowledge in the stochastic reservoir model HERESIM. The geometries of the reservoir units resulting from the DIONISOS simulation have been used as input data in HERESIM. And the global trend of the sand-shale ratio evolution in the studied area has been taken into account as an external drift in the geostatistical simulations. For that purpose, the usual algorithm in HERESIM has been extended for non-stationary cases, by using the facies proportion blocks instead of one single proportion curve.

The coupling of both methodologies allows to give more geologically constrained images of the reservoir.

4-D Nonlinear-Dynamical Fluvial Modeling Using Deterministic Equations and Fuzzy Logic

Dwaine H. Edington (*Edingtond@aol.com*) and **Timothy A. Cross** (*tacross@mines.edu*),
*Department of Geology and, Geological Engineering, Colorado School of Mines, Golden,
CO 80401*

The results we obtain from reservoir and aquifer flow-simulation models are directly affected by the specific interpretation of the lithologic and permeability heterogeneities that we supply to the model. Minor variations in the properties and spatial distribution of heterogeneity may lead to large variations in the model outcomes. Although the exact geologic conditions being simulated may not be known, if the range of the possible conditions are determined then the range of outcomes is constrained. One method of restricting the range of possible geologic conditions is through stratigraphic or sedimentologic forward models which replicate conditions at sampled positions within the 3-dimensional stratigraphic volume.

A four-dimensional (time-space), nonlinear-dynamical forward model of fluvial deposition, FLUVSIM, is being developed. This program incorporates the following features. (1) It simulates three-dimensional sedimentation and erosion at the channel-belt/floodplain scale (subsequently we plan to simulate geometries and petrophysical properties of sediments within channel belts). (2) The program is deterministic; that is, it does not use randomly generated processes or events in the simulations. (3) It simulates the interconnected alluvial/fluvial/floodplain/lake environments as a nonlinear dynamical system that can achieve self-organized critical states. It incorporates the concepts of process/response feedbacks, thresholds, and memory. (4) It uses fuzzy logic to determine where, how much, and what kind of sediment to deposit and erode.

FLUVSIM differs from previous fluvial sedimentation models in several ways. Perhaps the most important is the incorporation of feedback loops, buffers, thresholds and memory into the stratigraphic/sedimentologic process/response system. Processes and responses within rivers and their contiguous geomorphic environments are integrated through multiple feedback mechanisms, many of which are nonlinear. As the degree of coupling increases between the multiple processes and responses, these systems behave in states of self-organized criticality. If the system moves away from the critical state, self-correcting events force the system to return to the critical state. It is possible for either a large or small perturbation to disrupt the system so that it seeks a new critical state if a crucial threshold is crossed. An example of a threshold in this model is the process of avulsion. Avulsions occur only when the river is flooding (trivial) and only when there is a sufficient gradient advantage and energy potential (a consequence of history) that causes the river to seek a new course (nontrivial).

Although the system may be unstable at many different points within the model space, the system as a whole is metastable, meaning that it can shift from one state to another without being forced by some high-magnitude forcing function. Given identical initial conditions, it is likely that a river will not respond to identical, small, perturbations in the same manner every

time. The river will adjust several system parameters simultaneously as it seeks a new equilibrium. Some of these adjustments may be in directions contrary to prevailing wisdom.

Many geologic processes and responses exhibit cyclicity as a consequence of nonlinear dynamical behavior, and rivers and their deposits are no exception. Cyclicity is not necessarily imposed by an external forcing function. In a system characterized by nonlinear dynamics, cyclicity results from a network of coupled processes and responses (feedback) that operate at different fundamental frequencies. Nonlinear dynamical systems may also include memory. Memory refers to the sequential history that the system experiences. The current state of a fluvial system is partially constrained by what happened to the system before the current time. For example, the channel dimensions at any one time is partially a function of the discharge history of the channel. The susceptibility to overbanking, crevassing and avulsion is also a consequence of history of previous overbanking events and duration for compaction.

In a complex, multiple process, multiple component, interleaved system such as this, conventional linear programming is not the only choice for effecting a realistic simulation; it may not be the most appropriate. We utilize fuzzy logic, in addition to deterministic equations, in the FLUVSIM forward model. There are two main advantages of using fuzzy logic for such complex systems: (1) fuzzy models can use qualitative data (linguistic variables) and knowledge; (2) fuzzy models can incorporate complex, nonlinear functions.

Fuzzy logic is used as a proxy for the complex process/response relationships normally found in stratigraphic modeling. Erosion and deposition is controlled by a fuzzy system consisting of fuzzy sets and fuzzy rules rather than a set of mathematical equations. Fuzzy logic addresses an intrinsic imprecision. Fuzziness is a measure of how well an instance (value) conforms to a semantic ideal or concept (the linguistic variable or domain). Fuzzy logic recognizes that there is an inherent ambiguity or imprecision with linguistic variables such as "near" and "far."

In the current version of the FLUVSIM model there are several input domain variables that determine two output domains (AMOUNT and SEDIMENT TYPE). Three of these input domains include: DISTANCE, NUMBER_OF_SEDIMENTATION_EVENTS and ACCOMMODATION. Implementing the fuzzy logic system involves two steps: (1) Creating fuzzy sets within each of these domains, and (2) writing fuzzy rules that operate on these sets. The program gives the user full control on implementing the fuzzy logic system.

Transport and Deposition of Heterogeneous-Sized Sediment in a Non-Marine Sedimentary Basin

P.B. Flemings (*flemings@geosc.psu.edu*), 442 Deike Building, Penn State University, University Park, PA 16801 and **J. Carlson** (*jcarlson@grabau.mit.edu*), Building 54-827, MIT, Cambridge, MA 0-2139

A fine-scaled sediment transport model is integrated with a large-scale basin model to simulate erosion, transport, and deposition of heterogeneous-sized sediment in a fluvial system. To account for the heterogeneous-sized sediment, a modified version of Einstein's (1941) sediment transport equation is combined with a macroscopic diffusion analysis. The approach we employ is similar to one presented by Rivenaes (1992), who modeled the erosion, transport and deposition of a bimodal sediment mixture by assigning a different diffusivity to each sediment size. This model expands on his approach by using a fine-scaled sediment transport model to calculate diffusivities as a function of size distribution and hydraulic conditions.

The solution is used to model the infilling of a large sedimentary basin. Figure 1 illustrates one example where the input sediment flux is composed of 50% one millimeter grains and 50% ten millimeter grains. An alluvial fan progrades as coarse sediments prograde over fine sediments until steady-state aggradation is reached where composition contours are vertical and the profile does not change through time. Figure 2 illustrates the detailed results for the steady-state of Figure 1. Unlike previous single-component diffusion models (e.g. Flemings and Jordan, 1989), the bed composition (Figure 2c) is a direct output of the model. Four variables control the downstream sorting profiles: 1) Hydraulic Conditions--If the ratio of the mean bed shear stress to the critical shear stress of the median grain size is approximately one, sorting is much more efficient than if it is significantly greater ($\tau/tc_{50} > 2$); 2) Grain Size--large grains are less mobile than small grains, hence the greater the difference in grain size the more efficient the sorting; 3) Hiding--the degree to which small grains are hidden behind large grains can be constrained from empirical studies; 4) Basin Subsidence--if variables #1, #2, and #3 can be constrained, the final key control on describing downstream sorting is the basin subsidence. We explore each of these components and show how their variation controls the composition of the resultant sedimentary basin.

One insight that fell out of this analysis is that, given the assumption that stream width widens to accommodate increasing shear stress, the effective diffusivities do not change significantly even as the bed changes from coarse to fine in the downstream direction (Figure 2d). This result suggests that historical efforts to approximate fluvial systems as a diffusive process were a reasonable assumption. Paola et al. (1992) envisioned this and we have gone beyond their approach by explicitly modeling how grains sort downstream as a function of hydraulic conditions.

References Cited

Einstein, H.A., 1941, Formulas for the transportation of bed load: American Society of Civil Engineers Proceedings, v. 67, p. 351-367.

Flemings, P.B., and Jordan, T.E., 1989, A synthetic stratigraphic model of foreland basin development: Journal of Geophysical Research, v. 94, p. 3851-3866.

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.

Rivenaes, J.C., 1992, Application of a dual-lithology, depth-dependent diffusion equation in stratigraphic simulation: Basin Research, v. 4, p. 133-146.

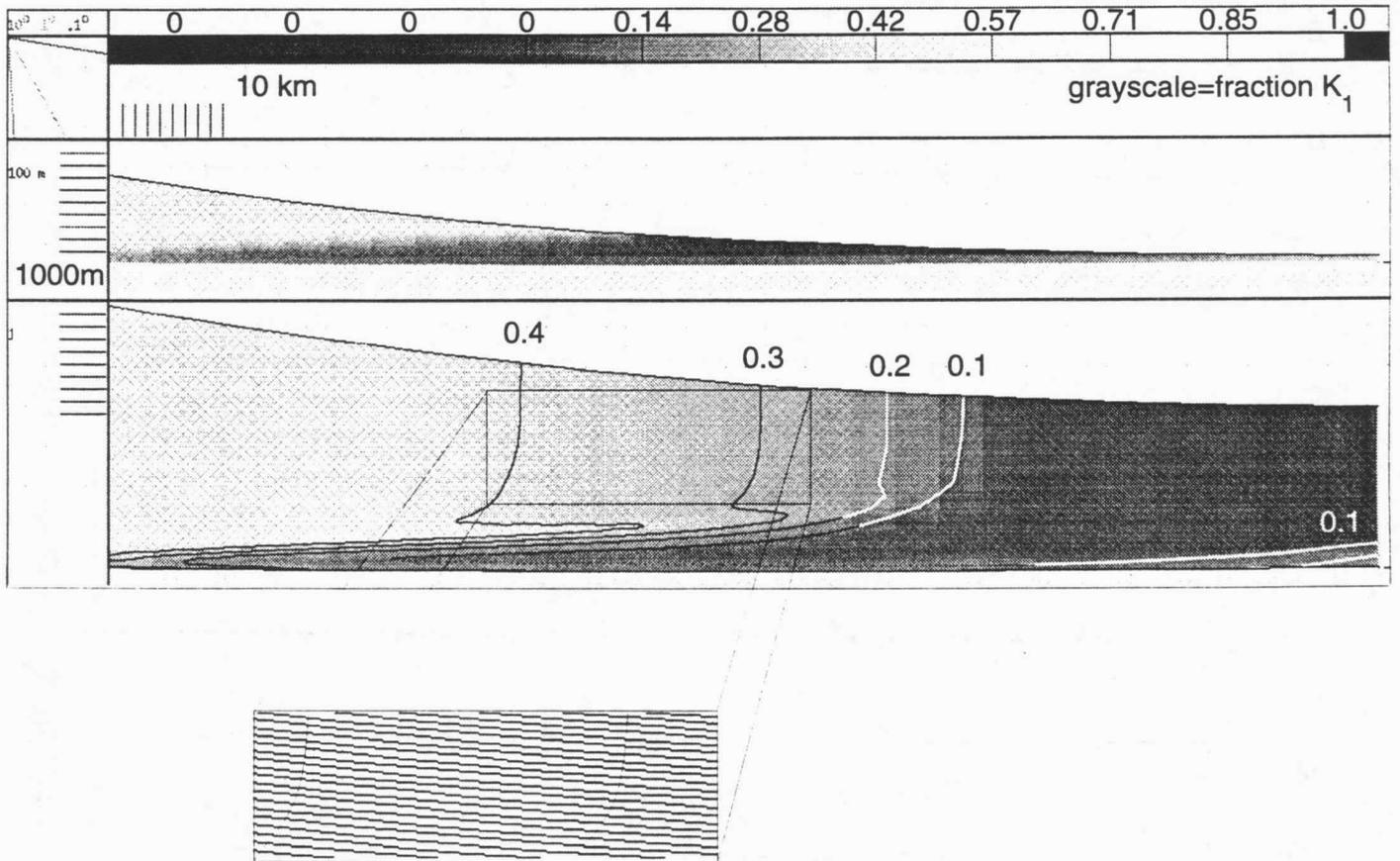


Figure 1

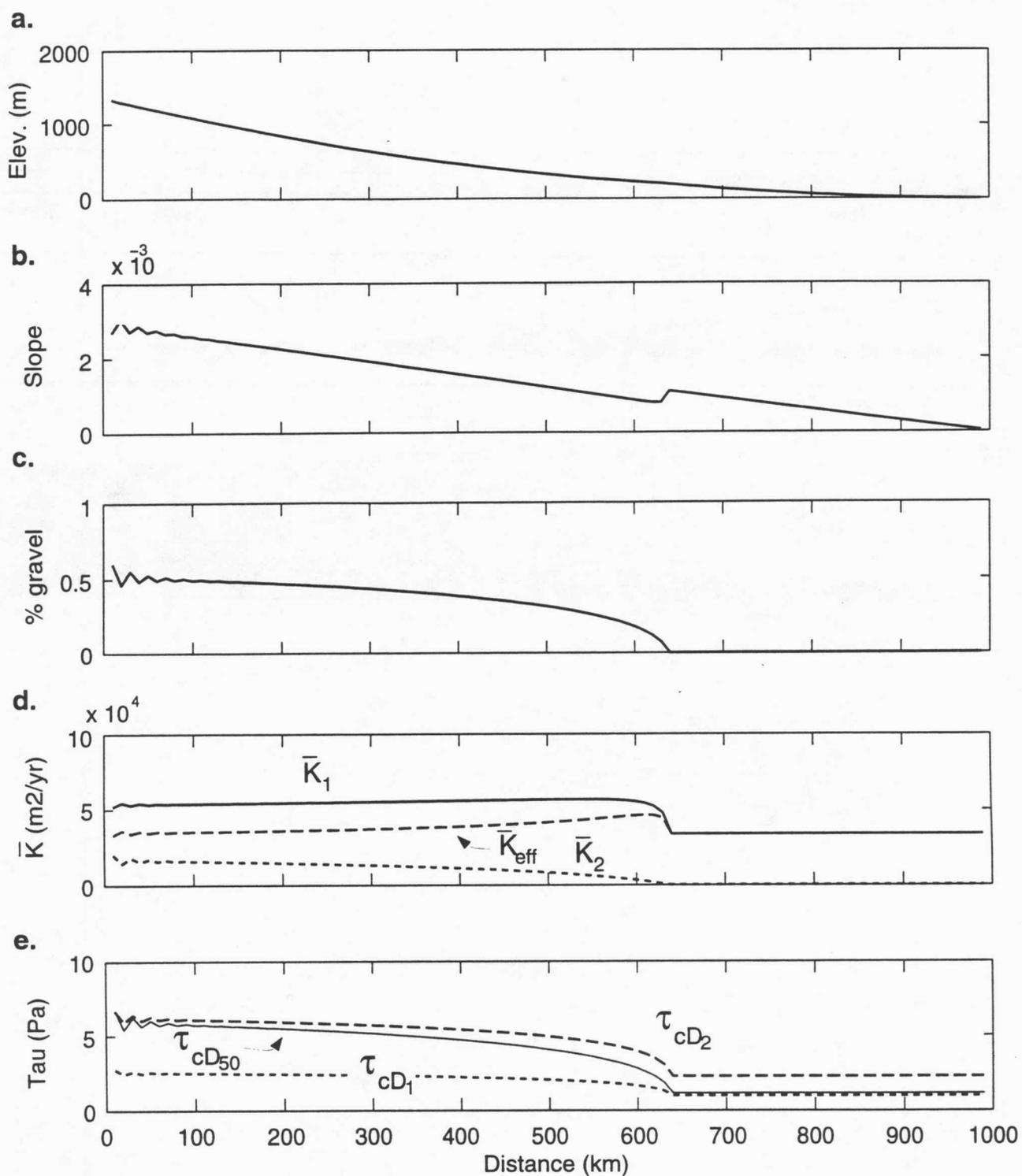


Figure 2

Flemings & Carlson, Transport and Deposition of Heterogeneous-Sized Sediment . . . submitted to NES

Integrated Approaches to Advanced Stratigraphy: Seismic Interpretation and "STRATA" Modeling of the Neogene Baltimore Canyon Trough

Peter B. Flemings (*flemings@geosc.psu.edu*), **Ruth Robinson** (*ruth@geosc.psu.edu*), **Andy Hoover**, **Roberta Hotinski**, **Steve Nelson**, **Chris Poulsen** and **Glenn Spinelli**, *Deike Building, Penn State University, University Park, Pa. 16802*

We interpreted 7 dip and 4 strike seismic lines from the 1992 R.V. Ewing Seismic Survey (co-chief scientists Greg Mountain, Lamont-Doherty Geological Observatory and Ken Miller, Rutgers University) to serve as a foundation for forward modeling the stratigraphic evolution of this well-studied passive margin. The study focussed on the Miocene deposits of the Baltimore Canyon region; five major sequences were interpreted by combining the seismic data with wireline and published biostratigraphic and lithologic core studies. Four of our major sequences correlate with those of Greenlee et al. (1992). We use their sequence dates to approximate accumulation rates for the margin.

"STRATA", a basin-modeling package which uses a diffusion-based (slope-dependent) sediment transport algorithm, is used to forward model the stratigraphic evolution of the passive margin. The clastic flux is assumed to be constant and is obtained by dividing the area of sediment deposited during the Miocene (since Strata is a 2-D model) by the duration of this period. A tectonic subsidence rate of 0.0675 mm/yr is superimposed upon an original 200 meter bathymetry and isostasy and compaction are allowed to occur. Finally, the modeled stratigraphic architecture derived from our seismic-derived sea-level curve is compared to the modeled stratigraphy resulting from Haq et al.'s (1987) sea-level curve.

The two simulations reproduce the approximate dimensions and foreset angles of the actual platform (e.g. Figure 1). Our seismic-derived sea-level curve assumes sinusoidal variation around the estimated amplitudes, whereas Haq et al.'s (1987) curve is characterized by almost instantaneous sea-level falls. This has a profound affect on the accumulation of highstand deposits. With our sea-level curve, the rate of fall is slower and greater highstand systems tracts are preserved; the Haq et al.'s (1987) abrupt sea level falls produce thin or non-existent highstand systems tract, in contrast to the stratigraphic record. This is due in part to STRATA's inability to simulate local incision of channels on the platform. Instead, the entire shelf is eroded as baselevel is lowered, removing a significant portion of the previous highstand systems tract which would be preserved in an actual platform.

STRATA is a useful teaching tool that allows easy change of input parameters and rapid simulation and visualization. As part of our class project on the stratigraphic evolution of the Baltimore Canyon Trough, we were able to test how stratal geometries, the generation of unconformities, and the magnitude and spatial variation of sediment accumulation are affected by variations in sealevel curves and subsidence history.

STRATA is available as freeware over the Internet (<http://hydro.geosc.psu.edu>) and this simulation can be observed directly at that site.

References

Haq, B. U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea-levels since the Triassic: *Science*, v. 235, p. 1136-1167.

Greenlee, S.M., Devlin, W.J., Miller, K.G., Mountain, G.S., and Flemings, P.B., 1992, Integrated sequence stratigraphy of Neogene deposits, New Jersey continental shelf and slope: Comparison with the Exxon model: *Geological Society of America Bulletin*, v. 104, #11, p. 1403-1411.

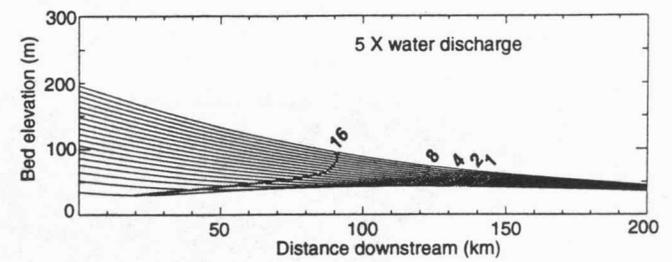
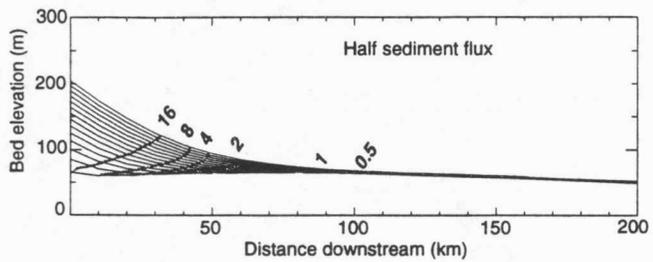
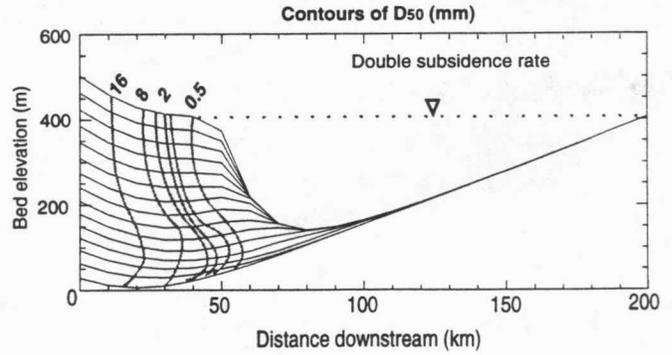
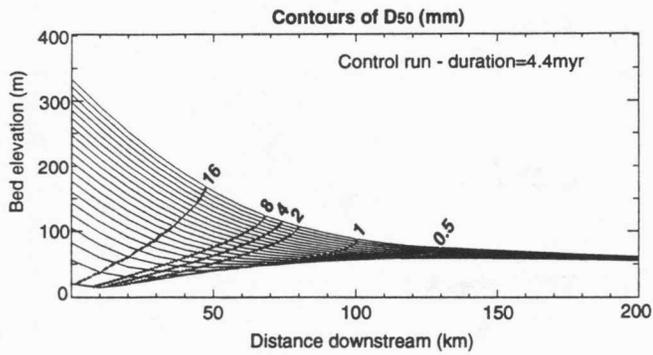


Figure 1. Longitudinal profiles of an alluviating river, showing bed elevation through time. **A.** Control run. Grey lines represent median (D_{50}) grain-size contours (mm). Subsidence profile is exponential in **A**, **C**, and **D**, and linear in **B**. Sediment feed size distribution is bimodal. All profiles have increasing channel width and discharge downstream. **B.** Doubling subsidence rate has the greatest effect on downstream fining rate. **C.** Halving sediment flux slightly increases fining rate due to reduced bed slope and improved sorting. **D.** Five-fold increase in water discharge increases the downstream fining rate by almost half.

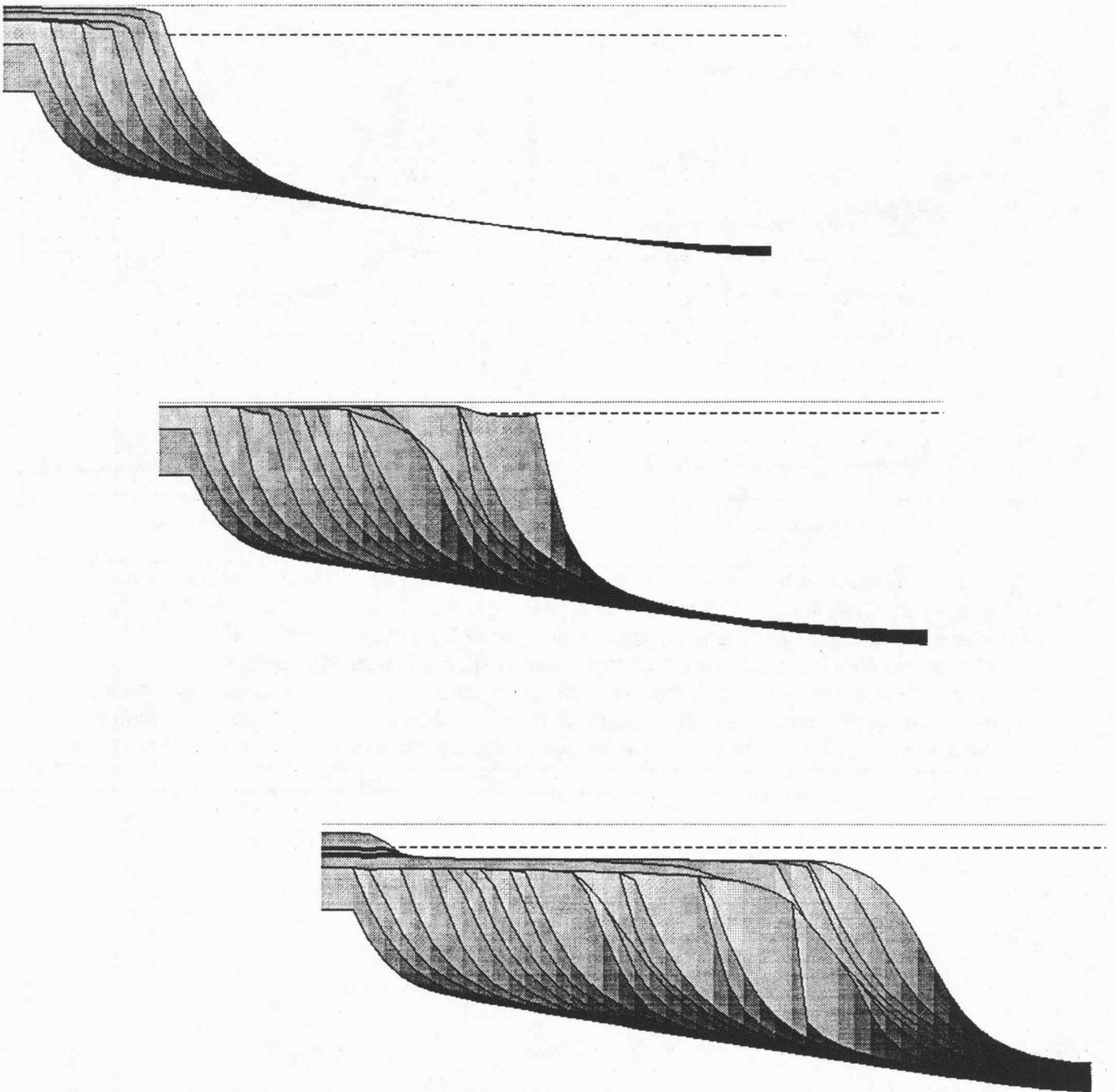


Figure 2

Flemings et al., STRATA2.1: A Simulation of Neogene Baltimore Canyon Strata . . . submitted to NES

KANMOD -- A 2D Carbonate Modeling Program

John A. French, *Interpretive Imaging, LLC, 4891 Independence Street, Suite 250, Wheat Ridge, CO 80033* and **W. Lynn Watney** (*lwatney@pcmail.kgs.ukans.edu*), *Kansas Geological Survey and Energy Research Center, 1930 Constant Avenue, Campus West, Lawrence, Kansas 66046*

A two-dimensional stratigraphic computer simulation referred to as KANMOD has been used to experiment with sedimentation and stratigraphy associated with high frequency minor cycles, depositional sequences, and sequence sets in Pennsylvanian carbonate-dominated strata in Kansas, USA (French and Watney, 1990; Watney, French, and Guy, 1996). The model simulates accumulation of carbonates, condensed sections, and paleosols. The basic stratigraphic unit that is generated by the model is the depositional sequence. Primary types of genetic units that comprise these depositional sequences can be produced, including flooding units, condensed sections, late-highstand (or forced-regressive) units containing complex internal stratigraphy, minor cycles within the depositional sequence, and subaerial-exposure surfaces. Lowstand, transgressive, and highstand systems tracts can be developed under the proper conditions.

This simulation program written in Turbo Pascal on a PC utilizes an a priori numerical approximation algorithm involving a predefined relation between sediment accumulation rate, water depth and depositional slope. Sediment type is either high energy or low energy, defined by the depositional slope. While the sediment responds to a gradient of the depositional slope, the process is not driven by the gradient itself (there is no dh/dx relation, for example, that controls sedimentation).

Input parameters include eustacy, subsidence, rates of sediment accumulation, and initial depositional profile. Accumulation rates decrease with increasing water depth to a constant low value, e.g., 0.01 meters per thousand years below 115 ft (35 m), an approximation of the base of the euphotic zone in the midcontinent Pennsylvanian sea. Also, sediments are slowly eroded during subaerial exposure. Carbonate sediments deposited within defined depth ranges are assigned to 11 maximum separate colors according to water depth and energy level. Subaerial exposure surfaces and condensed are also recognized by separate colors. Isochronous depositional surfaces can be included at user-selected intervals to identify where the depositional surface was at various times during development of the deposit. The output is a time vs. elevation plot of the sealevel curve and initial depositional surface, and a cross section showing incremental sedimentation at each timestep. Sediment is deposited as pixels, assigned to a lithofacies according to the algorithm. Model runs typically are 20 seconds on a 100 Mhz pentium PC.

The model generates both a color 2D image and selected detailed stratigraphic columns along the 2D image. Run length of KANMOD can be changed between two basic scales: (1) 100,000 to approximately 2 million years for 4th-order sequences and 5th-order minor cycles; or (2) longer term, 5+ million years for 3rd-order sequences. Time steps differ with run length; shorter runs are composed of shorter time steps.

The horizontal and vertical scales of the graphical output can be changed for successive runs to maximize the image. Parameters that can be varied include the duration of individual runs and the vertical exaggeration of the output. Smaller areas of the output can be selected and expanded to full screen by drawing a box around the area of interest and repeating the run. The second screen then is filled with the boxed-in area.

References

French, J.A., and Watney, W.L., 1990, Computer modeling of the Midcontinent cyclothems and its application in the prediction of hydrocarbon reservoirs (abst.): American Association of Petroleum Geologists Bulletin, v. 74, p. 657.

Watney, W.L., French, J.A., and Guy, W.J., 1996, Modeling petroleum reservoirs in Pennsylvanian strata of the Midcontinent, USA: *in*, Forster, A. and Merriam, D.F., eds., Geologic Modeling and Mapping, Plenum Press, New York, p. 43-77.

Concepts and Applications on a 3D Multilithological Diffusive Model

D. Granjeon (*didier.GRANJEON@ifp.fr*) and **Ph. Joseph** (*Philippe.JOSEPH@ifp.fr*),
Institut Français du Pétrole, 1 et 4, avenue de Bois-Préau, BP 311 - 92506 Rueil-Malmaison Cedex, France

A three dimensional stratigraphic forward model has been built at IFP to simulate geometries and lithologies of coastal environments, e.g. coastal plain, shoreface and upper offshore in a high resolution sequence stratigraphic framework on temporal and spatial macro scales (hundreds of thousand to tens of million years, and tens to hundreds kilometers).

The model is based on average physical principles applicable to such temporal and spatial scales. An improved diffusion equation, taking into account the water discharge, simulates the fluvial and marine sediment transports, while an advection equation is devoted to the simulation of the wave activity.

The main parameters of the model answer to three major questions : (1) how many space is created in the basin ? Tectonic subsidence maps and an eustatic curve are defined by the user. The model is able to estimate the isostatic or elastic flexure of the lithosphere in response to sediment loading, and to compute the compaction of sediment by use of porosity - depth laws.

(2) how many sediments are introduced and / or produced in the basin ? In order to simulate the distribution of several lithologies (sand, shale, carbonate, ...) in the basin, each lithology are introduced separately at the boundary of the basin. The carbonate lithologies are produced in the marine environment. The production rate is expressed as a function of the bathymetry and the siliciclastic discharge.

(3) how these sediments are transported through out the basin ? For each lithology, an improved diffusion equation is used to estimate the lithology transport. The diffusion coefficient is a function of the bathymetry and of the global water discharge, which is computed by the model using a tree algorithm simulating the formation of average channel belts.

The basin is discretized with a regular mesh, and each equation is solved using a numerical explicit finite difference scheme.

Although based on simple physical laws, the application of this 3D multilithological diffusive model on some theoretical and real cases has proved its geological consistency. An inverse model has been developed in order to calibrate the model parameters (accommodation, sediment supply, diffusion laws) from the geological parameters (sediment thickness and facies obtained from well log analysis, ...) in order to fit the results of the diffusive model onto the well log data.

The model has been successfully applied on three field studies : the Lower Cretaceous mixed carbonate - siliciclastic formation (total duration = 10 million years) of Paris Basin, France, in 3D and at a regional scale (200 x 240 square kilometers), the Cenomanian carbonate formation (total duration = 3 millions years) of Oman Basin at a regional scale (200 kilometers), and the Campanian siliciclastic formation (total duration = 4 million years) of San Juan Basin, USA, at a reservoir scale (20 kilometers).

Despite of these encouraging results, some points need to be tested or improved such as littoral drift and turbiditic transport.

These successful applications validate the global physical principles used in the model which provides a quantitative tool for better understanding the 3D carbonate and siliciclastic filling of a basin.

How to know when you get it right (formally and quantitatively)

Cedric Griffiths (*cgriffiths@ncpgg.adelaide.edu.au*), **Taizhong Duan**, and **Andy Mitchell**,
*National Centre for Petroleum Geology and Geophysics, Thebarton Campus, Adelaide
University, Adelaide, SA 5005, South Australia*

Forward modelling of stratigraphic units has proceeded apace in recent years. Many groups are now producing simulated 2D sections and 3D volumes that can be compared to observed sections derived from seismic lines, boreholes, or outcrop. The question remains however as to the degree of similarity between any given simulated section and the observed section that we are trying to match. This becomes of vital importance in the design of forward modelling routines that automatically modify input parameters to converge on the observed section. In this respect forward modelling is no different from any conditioned simulation. Simulated and observed sections may superficially look similar to each other, and yet differ 'significantly' in the very detail that we wished to predict from the modelling exercise.

There are several means by which we may compare sections or volumes. In the spatial domain we could for example define the shape of each component 'chromosome' and compare the shapes. We could split each section or volume into 1D pseudo-wells and compare the succession of time intervals, thicknesses, lithologies, water depths, depositional facies, systems tracts etc. We could define each bounding surface as a plane and compare planes. In the frequency domain we could compare the 1D spectra of bed bundling or 2D FFT's of each surface. We could compare the Walsh or Fourier transforms of a series of vertical sections.

One approach which is flexible and readily applied to 2D and 3D problems is that of syntactic pattern matching. Using this approach a distance measure is defined between any pair of 1D sequences of units such that we can formally compare the similarity. Each one-dimensional sequence can be represented by a string of lithology symbols, depositional facies symbols, system tract codes, etc. Each symbol can also have a vector of attributes that can provide other information such as thickness, age, water depth etc. The distance/ dissimilarity of any two sequences is then defined as consisting of both their syntactic and attribute distances. The syntactic distance measures the difference of symbol status between two or more sequences and the attribute distance measures the difference of, for example, thickness of corresponding symbols between two or more sequences. In the example illustrated above (using the simulations published in Schroeder and Greenlee, 1993) we can see that the proximal similarity between observed and simulated sections is greater than the distal similarity, and also that there is little quantitative evidence for preferring the Greenlee and Moore sea level curve over the haq curve, at least using geometrical criteria.

If the shape of a chromosome in section is important then we can use 2D cross-correlation techniques to compare simulations. The example shown here uses a simple 2D cross-correlation to compare four similar clinoform shapes. Serial 1D syntactic comparison at 'appropriate' spacings can be used to compare series, sections, or volumes in 1-, 2-, and 3-D. Serial 1D comparisons can give a formal, quantitative test of section equivalence but they are difficult to use to interactively control a forward model due to the non-uniqueness of the distance function. More work is needed in this area.



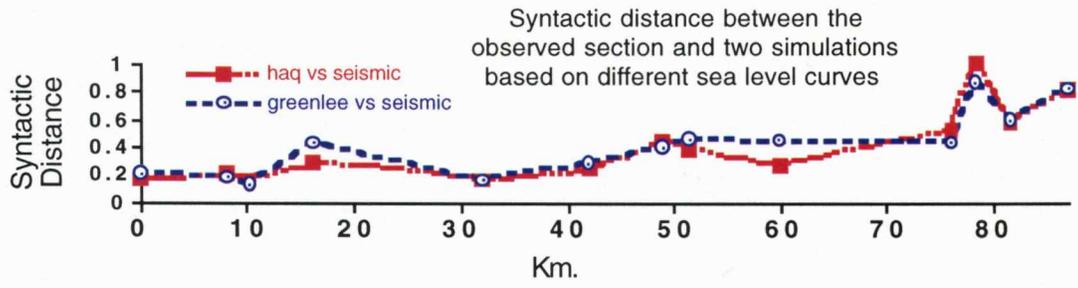


Figure 1--Griffiths, Duan, and Mitchell

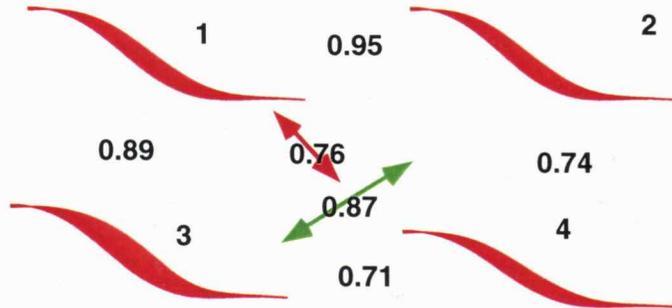


Figure 2--Griffiths, Duan, and Mitchell

Stratigraphic Modeling of Cyclic and Chaotic Behavior on Continental Margins

John W. Harbaugh (*harbaugh@pangea.stanford.edu*), *Department of Geological Sciences, Stanford University, Stanford, CA 94305-2115*

There is wide interest in cyclic sequences of beds that have been deposited near the margins of continents. In many places, lesser cycles within greater cycles have been identified, and in some localities, hierarchies of as many as five different cycles have been interpreted. Most authors interpret these cyclic sequences to have formed in response to changing sea levels caused by external "forcing functions" that affect climate, such as alternations in the inclination of the Earth's axis, or fluctuations in the sun's radiant energy.

There is little doubt that changes in water depths have been influential in creating cyclic deposits, but causes other than world-wide fluctuations in sea level also may be important. Alternatively, cyclic sequences may reflect complex responses of a coupled dynamic system that links variations in continental elevations, variations in the rate of subsidence at continental margins, variations in sea level, and variations in the rate at which sediment eroded from the continents is transferred to the sea.

It is well known that most actual dynamic systems exhibit cyclic and chaotic behavior, as for example, vibration in machinery and oscillations in electrical circuits. Few attempts, however, have been made to represent aspects of the behavior of the Earth's crust as truly dynamic systems in which the components are linked together so that every component affects every other component. The problem is that there is little knowledge of how to create such systems. To do so requires mathematical simulation models in which the components and their interdependencies are represented by equations. Computers then can be used to solve the equations numerically, and the succession of solutions represents the behavior of the model.

DYNASED consists of equations that links variations in continental elevations with variations in sea level, and with variations of the rate at which sediment derived from the continents is transferred to the sea. It is a simple model with only three variables and three equations, but it responds with astounding complexity when the control parameters (which consist of coefficients, exponents, and lags) are adjusted. For example, with a specific setting of the control parameters, DYNASED may respond for many thousands of iterations with a high degree of cyclicity, with lesser cycles nested within successively greater cycles. Suddenly, however, its response may drift from cyclicity, to chaos, and then return later to cyclic response, and so on. Experiments spanning millions of iterations are feasible.

While DYNASED is essentially one dimensional (the one dimension represents variations in sea level and variations in the general elevation of the continents), its responses also may be viewed as two-dimensional stratigraphic cross sections in which the dispersion of clastic sediment is represented by the diffusion equation, with dispersion rates being sensitive to variations in sea level and the rate at which sediment is supplied to the continental margin.

The idea is to see how the features of actual stratigraphic sequences formed at continental margins might correspond to those produced in simulations by DYNASED.

It seems unlikely that simple relationships exist between world-wide fluctuations of sea level, and deposition at specific localities. A thick sequence of beds deposited in shallow water implies local subsidence of the crust to accommodate the sequence. It is likely, however, that local subsidence is coupled in some manner with fluctuations in sea level, although the manner in which such a coupling operates is obscure. Any such coupling, however, is likely to involve both cyclic and chaotic responses. DYNASED, as primitive as it is, provides a means of exploring such couplings.

In conclusion, it is suggested that geologists who devise models of the way things operate in the earth's crust, also attempt to represent the models as coupled, dynamic systems. If they are able to do so, simulation experiments may reveal unsuspected behavioral responses that are likely to be both cyclic and chaotic.

Modeling of Sediment Distribution and Currents in the Western Baltic Sea

J. Harff (*harff@geo.io-warnemunde.d400.de*), **W. Lemke**, **A. Mutzke**, **T. Seifert**, and **F. Tauber**, *Baltic Sea Research Institute (IOW), Seestr.15, D-18119, Rostock-Warnemünde, Rostock, MV, 18119 Germany*

The Baltic Sea is a semi-enclosed marginal sea and represents the largest modern brackish water reservoir. The Baltic Sea is connected with the North Sea and the world ocean by the Danish straits through which marine oxygen rich water flows into the Baltic. Its bottom relief is characterized by a cascade of basins subdivided by shallow sills. The Darss sill represents as the Baltic's "bottle neck" a key area for the water exchange with the North Sea. The current field is governed generally by the main wind directions from the West and from the East. Oceanographic measurements and satellite images confirm a complex mesoscale dynamics in the western Baltic consisting of coastal jets, eddies and topographically guided patterns. Due to the low water depth (18 m at the Darss sill in average) these patterns influence the depositional processes of sediments. Little is known by now whether the sediment distribution pattern is mainly determined by strong short-term events or more by long-term current trends. As a first attempt to understand the complex relation between sediment distribution and the governing current system the granulometric facies of sediments along the German coast of the Darss sill is compared with results of oceanographic numerical modeling of the current field. The sediment distribution is displayed as the result of regionalized classification of granulometric data from the German Darss Sill area (Davis et al., 1996). Numerical classification of sediment samples led to three main sediment types: poorly sorted coarse lag sediments of eroded till, fine grained well sorted sediments of depocenters and poorly sorted fine grained sediments representing a channel facies. For a first comparison results of a 240 hours wind registration from the Darss sill monitoring station was used as driving force for a high resolution numerical model (free surface version of the BRYAN-COX-SEMTNER code with 2 km horizontal and 2 m vertical resolution, see Seifert & Fennel, 1994). The model shows a highly varying 3-dimensional current field which is in correspondence with acoustic current profiles taken by shipborne ADCP measurements.

Comparing the regional distribution pattern of sediment types with the nearbottom current pattern one can detect typical correspondences: Erosional facies along the Darss sill coast coincides with coastal jets and uniform water transport from southwest to northeast. Shallow depressions north of the Zingst coast are determined sedimentologically by depositional facies and coincide with changing current dynamics and circular transport. Poorly sorted fine grained sediments are found exclusively in the Kadet Channel caused obviously by typical channel currents. The comparison of current systems and sediment distribution gives hints for the driving forces of erosion, transport and deposition at shallow sills of the Baltic Sea. As the next step in the concept long-term runs and current statistics are planned before the sedimentary processes in geologically relevant time scales in the Baltic can be modeled.

References

J.C. Davis, Harff, J., Lemke, W., Olea, R.A., Tauber, F., Bohling, G., 1996, Analysis of Baltic Sedimentary Facies by Regionalized Classification: *Geowissenschaften*, vol. 14, no. 2, 67-72.

Seifert, T., Fennel, W., 1994, Numerical Experiments in the Transition Area between Baltic Sea and North Sea: *Proc. 19th Con. Baltic Oceanographers*, Sopot, Poland 1994.

Data Based Modeling of the Ocean-Sediment System in Large Basins

B. J. Haupt and K. Stattegger (*KSTATTEGGER@GPI.UNI-KIEL.DE*), *Geological-Paleontological Institute, University of Kiel, Olshausenstrasse 40-60, D-24118 Kiel, Germany*

Numerical modeling of oceanic circulation and resulting sedimentary patterns provides a quantitative means for evaluating and understanding the complex interactions of the ocean-sediment system.

SCINNA (= Sensitivity and Circulation in the Northern North Atlantic(NNA)), a three-dimensional fully prognostic ocean general circulation model (OGCM), is used for modeling the oceanography of the Greenland, Iceland, and Norwegian (GIN) Seas and their adjacent basins. The fine resolution of 55 km box length in latitude and longitude and a total of 17 vertical levels allows a realistic representation of the topography.

The model is forced by prescribed sea surface temperatures and salinities, thereby introducing the effects of surface heat and freshwater fluxes.

The prognostic sedimentation models SENNA (= SEDimentation - erosion, transport and deposition - in the NNA) and PATRINNA (= PARTicle Tracing In the NNA) are driven by the thermohaline oceanic circulation and coupled to an OGCM. SENNA and PATRINNA combine two coupled models: the 3-D models calculate the sediment transport and the separate particle path in the water column. In SENNA the 1 centimeter thick 2-D bottom layer considers the erosion, transport and deposition of sediments; in PATRINNA single particle drifts parallel to the sea floor.

Modeling the Last Glacial Maximum on a 21600 calendar-years time slice, the most probable scenario for the glacial summer resembles very closely the modern winter with ice-free GIN Seas. Proceeding to the subsequent Meltwater Event (13500 yrs B. P.), several possibilities for meltwater discharges from the Laurentide and European ice sheets have been modeled which lead to dramatic changes in ocean circulation and deepwater formation.

The simulated sedimentation patterns and particle paths fit very well the observed sediment distributions, e. g. the large sediment drifts south of the Greenland-Scotland Ridge. The strength of these models is the predictability of tracing transport pathways for variables such as sediments, water masses, pollutants, and organic material for variable scenarios, natural or artificial.

A crucial point is the primary model initialization which should be based on consistent observational data. To fill a small-scale grid of a large-scale basin, this data cannot be easily obtained. Even for modern state control-experiments, available data sets are not always physically consistent to drive a model in a realistic manner. Going back on the geologic

record, a sound data base for modeling needs, e. g. proxies in paleoceanography, is much more difficult to find, especially if one wants to cover several distinct time slices. Although we have poor data and sophisticated models, sensitivity experiments using varying input data can help substantially evaluating realistic model scenarios, and determining the influence of single model-parameters.

Future model experiments will concentrate on climatically induced changes in oceanic circulation and its sedimentary response with special focus on (i) increasing sea surface temperatures starting a greenhouse scenario by triggering a new meltwater event and (ii) decreasing temperatures that approximate the icehouse state.

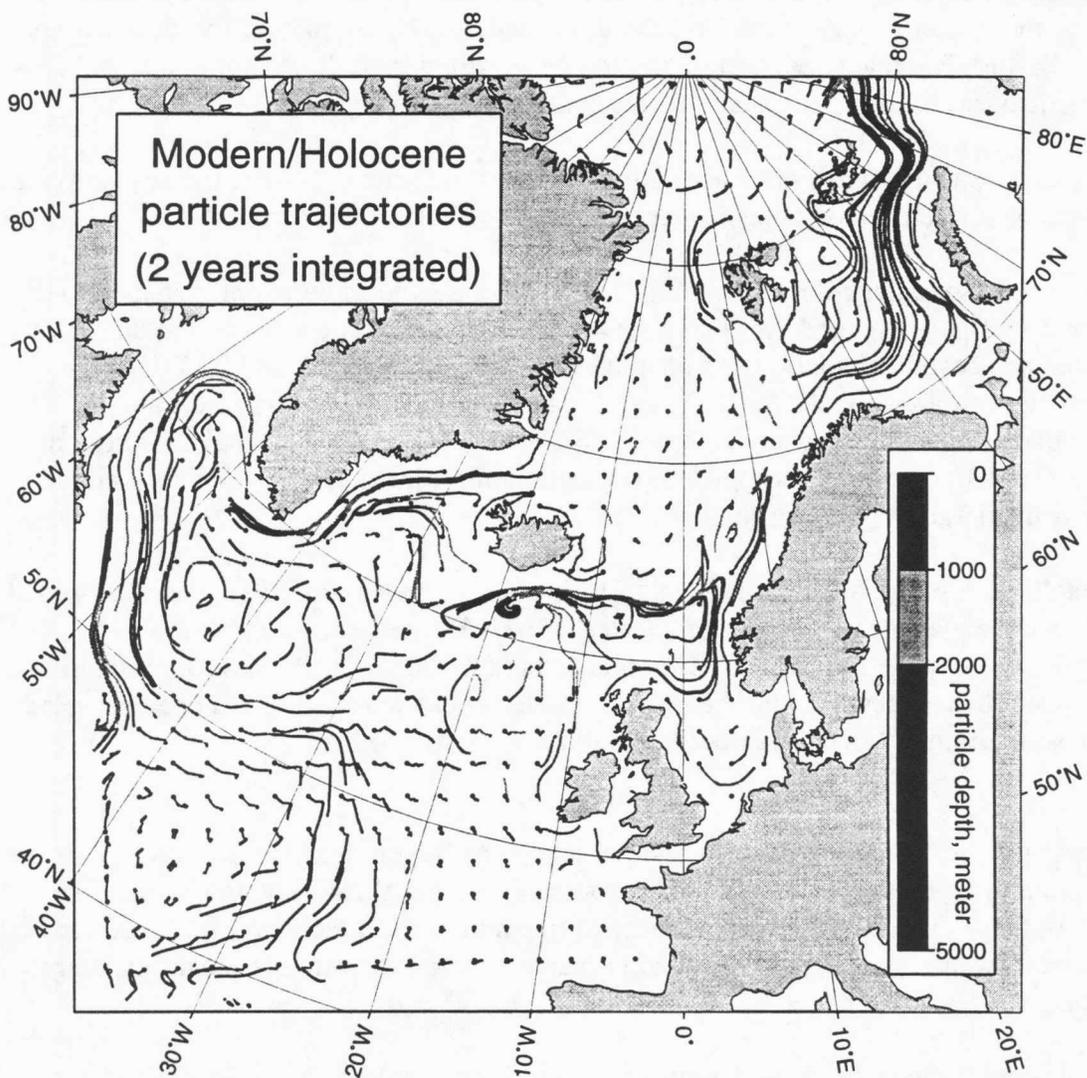


Figure 1.

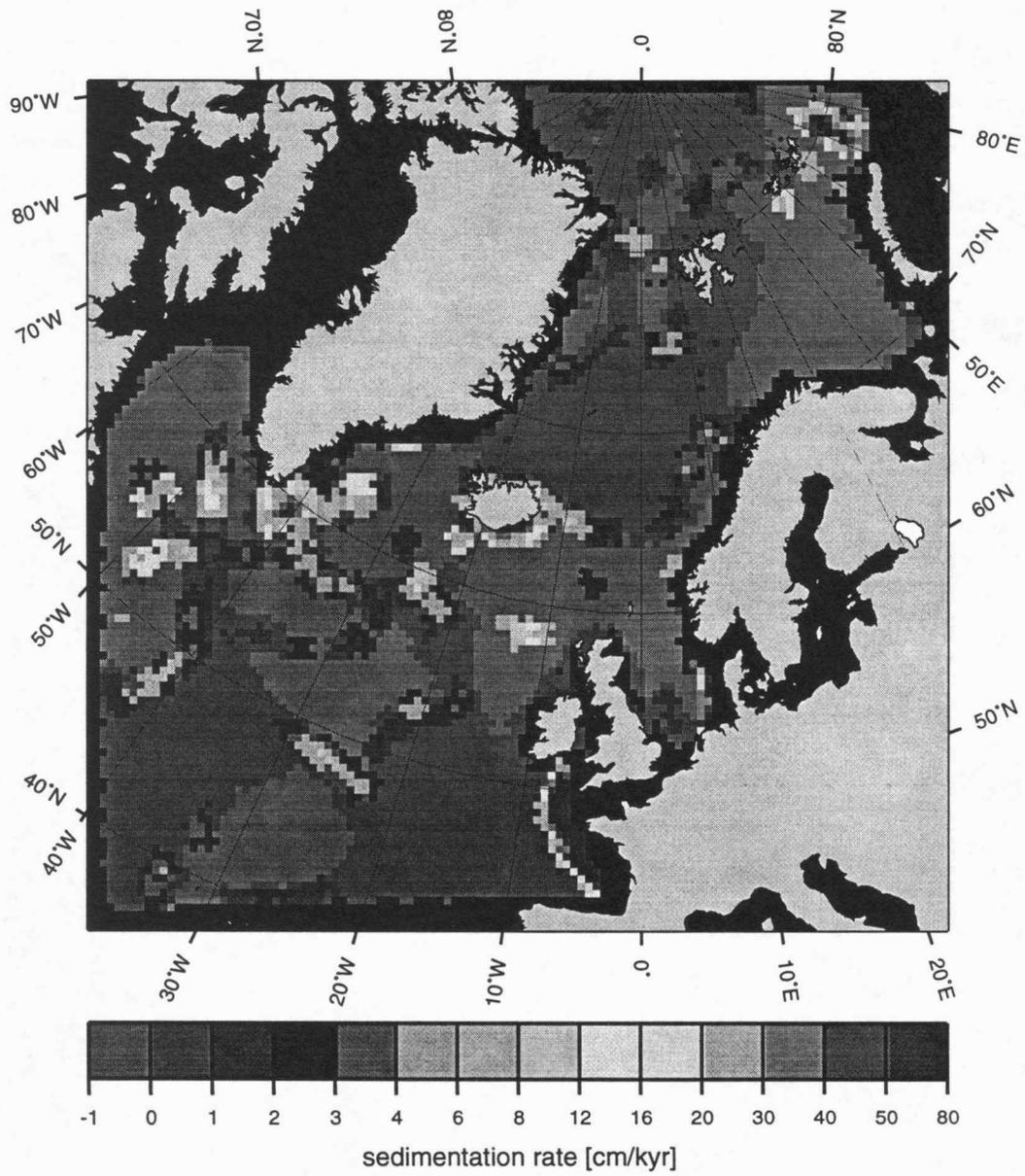


Figure 2.

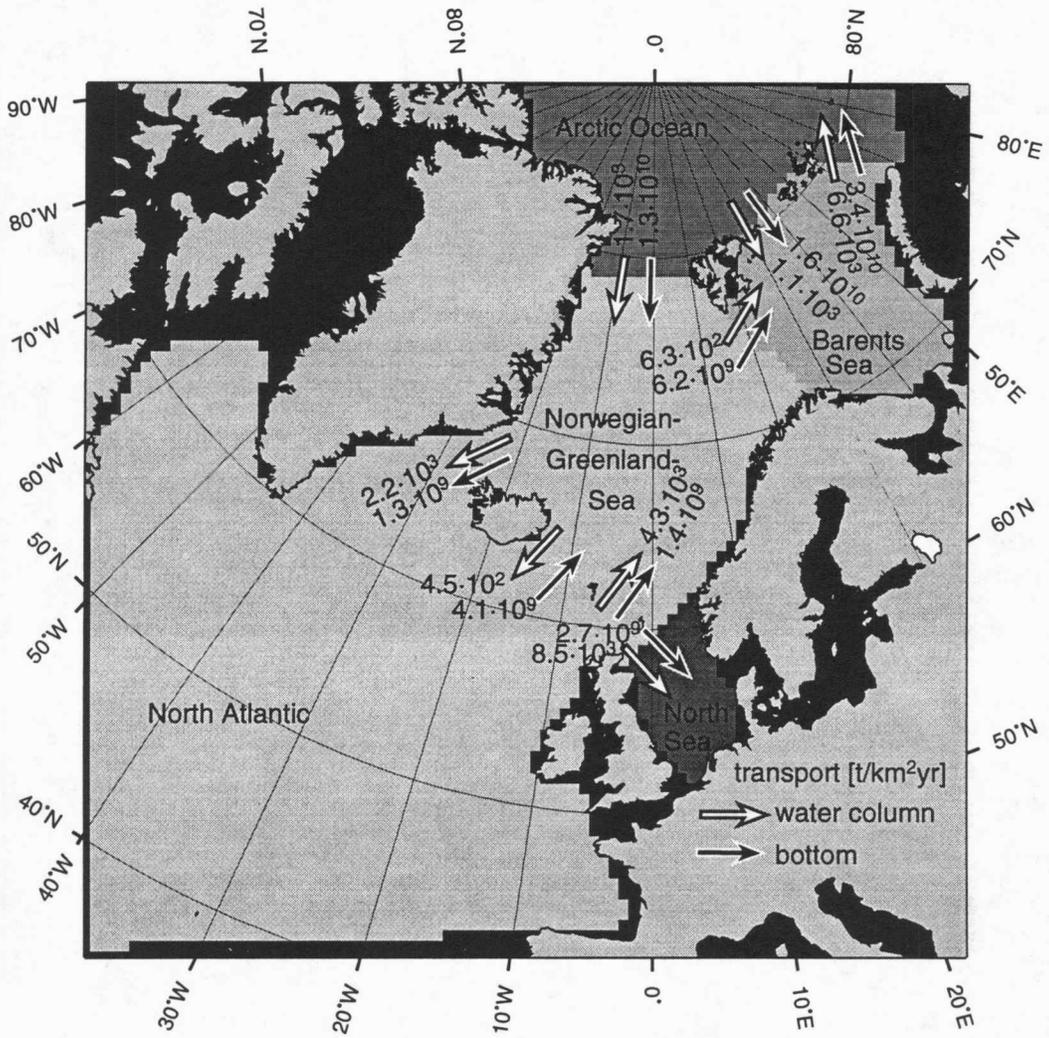


Figure 3.

Modelling Tectonic, Climatic and Eustatic Effects on Orogen/Foreland Basin Systems

David D. Johnson (*David.D.Johnson@erpddj.exxon.sprint.com*), *Dalhousie University*¹

In orogen/foreland basin systems, the development of basin stratigraphy is strongly influenced by the rates of several first order processes: orogen tectonics, surface processes, climate, isostasy and eustasy. A composite kinematic planform model has been developed to look for stratigraphic signatures that reflect the dominant influence of one of these basin controlling processes or the interaction among several processes.

The orogen/foreland basin model links component models of orogen tectonics, surface processes, orographically controlled precipitation, lithospheric flexure and eustasy in an internally consistent manner (Fig. 1). Critical Coulomb wedge theory is used to create a doubly-vergent wedge-shaped orogen. The surface processes model couples diffusive and advective transports to erode, redistribute and deposit material. Fluvial transport is determined by both surface slope and discharge; the latter is controlled by precipitation and collection. Orographic rainfall is determined by topography, extraction efficiency and vapour flux. The isostasy model uses either an elastic or a thermally activated linear viscoelastic plate rheology to flexurally compensate for changes in orogenic, sedimentary and water loads. Eustasy is uniform change in model sea level.

Model results show, in planform and section, parallel and oblique continent/continent collision and orogen growth with pro- and retro-foreland basins. The effects of basin setting, along-strike changes in tectonics, prevailing 'wind' direction and feedback among processes on the rates of orogen growth and basin filling are illustrated. Stratigraphy is shown as facies bounded by chronostratigraphic and erosional surfaces. Facies are described by characteristics of the model's depositional environments.

Synthetic stratigraphy is presented for orogen/foreland basin systems that have experienced changes in tectonics, climate or eustasy as either step or sinusoid functions. Stratigraphic assemblages show both the transient and steady state system response to these changes. Response times are estimated for tectonic and climatic forcing and used to illustrate how stratal geometry and facies distributions vary when the period of forcing is either approximately the same as or much greater than the response time (Figs. 2 & 3).

Tectonic and climatic processes are shown to have similar effects on landform evolution and therefore the distribution of alluvial, coastal and marine facies. These similarities allow combinations of tectonic and climatic forcing to enhance or retard their mutual effects on stratigraphic development. Eustasy is shown to have a subordinate effect to tectonic and climatic processes on alluvial plain development and a dominant effect on landform evolution proximal to the coast (Fig. 4).

¹ Present Address, EXXON Production Research Company, P.O. Box 2189, Houston, TX 77252-2189

David D. Johnson, Modelling Tectonic, Climatic and Eustatic Effects on Orogen/Foreland Basin Systems,
Figures 1a and 1b

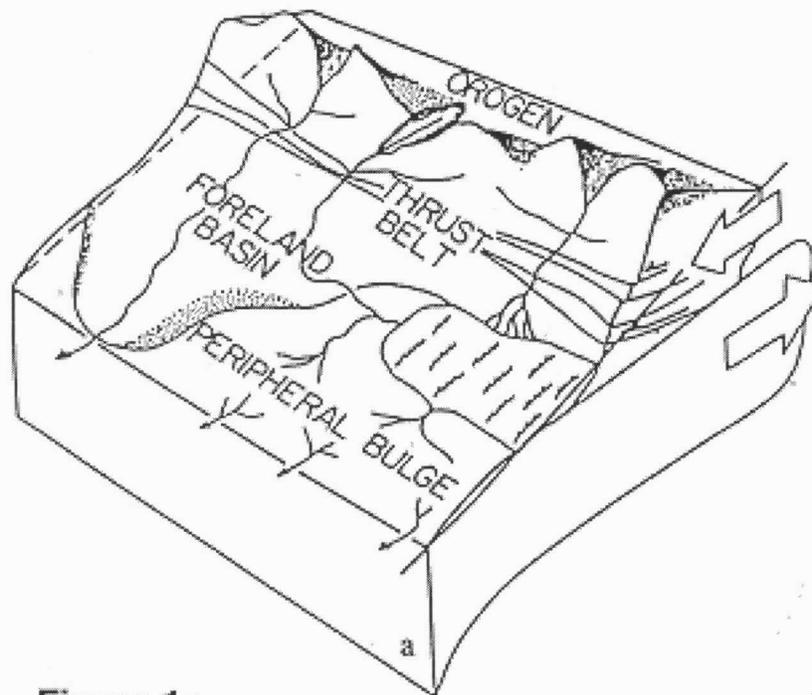


Figure 1a

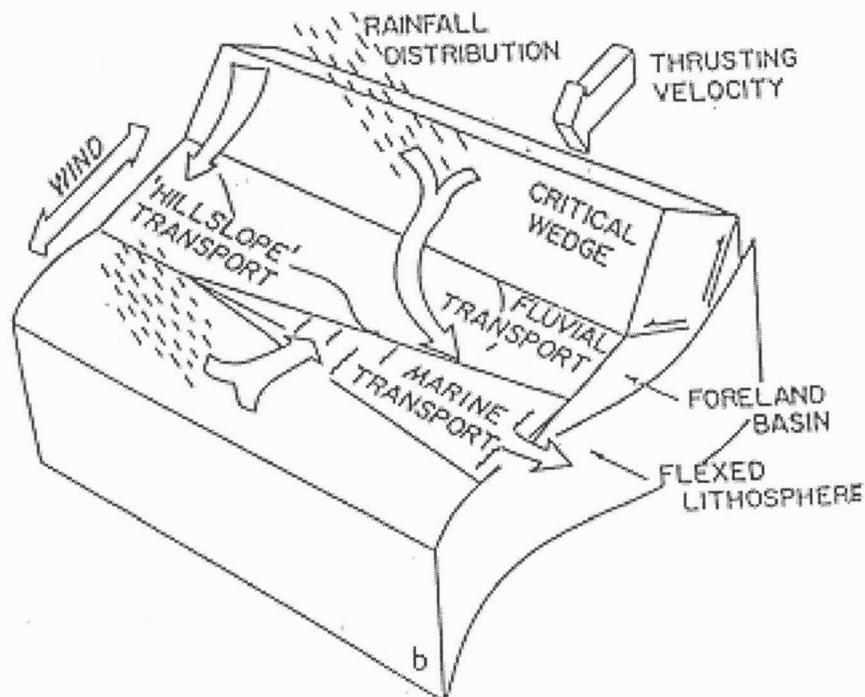


Figure 1b

MT6 at 15 My - Periodic v_T , Constant Q_V and v_E

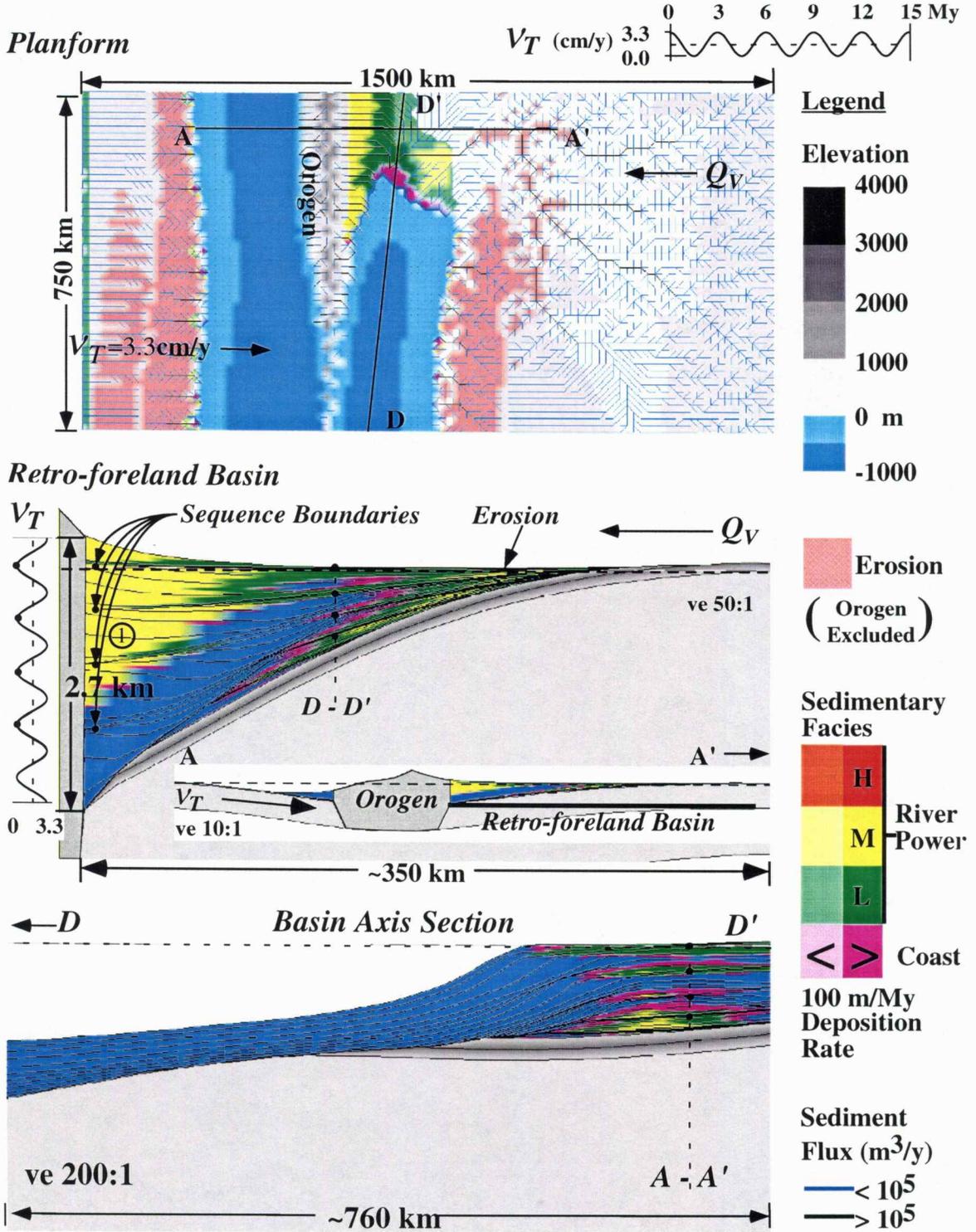


Figure 2. Model MT6 is shown in planform, transverse section (regional A-A' and retro-foreland basin) and longitudinal section (D-D') at 15 My. MT6 is characterized by stacked sequences. Sequence boundaries are in phase (coeval) with times of minimum v_T (tectonic convergence, dots). Vapour flux (Q_V) and eustasy (v_E) are constant.

MT7 at 15 My - Periodic v_T , Constant Q_V and v_E

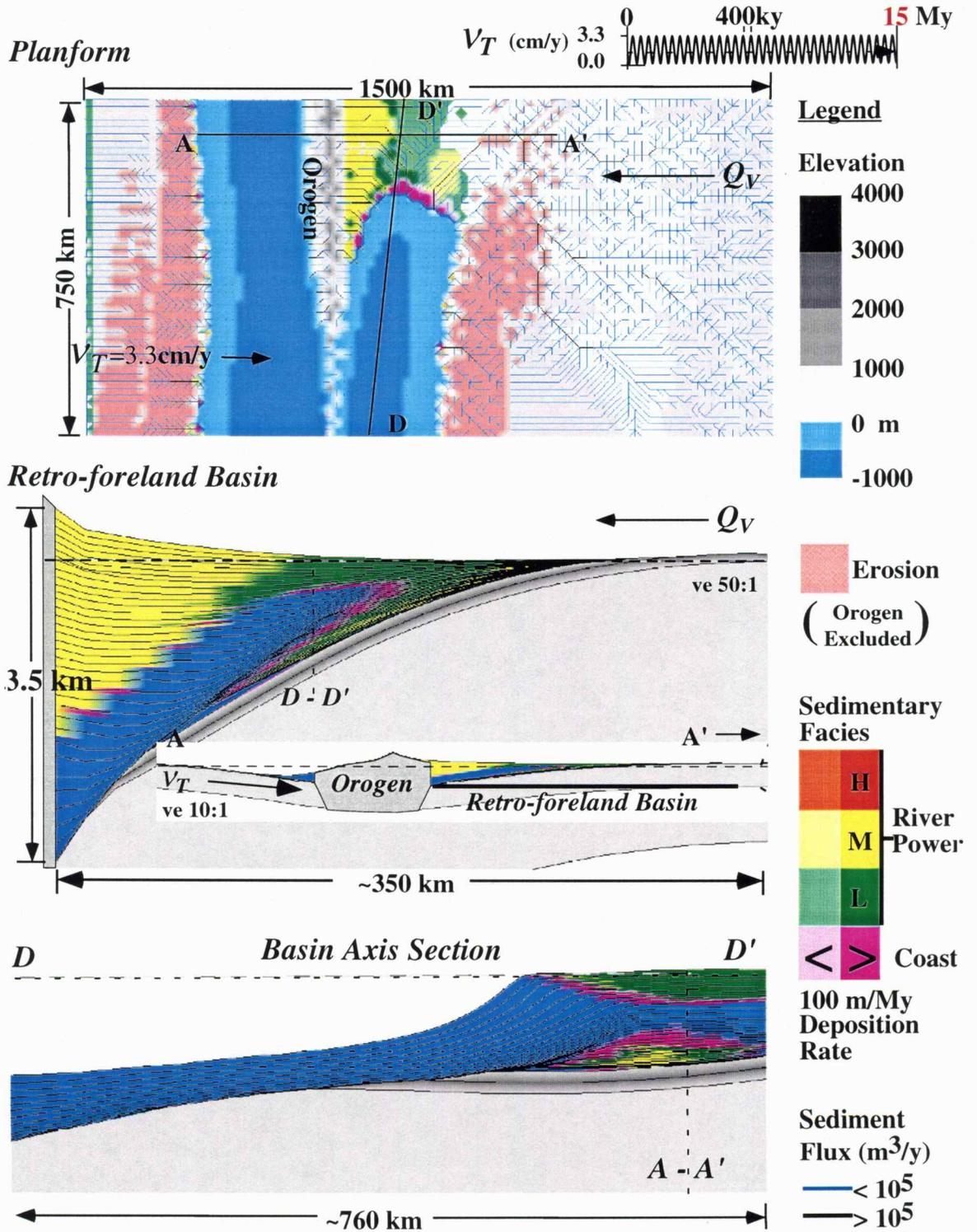


Figure 3. MT7 shows in planform, transverse sections (regional and retro-foreland basin) and longitudinal section (D-D'), the development of an orogen/foreland basin system with 400 ky periodicity in orogen tectonics. MT7, unlike MT6, does not show well developed sequences.

ME4 at 15 My, Periodic v_E , Constant Q_V and v_T

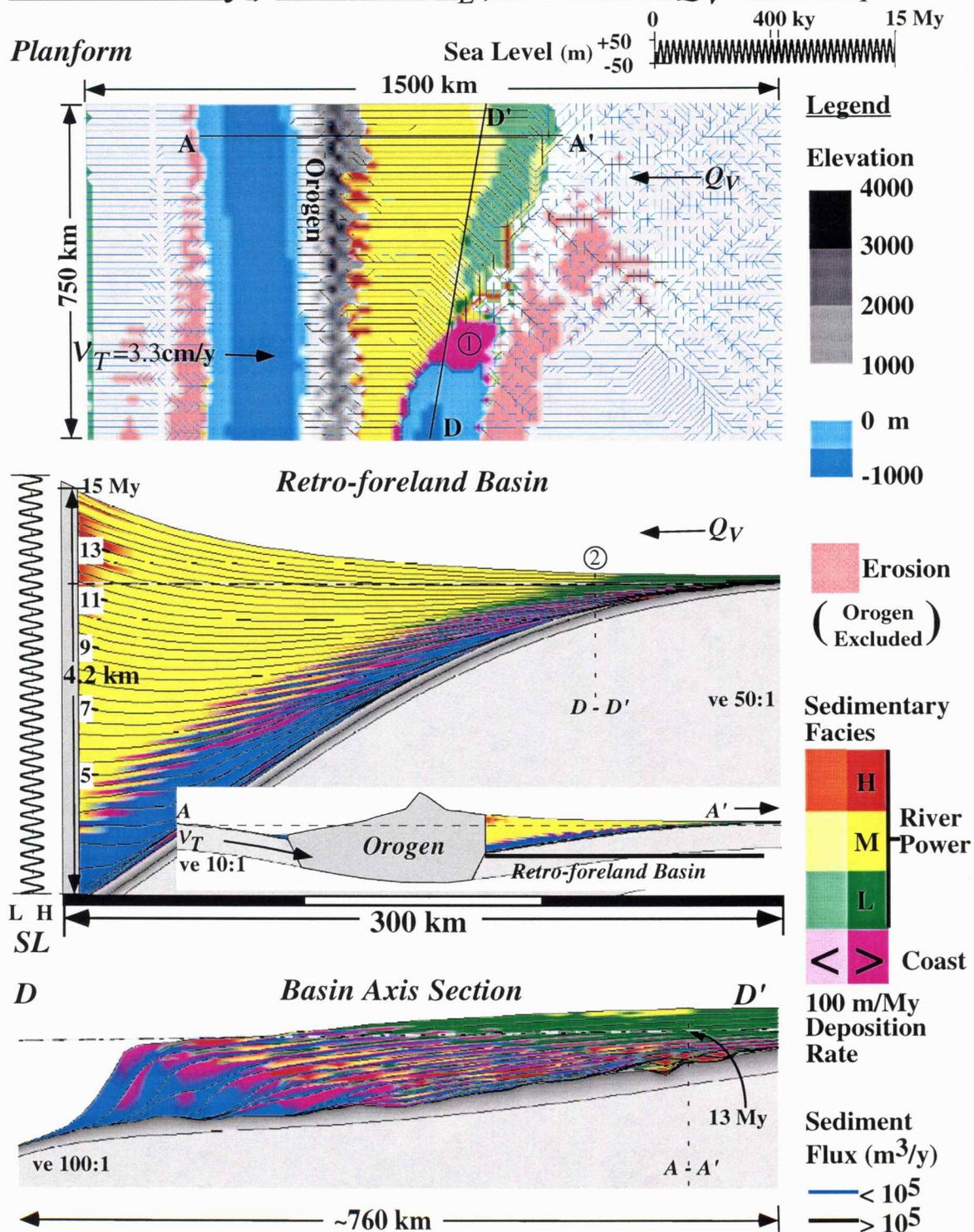


Figure 4. ME4 is shown in planform, transverse (A-A' & retro-foreland basin) and longitudinal section (D-D') at 15 My. Time lines are at 400 ky intervals (black lines) and are coeval with the maximum rate of sea-level rise.

Estimation of Stratigraphic Modeling Parameters from Well Logs and Seismic Data

P. Joseph (*philippe.joseph@ifp.fr*), **D. Granjeon**, and **M. Rabineau**, *Institut Francais du Petrole, 1-4, avenue de Bois-Preau, BP 311 - 92506 Rueil Malmaison Cedex - France*

The use of stratigraphic modeling for operational cases (intensive exploration, field appraisal) enforces the fit of the simulations to available data (wells, seismic). This fit is obtained either by manual trial-and-error methods, or by numeric optimization. In both cases, it is necessary to estimate as well as possible the input parameters of the model, in order to converge quickly towards an acceptable solution. This paper presents the methodology applied to get a first estimate of these parameters.

3D multilithological diffusive modeling needs four types of input data:

- initial topography of the basin,
- accommodation maps at different ages, defining the evolution through time and space of the available space for sedimentation in the basin,
- sediment supply; for siliciclastic sediments, the location of the sources (rivers) at the borders of the basin and the amount of sediment (sand, shale) entering the basin must be specified through time; for carbonate sediments, evolution of productivity rates must be defined,
- parameters for transport laws (diffusion coefficients), which control the way sediments are eroded, transported and sedimented throughout the basin.

Interpretation of facies and depositional environments from cores and well logs leads to the identification and correlation of genetic units. Facies and environments are then interpreted in terms of paleobathymetry. Accommodation is estimated by summing the stacked thickness of sediments (decompacted if necessary) and the paleobathymetry. Evolution of accommodation through time is based on a time schedule given by fauna dating, or by some hypotheses concerning the duration of each genetic unit. If wells are numerous, accommodation maps are directly obtained by interpolation; if not, seismic maps help to estimate the thickness of sediments between markers, and the bathymetric evolution is derived from trends on wells or from seismic stratigraphy. Seismic data also enable to identify structural elements (faults or folds) which define discontinuities in accommodation maps.

The amount of sediments (supplied or produced in the basin at each time step) may be approximated by combining sedimentation rate computed at each well and basin dimensions; sand/shale or carbonate/shale ratios computed from well logs enable to roughly estimate the relative proportions of the different lithologies. This evaluation of the sediment supply must be compared to the volume of sediments calculated from seismic maps. Seismic interpretation also provides information on the location of the main sources of sediment (rivers, canyons...) or the morphology of the drainage area.

Transport parameters are derived mainly from an estimation of the bathymetric profile. This profile may be reconstructed as a first approximation from the facies evolution along chronostratigraphic time lines correlated between wells. This correlation provides mean values for depositional slopes which must be controlled with data on equivalent modern or ancient environments (outcrops). These slope values help to estimate transport parameters, like diffusion coefficients, specific for each sedimentary environment. Moreover, diffusion coefficients depend on the different lithologies, and may be roughly estimated from the mean ratio of these lithologies in each environment.

Because of the complex response of the stratigraphic model, this first estimate of the modeling parameters must be adjusted during simulation. Some examples of the estimation method will be demonstrated during the presentation.

Construction and Application of Stratigraphic Inverse Models

Margaret A. Lessenger (*mlesseng@mines@colorado.edu*) and **Timothy A. Cross** (*tacross@mines.edu*), *Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401*

Stratigraphic inversion is a quantitative technique that extracts values of process parameters - such as tectonic movement, sea-level change, sediment supply and basin topography - which operated to produce an observed stratigraphy. Like mathematical inversion methods used in other disciplines (e.g., geophysics, economics, hydraulics), the stratigraphic inverse model has three components. It contains (1) a forward model that simulates stratigraphy through the operation of a set of process parameters; (2) a set of observed data which are comparable in type to forward model predictions; and (3) a set of equations and algorithms that compare the values of forward model predictions with observations, and simultaneously adjust values of all forward model parameters to create a better match between predictions and observations. The inverse model iteratively reduces differences between forward model predictions and observations until a best match is achieved. Through these procedures, the inverse model estimates the degree of accuracy and uncertainty of values of forward model parameters as compared to observations. One can then run the forward model within the ranges of uncertainties to determine a probabilistic distribution of predicted stratigraphy.

Inversion of stratigraphic data requires specific philosophical and technical approaches because of the nature of the stratigraphic process/response system. The system is nonlinear, multivariate, and possesses multiple feedback loops among interdependent processes and responses. Inverse model construction must be sensitive to these attributes.

One requirement of the inverse model is that the observed and modeled data which are compared must be of the same type. Forward models are time simulations. By contrast, stratigraphic data are physical, lacking a time framework except via stratigraphic correlation. Consequently, to compare simulated with observed data of the same types, time value must be added to the observed data. With all stratigraphic data types, physical attributes of strata must be placed within a time framework for inversion to work. Inversion on incorrectly correlated stratigraphic units or on units correlated lithostratigraphically will produce weak or inaccurate results.

Multiple kinds of data can be used for inversion, each providing different types and quantities of information about the historical operation of stratigraphic processes. Stratigraphic inversion must take advantage of the strengths and information content of different data types, while minimizing their weaknesses. As an example, the information content of stratigraphic geometries (as portrayed on seismic lines or in cross sections of properly correlated well logs) is notably weak. By contrast, sedimentary facies, cycle thickness and symmetry, and cycle stacking patterns contain rich, robust information which make stratigraphic inversion possible. These stratigraphic attributes are robust because, when placed within a time framework, they are sensitive recorders of mass distribution through time. Because the stratigraphic process/response system conserves mass, monitoring the

distribution of mass through time places severe constraints on the possible outcomes of the inversion.

Interdependencies, feedback and buffers of the multivariate process/response system cause linear inversion on single parameters to be of little value. Experiments comparing linear and multivariate inversion show that the solutions from linear inversions or inversion on single parameters are inaccurate and fall outside the range of uncertainty established by the multivariate inversion. Because of the nonlinear dynamical nature of the stratigraphic process/response system, gradient descent inversion methods are weak.

Estimating Accuracy and Uncertainty of Stratigraphic Predictions from Inverse Numerical Models

Margaret A. Lessenger (*mlesseng@mines@colorado.edu*) and **Timothy A. Cross** (*tacross@mines.edu*), Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401

Inverse modeling experiments with a synthetic stratigraphic cross section that resembles the Mesa Verde Group of the San Juan basin, Colorado, reveal strategies for predicting stratigraphic architecture and facies distributions from limited data. Values of stratigraphic process parameters and responses are completely known for the synthetic cross section. By sampling the cross section with variable numbers and positions of "pseudowells" and by varying the accuracy and resolution of stratigraphic correlations, it is possible to evaluate how well inverse stratigraphic modeling techniques will estimate process parameters of real sedimentary basins.

The inverse model accurately recognizes the relative contributions of different stratigraphic processes to observed stratigraphy. Short-term eustasy strongly affects sediment volume partitioning, cycle symmetry and frequency of unconformity and hiatal surfaces more than other process parameters. Tectonic movement and lithosphere strength affect stacking patterns of progradational/ aggradational units, large-scale symmetry of stratigraphic sequences and basin shape. Sediment supply changes aspect ratios (thickness:width) and volumes of sediment within facies tracts, but does not cause sediment volume partitioning or affect stacking patterns. These experiments refute the common assumption that a change in the value of one process parameter can be fully compensated by an opposite change in value of another parameter to produce an identical stratigraphic response.

Accuracy and resolution of stratigraphic correlations affect the accuracy of the inversion, but in different ways. Inversions based on low resolution correlations tend to underestimate tectonic subsidence, and are poor estimators of eustasy. If high-resolution correlations are less certain than low-resolution correlations, it is better to reduce the resolution of correlations, than to entirely miscorrelate. For example, an inversion using a twofold division of the Mesa Verde across all facies tracts produces a cross section very close to the truth, whereas an inversion using three, incorrectly correlated divisions of the Mesa Verde produces a very poor result.

Paleogeographic and spatial positions of wells affect the ability of the inversion to accurately estimate tectonic subsidence and stratigraphic architecture. Widely spaced wells give more information about tectonic subsidence than closely spaced wells. Inversion of a single well is nearly equivalent to inversion of multiple, closely-spaced wells in estimating the geometry, thicknesses and lateral extents of facies tracts.

Observing model behavior also teaches us about likely sources of error. One particularly useful example is the use of the inverse model to identify which stratigraphic correlations are incorrect, and in which geographic positions. Incorrect stratigraphic correlations usually

cause imbalances in the sedimentary mass within different facies tracts. Because the models conserve mass, the inverse model consistently tries to squeeze more sediment mass into the facies tracts which have a deficiency and remove sediment mass from the facies tracts which have an excess. The model behavior thus identifies where the incorrect stratigraphic correlation resides and in which directions the line of correlation should be moved.

These experiments are teaching us how variations in information quality and data types affect the accuracy and uncertainty of quantitative stratigraphic prediction. This knowledge will assist decision-making by framing questions such as: "How much and what type of additional data must I collect to improve the accuracy of stratigraphic prediction by X%?"; "Would the addition of seismic data provide more or less value than additional well information in select locations?"; "Is high-resolution correlation as important at the scale of exploration as it is for reservoir characterization?"

Accommodation : Sediment Supply Ratio (A/S) a Key Parameter for Stratigraphic Modeling

Jean-Christophe Navarre (*NAVARRE@elf-p.fr*) and **Martine Bez** (*m.bez@elf-p.fr*), *Elf Aquitaine Production, CSTJF avenue Larribau, 64018 PAU cedex, FRANCE*

Stratigraphic models should predict the range of possible stratigraphic geometries and facies distributions between and beyond wells control. The input parameters of the model include tectonics, eustasy and sediment supply. These parameters are constrained by the stratigraphic record derived from well log, core or field data. This stratigraphic record is best interpreted and modeled using one main parameter, accommodation : sediment supply ratio (A/S) which varies with base-level cycles.

Surface and subsurface strata within the Mesa Verde Group (Upper Cretaceous), San Juan basin (Colorado) are subdivided into stratigraphic cycles of at least three temporal scales (long-term, intermediate-term and short-term). All scales of cycles record oscillations of base-level (fall and rise) and concomitant variations of increasing and decreasing A/S ratios. Cycle symmetry, stratigraphic architecture, facies assemblage and sediment preservation, between coastal-plain and shoreface strata, are function of their position in the long-term base level cycle. They are detailed in detail for intermediate-term stratigraphic cycles.

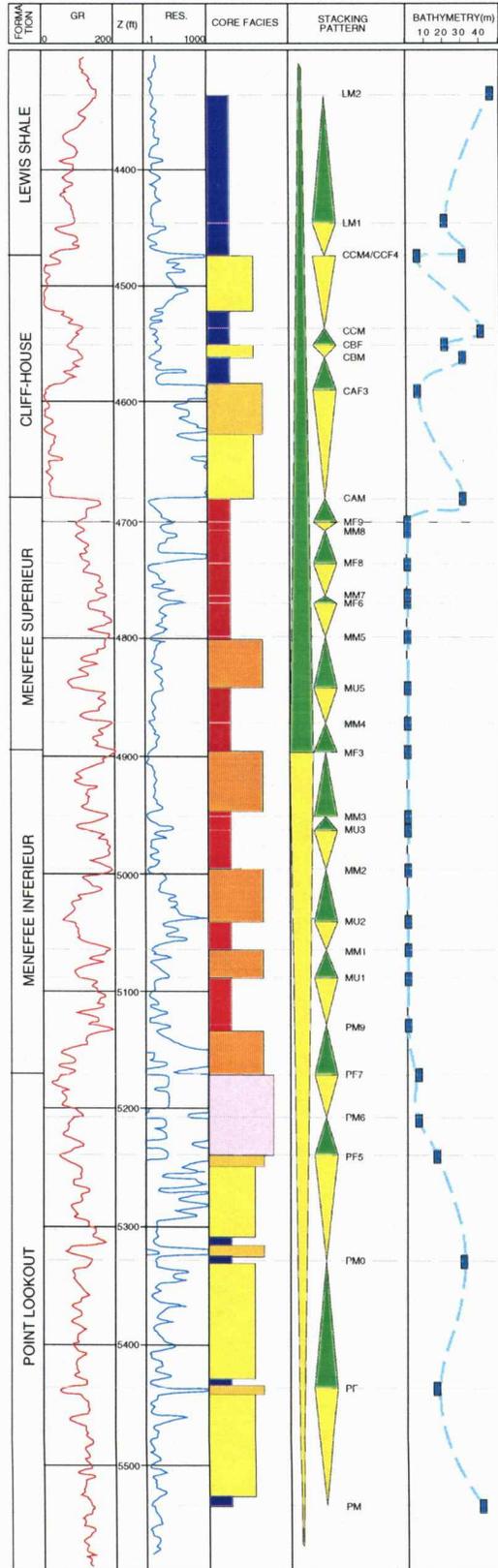
During long-term base-level fall hemicycle, in low accommodation settings:

- Intermediate-term cycles in coastal plain strata are represented by:
 - Accumulation of crevasse splay/crevasse channel deposition and the formation of an erosional or sediment bypass surface of unconformity during base-level fall hemicycles,
 - Accumulation of amalgamated channelbelt sandstones on top of the unconformity surface, during base-level rise hemicycles.
- Intermediate-term shoreface cycles are recognized by changes in the aggradation to progradation ratio and are composed of heterogeneous sandstones.

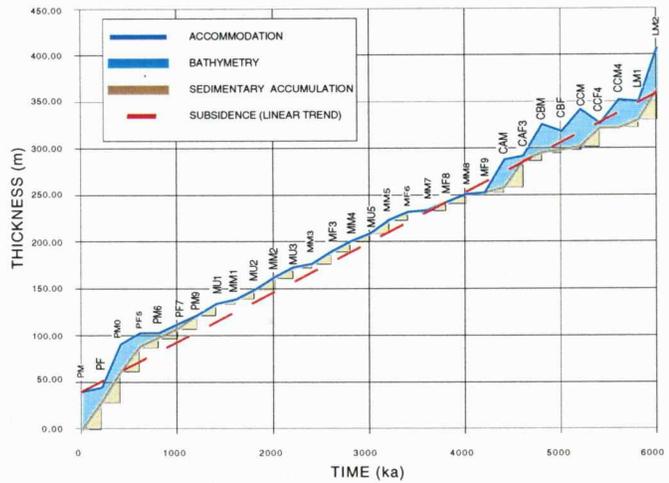
During long-term base-level rise hemicycle, in high accommodation settings :

- Intermediate-term cycles in coastal plain are symmetrical.
 - The base-level fall hemicycle consists of facies recording a gradual filling of lakes or wetlands.
 - During base-level rise hemicycle, facies successions are just the opposite and record gradual flooding of the floodplain.
- Intermediate-term shoreface cycle are generally base-level fall asymmetrical and composed of homogeneous sandstones. They consist of :
 - An alternation of tidally dominated estuarine and bay sandstones and mudstones during base-level rise,
 - Shallowing-up and bed-thickening-up hummocky cross stratified back-barrier and bay sandstones during base-level fall.

Knowledge of these facies changes within a stratigraphic context is an invaluable aid to predict geometries and facies distributions. Consequently, accommodation curves based on stratigraphic cycles stacking pattern and facies interpreted in bathymetry value are essential for correlation and stratigraphic models.

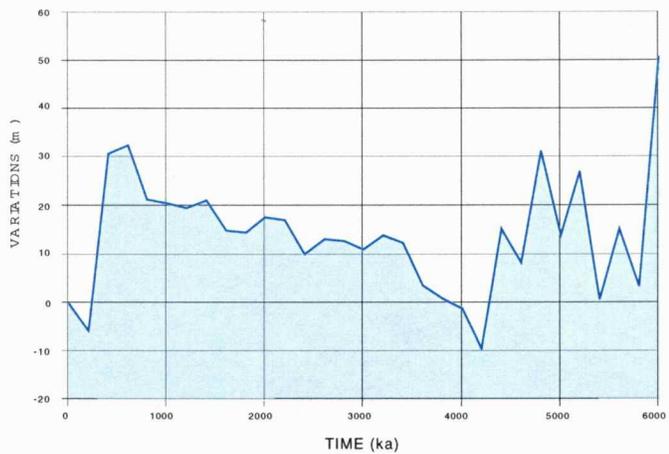


ACCOMMODATION CURVE = BATHYMETRY + SEDIMENT THICKNESS



MODIFIED FISHER DIAGRAM

STRATIGRAPHIC CYCLE = TIME UNITS



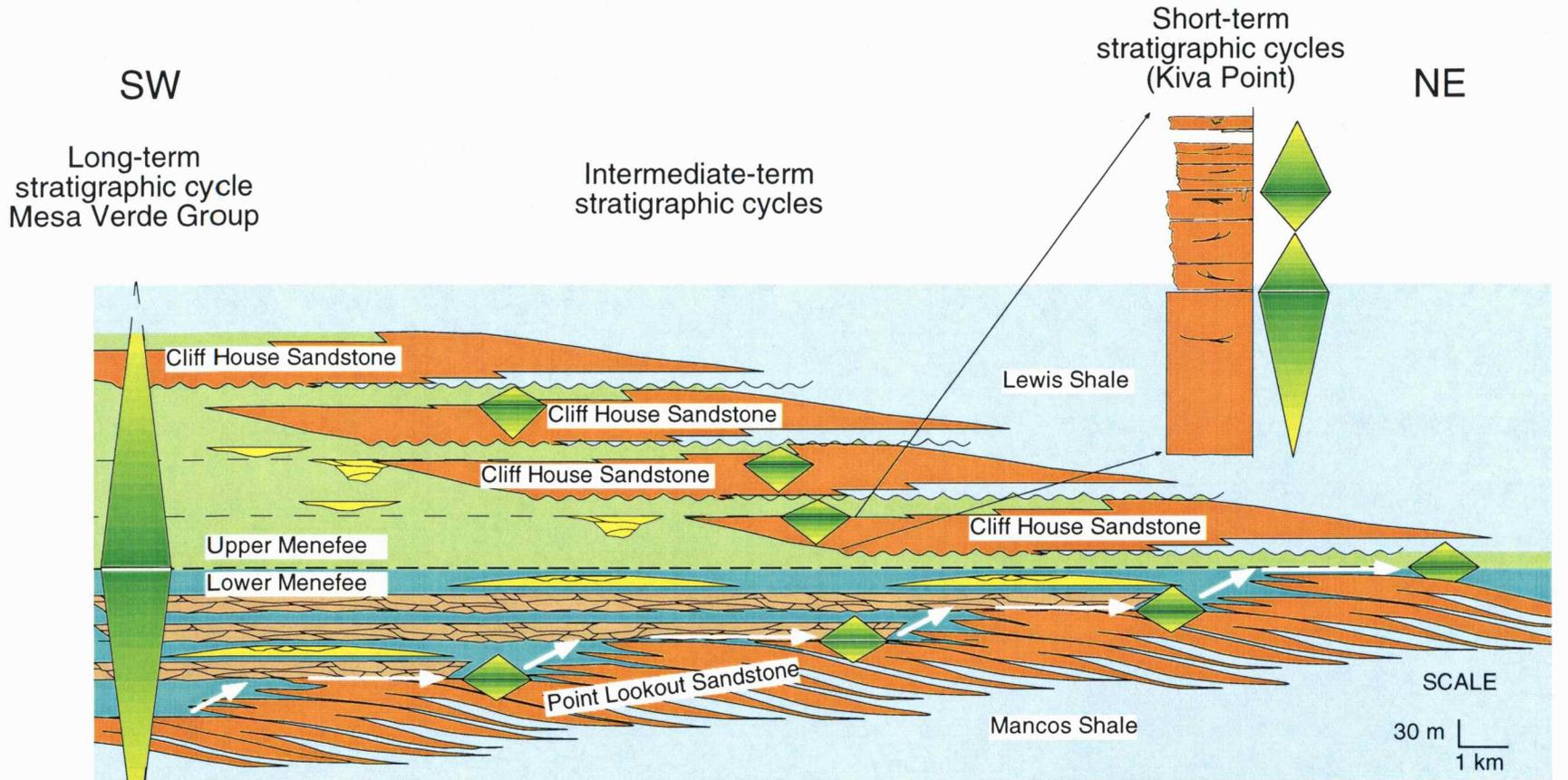
EUSTATIC CURVE = ACCOMMODATION - SUBSIDENCE

ACCOMMODATION CURVE : A KEY PARAMETER FROM WELL LOG

SAN JUAN BASIN - WELL 62 : LOG COMPOSITE, STACKING PATTERN AND BATHYMETRIC CURVE



Mesa Verde Stratigraphic Architecture



FUZZIM Replacing Equations with Common Sense Rules

Ulf Nordlund (*ulf.nordlund@pal.uu.se*), *Institute of Earth Sciences / pal, Norbyv. 22, S-752 36, Uppsala, Sweden*

FUZZIM is a 3D simulation program for modelling large-scale deposition and erosion at an ocean margin over geological time-spans. It was developed as a research tool at the Inst. of Earth Science at Uppsala University, Sweden.

FUZZIM is fundamentally different from other comparable simulation programs in that most mathematical functions have been replaced by fuzzy systems (Nordlund, in press). A fuzzy system consists of a series of logic rules using fuzzy sets instead of conventional two-valued sets. In contrast to conventional sets (which are always either true or false), fuzzy sets allow formal representation of partial truth. This makes them ideal for treating qualitative data involving vagueness and ambiguity. A logic rule may look like: **IF deep AND far_from_source THEN deposit_little AND deposit_fines**, where **deep**, **far_from_source**, **deposit_little**, and **deposit_fines**, are all fuzzy sets defined on the domain variables depth, distance, amount and grain size, respectively. The structure of a simple fuzzy system is shown in Figure 1.

Apart from the usual parameters such as sea-level curve, sediment input, subsidence, etc., FUZZIM requires a fuzzy system (some technical details about FUZZIM are given in Table 1). Because the rules of a fuzzy system are very similar to the linguistic sentences we use in every-day communication, it is usually very easy to define a fuzzy system. Roughly speaking: If you can express it in words, you can most probably also include it in your simulations. The rules and sets can also be defined interactively in FUZZIM, even during a simulation run. The strategy for deposition and erosion can thus be completely changed in a matter of minutes, allowing for rapid analysis and testing of hypotheses, and facilitating calibration work considerably. Use of fuzzy techniques also means that specialised technical expertise is not required to use FUZZIM anyone can define a fuzzy system. The simulation results will, however, inescapably reflect the users geological or sedimentological knowledge since they are so closely related to the quality of the fuzzy system (mainly how realistic the rules are). It is, of course, also possible to use pre-defined fuzzy systems with FUZZIM, in which case the modelling work becomes similar to that of other programs.

In FUZZIM, a hierarchical structure (Yager, 1993) based on priority among rules is used. This allows for systematic construction of fuzzy systems, defining general rules first and more specific rules later. A system can be refined indefinitely ultimately to consist of many highly specific exceptions to a few general rules. A high degree of complexity can be reached in this way without the modeller losing the thread on the way. It is important to understand that fuzzy does not imply lack of significance or accuracy. On the contrary: a fuzzy based system yields highly significant and accurate results by allowing for high complexity (detailed, as well as general knowledge can be incorporated).

Results from simulations using different fuzzy systems will be presented in order to show some of the advantages of a fuzzy approach in dynamic stratigraphic modelling.

References

Nordund, U., in press, Formalizing geological knowledge with an example of modelling stratigraphy using fuzzy logic: *Journal of Sedimentary Research*.

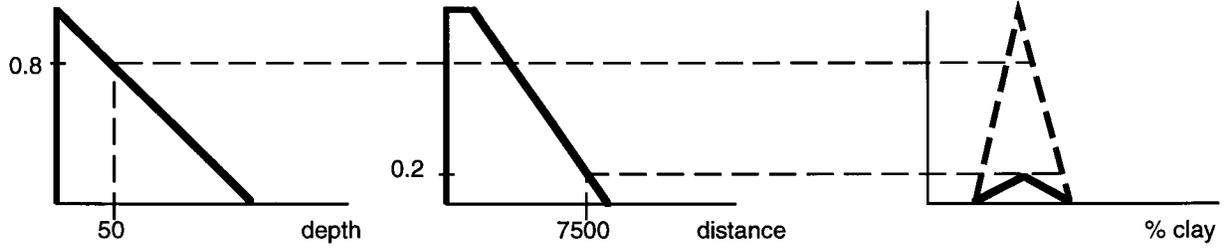
Yager, R., 1993, On a hierarchical structure for fuzzy modelling and control: *IEEE Transactions on Systems, Man, and Cybernetics*, v. 23, p. 1189-1197.

Figure Captions

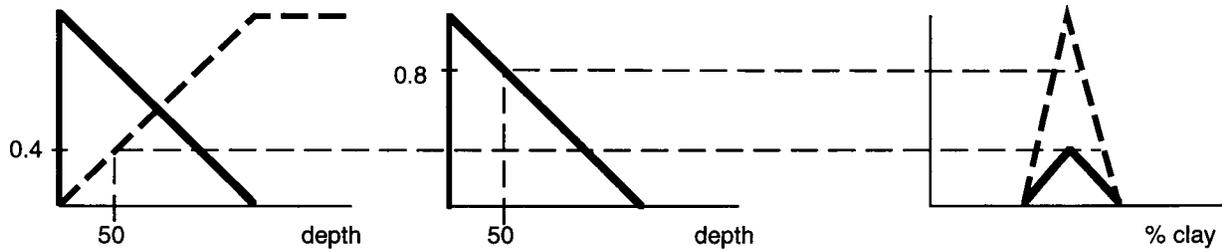
Figure 1. A) A simple fuzzy system consisting of three rules, all of which refer to the domain variable % clay. Input values are: depth = 50 m, and distance (to the river) = 7500 m. Evaluation of the first rule consists in finding the truth of the two conditions: 50 m is shallow, and 7500 m is near_source. The operator AND (conjunction) means that both conditions must be fulfilled, and the lower of the truth values derived (0.2) is therefore the limiting factor and is used to scale the conclusion set clayey_sand. B) The scaled sets from all three rules are then added, aggregated, to form a compound fuzzy set which constitutes the output of the fuzzy system. If a crisp number is desired (which is usually the case) this can be derived through defuzzification by computing the centroid (centre of gravity) for the compound fuzzy set. (Note that there exist several other methods for aggregation and defuzzification. The ones described here are those used in FUZZIM.)

A

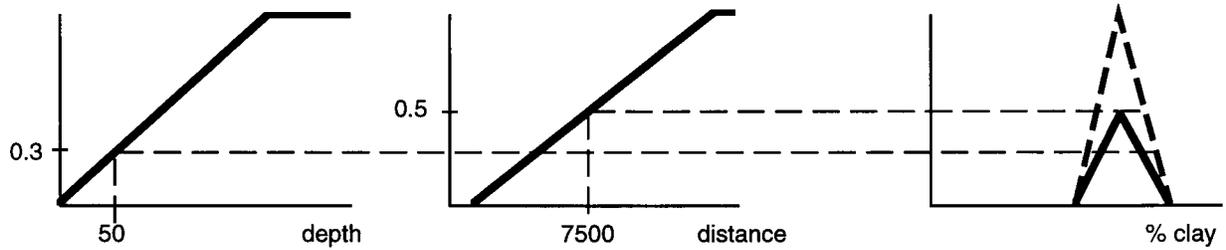
< IF shallow AND near_source THEN clayey_sand >



< IF NOT shallow AND shallow THEN sandy_clay >



< IF deep OR far_from_source THEN clay >



B

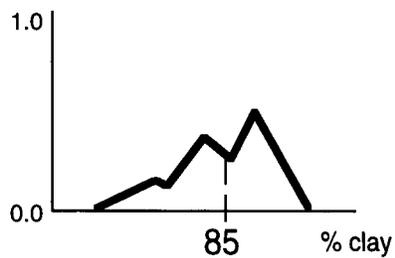


Figure 1

Scale-Invariance in Fluvial Sedimentary Basins

Jon D. Pelletier (*pelletie@GEOLOGY.GEO.CORNELL.EDU*) and **Donald L. Turcotte**,
Department of Geological Sciences, Snee Hall, Cornell University, Ithaca, NY 14853

Hewett (1986) and Tubman and Crane (1995) have presented evidence that horizontal and vertical porosity variations in fluvial sedimentary basins are scale-invariant. Scale-invariance means that the power spectrum has a power-law dependence on wave number k : $S(k) \propto k^{-\beta}$.

It is the purpose of our paper to present a model for the topography and porosity variations in fluvial sedimentary basins that produces the observed scale-invariance on the scale of meters to hundreds of kilometers. Fluvial sedimentary basins exhibit heterogeneity on all of these scales. Heterogeneity at the largest scale is associated with the boundaries of major genetic units of sediment such as channel belts. From scales of 1 meter to 1 kilometer, heterogeneities are associated with variations in porosity within the larger genetic units such as coarse-fine stratification of a point bar (Allen and Allen, 1990).

In this paper we present a two-dimensional model for the evolution of the topographic profile perpendicular to the depositional strike of a fluvial sedimentary basin with channel avulsion modeled by a random process in space and time (resulting in first-order heterogeneity) and depositional sediment transport governed by the diffusion equation (resulting in second-order heterogeneity). We also model the effects of erosion in several ways and show that the power spectra obtained by our model are independent of the different parameterizations of erosion. We consider both a continuous and a discrete model. We begin by idealizing the channels as parallel and of uniform capacity along the depositional strike. This reduces the model of two spatial dimensions: the height of the topographic profile (denoted h) and the direction perpendicular to the depositional strike (denoted x). The continuous version of the model is described by the equation

$$\frac{\partial h(x, t)}{\partial t} = D \frac{\partial^2 h(x, t)}{\partial x^2} + \eta(x, t) \quad (1)$$

where $\eta(x, t)$ is Gaussian, white noise. This equation is known as the Edwards-Wilkinson equation in the physics literature on stochastic surface growth (Edwards and Wilkinson, 1982). The power spectrum of the topographic profile predicted by the model, $S(k)$, is proportional to k^{-2} . This is the Brown noise often observed in topography. The power spectrum of variations in local elevation in time is $S(f) \propto f^{-3/2}$ (where f is the frequency). We show that these power spectra are unchanged when we relax the assumption of parallel channels to include any angular probability distribution of channel directions.

We inferred Brown noise paleotopography by analyzing the spatial distribution of wells showing hydrocarbons in the Denver and Powder River basins (meandering river depositional environments) and in a synthetic oilfield based on a caprock with Brown noise topography. Hydrocarbons are often found adjacent to the crests of low-porosity caprock that have obstructed the upward migration of hydrocarbons. The caprock will mimic the floodplain at

the time of its deposition. A model for the horizontal spatial distribution of hydrocarbons in a reservoir is one in which hydrocarbons are assumed to be accumulated in the crests of the caprock above a certain elevation. A synthetic oilfield was created by synthesizing a Brown noise surface and assuming that hydrocarbons are showing in domains where the caprock elevation is higher than a threshold value. We analyzed the spatial distribution with the use of the pair correlation function, the pairs of unit area showing hydrocarbon as a function of distance separating the pairs. The pair correlation function is a power-law function of distance separating pairs with an exponent close to $-1/2$ for the Denver, Powder River, and synthetic basin hydrocarbon distributions. From the similarity of the results we infer Brown noise caprock and paleotopography in the Denver and Powder River basins, consistent with the predictions of our model.

Grain size variations mimic the topographic profile perpendicular to the depositional strike with the coarsest material deposited at the channel banks and finer sediment deposited in topographic depressions such as abandoned channel segments. Pizzuto (1987) has modeled the topography and grain size variations perpendicular to the depositional strike with the diffusion equation. The coupling between grain size and topography suggests that porosity variations may exhibit the same power-law power spectra as the topographic profile. Variations in local elevation in time have a power spectrum $S(f) \propto f^{-3/2}$ according to the model we present. If the mean elevation of the sedimentary basin relative to its base aggrades in a constant long-term average rate over time, time and depth are proportional. To illustrate vertical scale-invariance in porosity, we computed the power spectrum of vertical porosity well logs in 15 offshore wells in the Gulf of Mexico, a deltaic sedimentary environment. Eight of the spectra are shown in Figure 1. At spatial scales above 3 meters we found an average power spectral exponent of -1.41 with a standard deviation of 0.22 . At smaller scales the variability decreases below the scale-invariant trend in most of the wells. This decrease in variability may be the result of a transition from second order heterogeneities (dominated by variations in porosity within the larger genetic units) to third order heterogeneities which result from the geometrical arrangements of individual depositional units.

Our model is consistent with the observations of Strauss and Sadler (1989) who have compiled data on fluvial sedimentation rates from time scales of minutes to 100 million years. Their data are plotted in Figure 2 where they are averaged in bin sizes logarithmically increasing in time. In this plot we have not included the data on time scales from 10^5 to 10^8 years since they are likely to be dominated by eustatic sea level variations rather than the mechanics of deposition and erosion. A least-squares linear fit to the logarithms (base 10) of the data yields a slope of -0.76 . Time series with power spectra $S(f) \propto f^{-2H-1}$ have variations in time $\sigma \propto t^H$, or $\sigma \propto t^{1/4}$ if $S(f) \propto f^{-3/2}$ as in variations in the surface elevation in time in our model. The sedimentation rate is then $\sigma/t \propto t^{-3/4}$, consistent with Strauss and Sadler's data.

We also investigate the distribution and persistence of bed thickness data in the context of our model. A synthetic bed thickness distribution is created in the following way: 1) a Gaussian synthetic noise with $S(f) \propto f^{-3/2}$ is created to represent changes in the local elevation due to deposition and erosion; 2) A linear trend is added to the noise to represent constant subsidence of the basin; 3) any sediment deposited that is subsequently removed is taken out

from the time series. Beds are defined by a series of consecutive timesteps with different elevations. Hiatuses are a series of consecutive timesteps with the same elevation. We found that hiatuses follow a fractal distribution and beds a log-normal distribution of thicknesses. Power spectral analyses of bed thickness time series revealed power-law power spectra with $\beta = 0 - 0.25$ increasing with increasing ratio of depositional to subsidence rates. Power-law power spectra with $\beta = 0.1$ have been observed for fluvial bed thickness time series by Plotnick (1996).

References

- Allen, P.A. and Allen, J.R., 1990, Basin analysis: principles and applications, Blackwell Scientific, Boston.
- Edwards, S.F., and Wilkinson, D.R., 1982, The surface statistics of a granular aggregate: Proc. Roy. Soc. Lond. A, 381, p. 17-31.
- Hewett, T.A., 1986, Fractal distribution of reservoir heterogeneity and their influence of fluid transport: SPE Professional Paper 15386.
- Pizzuto, J.E., 1987, Sediment diffusion during overbank flows: Sedimentology.
- Plotnick, R., 1996, personal communication.
- Strauss, D.J., and Sadler, P.M., 1989, Stochastic models for the completeness of stratigraphic sections: Math. Geol., 21, p. 37-59.
- Tubman, K.M., and Crane, S.D., 1995, Vertical versus horizontal well log variability and application to fractal reservoir modeling, in Barton, C.C. and LaPointe, P.R. (eds.): Fractals in Petroleum Geology and Earth Sciences, Plenum Press, New York, p. 279-294.

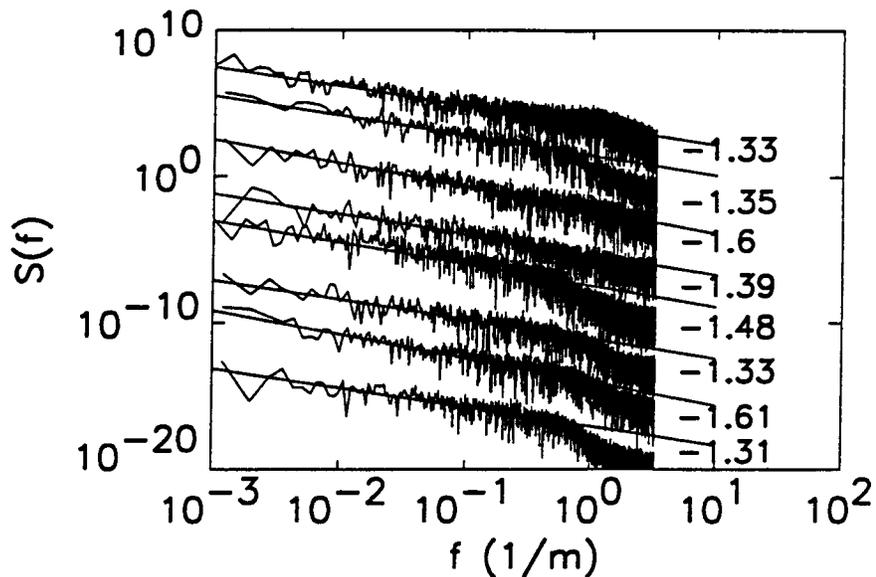


Figure 1. Power spectra of porosity as a function of wavenumber in units of meters⁻¹ in eight wells from the Gulf of Mexico. The spectra are offset so that they may be placed on the same graph.

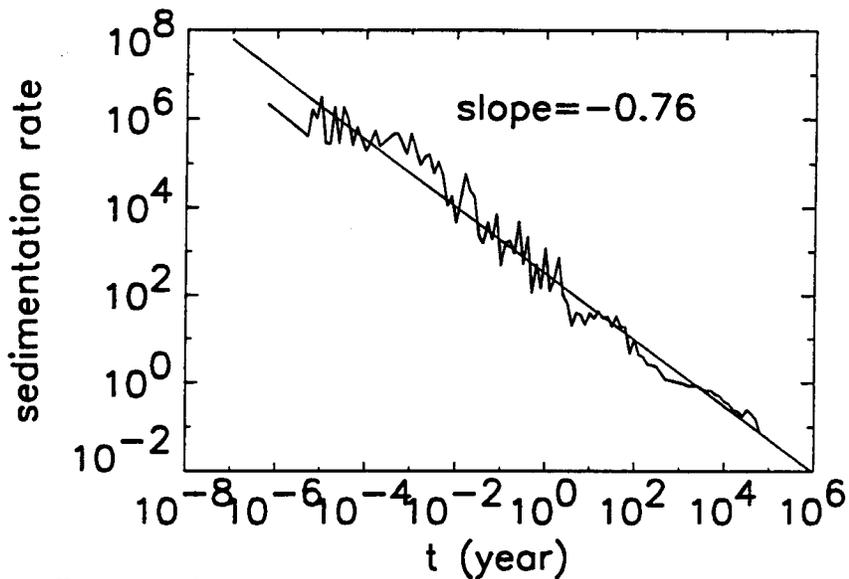


Figure 2. Sedimentation rate as a function of the time scale of observation. From *Sadler* [1995].

Phase Plots, Sedimentary Cross-sections, and Bifurcation Diagrams: Representing Output from a Dynamical Sedimentary Model

Brian S. Penn (*bpenn@elvis.geo.utep.edu*), *Institute for Resource & Environmental Geosciences, Colorado School of Mines, Golden, CO 80401* and **John W. Harbaugh** (*harbaugh@pangea.stanford.edu*), *Department of Geological Sciences, Stanford University, Stanford, CA 94305-2115*

DYNASED (DYNAMIC SEDimentary model) is a computer model based on tightly-coupled equations of near-shore sedimentary processes. DYNASED generates curves reflecting dynamic changes in hinterland elevation, sea level elevation, and sediment transport rate. These data reflect instantaneous changes in the state of the system through time. To facilitate better understanding of the functioning of DYNASED three types of visualization aids were implemented including: 1) phase plots; 2) sedimentary cross-sections; and 3) bifurcation diagrams.

The phase plot is a way of viewing DYNASED output in three dimensions. It is essentially a time series plot. Each axis in the phase plot corresponds to one of the three model variables, i.e., hinterland elevation, sea level elevation, and sediment transport rate, x-axis, y-axis, and z-axis, respectively. Data viewed in this manner can display cyclic and other complex relationships that are not apparent in one and two dimensional diagrams.

The sedimentary cross-section is used to translate the numbers generated by DYNASED into a geologically meaningful diagram. Using a simple diffusion model, cross-sections are generated based on sediment load and grain size distribution. Packets of sediment are eroded from the hinterland area and deposited in the adjoining basin. Sediment deposition is a function of current sealevel and the location of previously deposited sediment.

The bifurcation diagram shows relationships between variables. For instance: viewing a plot of variable k_7 vs hinterland elevation, h , over a narrow range in k_7 produces a graph of startling complexity with regions of uniform change and areas of complete disorder. This diagram is similar to diagrams that May (1976) produced in his analysis of the logistic equation. The bifurcation diagram clearly shows a range in complexity in DYNASED which is not apparent in either of the other two types of diagrams.

Viewing DYNASED data with these three techniques reveals many features not obvious in the original data. This is the edge of visualization technologies. A simple geologic cross-section does not convey the complexity of the system from which the cross-section was derived. The ease and comfort geologists have with cross-sections belies their underlying complexity and masks the dynamical nature of the system from which they were generated.

The Effect of the Phase Relationships of Insolation, Climate, Sediment Yield and Glacioeustatic Cycles on Stratigraphy^{1,2}

Martin A. Perlmutter (*marty_perlmutter@qmagate.anl.gov*), *Argonne National Laboratory, 9700 South Cass Ave., Argonne, IL 60439-4815* and **Roy E. Plotnick** (*plotnick@uic.edu*), *Department of Geological Sciences, University of Illinois at Chicago, 845 W. Taylor St., Chicago, IL 60607*

Primary procession, obliquity and eccentricity cycles periodically change the orbital configuration of the earth and the sun, altering the seasonal distribution of insolation. The atmosphere accommodates changes in insolation by varying the position and size of atmospheric circulation cells, shifting global climate patterns in the process, causing climate cycles. The warmest and coolest intervals during a climate cycle are referred to as the climatic maxima and climatic minima, respectively.

The climatic range of a cycle is intrinsically associated with (paleo)geography. Accordingly, the wettest or driest phases of a specific climate cycle are not associated with a particular phase of an insolation cycle when viewed globally. Some areas can become wetter while others become drier at the same point in an insolation cycle. In contrast, glacioeustatic cycles tend to track insolation cycles, with sea level highest when climate is warmest - the insolation maximum. As a result, there is no set phase relationship between climate cycles and glacioeustatic cycles; it is a function of location.

Preliminary evaluation of the effect of climate on sediment supply from modern river systems indicates sediment yield can vary by up to two orders of magnitude during one wet/dry climate cycle, depending on the succession. Different climatic successions produce different sediment yield cycles. Consequently, sediment yield cycles will not be globally synchronous with respect to glacioeustatic cycles, either.

Precessional cycles cause high frequency insolation maxima and minima. In a period with unipolar glaciation, lowest sea level will occur at the precessional minimum, when the opposing hemisphere is at a precessional maximum. Thus simultaneously, sediment yield cycles from areas with the same climatic succession but located in opposite hemispheres will have two distinct phase relationships with glacioeustasy. For example, maximum yield in some tropical monsoonal areas occur at the climatic maximum. In the same hemisphere as the glacier, this will occur at highstand sea level. In the opposing hemisphere, maximum yield occurs at lowstand sea level. In practice, the specific relationship of a sediment yield cycle to a glacioeustatic cycle is a function of the specific climatic succession of the area under investigation and the hemisphere of glaciation.

¹Work supported by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, under Contract W-31-109-Eng-38

²The U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

Precessional cycles depend on the existence of eccentricity. When eccentricity approaches the zero point of the cycle, precessional effects vanish. Thus, the antipodal phase relationship of the different hemispheres that occur at a precession scale may periodically invert on an eccentricity scale. At these times, the obliquity cycle can become dominant.

Variable phase relationships suggest areas where more care needs to be taken when interpreting stratigraphy. First, the regional climatic succession and the resulting sediment yield cycles can and should be incorporated into a stratigraphic evaluation a priori. Different locations will have inherently different patterns of clastic sediment delivery. Second, the time scale of the cycle being interpreted is very important. While climate cycles are continual, the preservation of the effects is dependent on how the phase relationships vary between the essential components - climate, yield and eustasy. If the relationship between the yield cycle and glacioeustasy invert on a variable, but eccentricity-controlled time scale, then the dominant pattern of deposition (volume, lithology, mineralogy) may reverse with it. This will be an important consideration when exploring for strata containing thick sand bodies. Third, direct comparisons should not be made between precession-scale strata deposited under similar climates in different hemispheres during glacial events.

Ecological Modeling in the Context of Stratigraphic Modeling: Building the Ecological Stage

Roy E. Plotnick (*plotnick@uic.edu*), *Department of Geological Sciences, University of Illinois at Chicago, 845 W. Taylor St., Chicago, IL 60607*

Although ecologists and paleontologists work, by nature, on different spatial and temporal scales, ecologists have become increasingly aware of the role of long-term environmental changes in structuring ecological patterns and processes. For example, Roughgarden et al., (1994) stated that "community ecology is witnessing a renewed recognition of slow processes with timescales of 104-107 years, such as sea-level changes and plate tectonics...." To borrow the metaphor of Roughgarden et al., the "ecological play" occurs in a theater constructed by geology and takes place "as the theater is being built." Numerical stratigraphic modeling is ideally suited for designing and building this "theater."

Any ecological model invoked to explain large-scale patterns must include a consideration of the heterogeneous distribution of habitats, changes in habitat distribution over time, and the effects that spatial heterogeneity has on population and community dynamics. These models must also include a consideration of the severity and frequency of abiotic perturbations. The last decade has seen the development of theoretical ecological models that are specifically designed to examine the biological aspects of such questions. The next logical stage is the integration of these ecological models with those, such as numerical stratigraphic models, that simulate the physical world.

A recently developed model, CAPS, examines the relationship between biotic dynamics, habitat heterogeneity, and disturbance. The landscape is represented in CAPS as a two-dimensional lattice, where each node corresponds to a habitat site. The species are sessile organisms that complete their life cycle in a single time step. Competition occurs each generation as propagules are distributed to adjacent sites. A species' probability of success in capturing a site is determined by the number of propagules of each type present on the site and its suitability. Rules for species interactions are fundamentally a stochastic cellular automaton, while rules for species dispersal are based on percolation and kinetic growth models.

Currently, habitat maps are produced from simple random models. Clearly, more realistic maps are required to represent structured landscapes. One approach is to use a stratigraphic simulation model to simulate seafloor topography and habitats. Similarly, a major goal of this research is to examine the relative effects of abiotic disturbances of different spatiotemporal scales, severity, and type. Realistic changes in habitat pattern can be output from an appropriate depositional model.

Stratigraphic models can be used to produce the environmental distributions, and changes in environments, in which ecological interactions can take place. They can also predict, as recently discussed by Brett (1995), the taphonomic processes that occur in different parts of the depositional sequence and thus the probability of fossil preservation. The integration of

ecological and stratigraphic models could make paleontology predictive, making it possible to forecast the taphonomic, environmental, and biostratigraphic distribution of fossil occurrences.

References

Brett, C., 1995, Sequence stratigraphy, biostratigraphy, and taphonomy in shallow marine environments: *PALAIOS*, 10:597-616.

Roughgarden, J., Pennington, T., and Alexander, S., 1994, Dynamics of the rocky intertidal zone with remarks on generalization in ecology: *Phil.Trans. Roy. Soc. London, B*, 343:79-85.

STRATSIM Modeling

Gary Priddy(*priddgw@texaco.com*), *TEXACO, Exploration Production Technology, 3901 Briar Park, Houston, TX 77042*

Stratsim is a numerical model and computer package to predict the stratigraphic configuration and primary depositional properties of clastic sediments. It is based on physical principles of fluid flow, and erosion, transport, and deposition of sediment, as controlled and modulated by eustatic, tectonic, and climatic variations.

Modeling results are constrained by known physical principles of sedimentation, by paleogeographic knowledge of the area of interest, and by well and seismic data. The outputs can be used for predicting petrophysical properties away from data points, and for estimating reservoir architecture beyond seismic resolution. Uncertainty estimates are also possible.

Specifically, a Stratsim study would include the following steps and associated information:

1. Reconstruct the base of the sequence of interest to its attitude before deposition, and infer the main vertical syndepositional movements -- if any -- prepare grids by importing existing maps or building new interpretation if necessary.
2. Perform actual runs, adjusting the model for a better match with existing data. Superimpose post-depositional structure.

The end product will be a dataset depicting the evolution and present-day state of the stratigraphic package. All presently known sequence stratigraphic controlling factors, plus others that may result from this interpretation will be incorporated into the model.

The resolution of the simulated sequence is typically 1 or 2 meters vertically, and several tens of meters horizontally. Although the results cannot be regarded as certain in every detail, they do represent a rigorous best-fitting picture. The dataset will be displayable in full three dimensions on a Silicon Graphics machine using Texaco proprietary software.

Required input information includes the following:

Lithologic variation with time, specifically relating grain size relationship to volumes present in the preserved rock. This input is combined with source rate to determine the sediment supply available for deposition.

The sediment source and sea(water) level fluctuations are also needed to develop the initial simulation.

In summary and as indicated above, the "container" is set by identifying the pre-depositional surface. The remaining input involves the sediment source and concentration, any static water levels occurring during the deposition and any associated tectonic effects.

The Roles of System-External and -Internal Mechanisms on Lateral and Vertical High-Resolution Stratigraphic Predictability - A Quantitative Case Study from the Late Paleozoic, Western U.S.A.

Eugene C. Rankey (*grank@kuhub.ukans.edu*), *Department of Geology, University of Kansas, Lawrence, KS 66045*

The stratigraphic record chronicles the influences and interactions of multiple processes and reflects controls both internal to, and external of, the sedimentary system. Forcing mechanisms may be changed, distorted, or blurred, however, when translated into a stratigraphic result. One goal of the stratigrapher is to distinguish the influences of internal and external controls on the development of the stratigraphic record. This study quantitatively contrasts depositional patterns in a series of time-equivalent sedimentary systems to evaluate the level to which they reflect the same external, presumably global, signal. It concentrates on Pennsylvanian (Virgilian) - Permian (Wolfcampian) strata in Idaho, Nevada, Utah, and New Mexico and documents vertical and lateral stratigraphic patterns from a variety of depositional settings. Each location was strategically selected for explicit, quantitative comparison. The results have significant implications for interpretation of the stratigraphic record, geostatistical simulation models, and general transportability of 'known' parameters (ie. eustatic sea-level).

The field data set of this study includes quantitative data on lateral continuity of individual beds and facies, >1000 m of measured section, and stratigraphic cross-sections of key intervals or facies documented by physical tracing.

Thickness and facies patterns in inner shelf systems (UT, NM) are up to twice as predictable as those in temporally equivalent middle shelf (NV) and shelf-edge (ID) settings. Regular vertical recurrence intervals for individual facies are present in sections with high vertical transition predictability ('non-random' by Markov chain analysis @ 95% C.I.; UT, NM), whereas statistically "random" sections don't have regular vertical recurrence intervals (Figure 1). Lateral facies changes are present in each area and contribute to system complexity both vertically and laterally. Laterally equivalent facies have low vertical transition probabilities and mutual substitutability (both commonly < 0.16), indicating absence of highly predictable relations between vertical and lateral facies transitions (ie. non-Waltherian facies changes are present). Even with the effects of autogenic processes reduced by "lumping" laterally equivalent facies, vertical predictability varies up to 310% among these systems (Figure 2). Likewise, with autogenic effects reduced and only four facies defined, preferred four-facies vertical transitions (based on highest probabilities) account for less than 5% of the actual four-facies successions present in parasequences and high-frequency sequences in each of the real systems.

Subaerial exposure of subtidal sediments, fluvial incision through marine strata, and low vertical transition probabilities between laterally equivalent facies suggest the influences of system-external forcing mechanisms. The level to which each succession reflects the same external, regional or global signal differs, as indicated by the considerable variability of

quantitative measures of predictability (thickness trends, Markov chain analysis, substitutability analysis, etc) among these time-equivalent sections, as described above. Thus, although some external, regional signal undoubtedly is present, it is expressed differently in each succession, apparently having been modified by processes internal to that depositional system.

The results of this study show that high-resolution predictability in different systems can vary significantly, even with the same external signal. Conversely, this study illustrates some of the complexity involved in deriving a purely external, high-resolution signal from the rock record. Vagaries of sedimentation, erosion, lateral facies changes, shelf position, progradation, non-linear responses, or other autogenic processes lead to complications that may modify a simple response to a global input. The observations documented herein necessitate critical evaluation of the application of concepts of Waltherian facies changes and simple linear responses to external forcing to geological applications such as high-resolution reservoir modeling or simulation. These data quantitatively indicate the influences that system-internal variables may exert on stratigraphic architecture and allow comparison of 'errors' of stratigraphic simulation models with deviations from predictions in real stratigraphic systems.

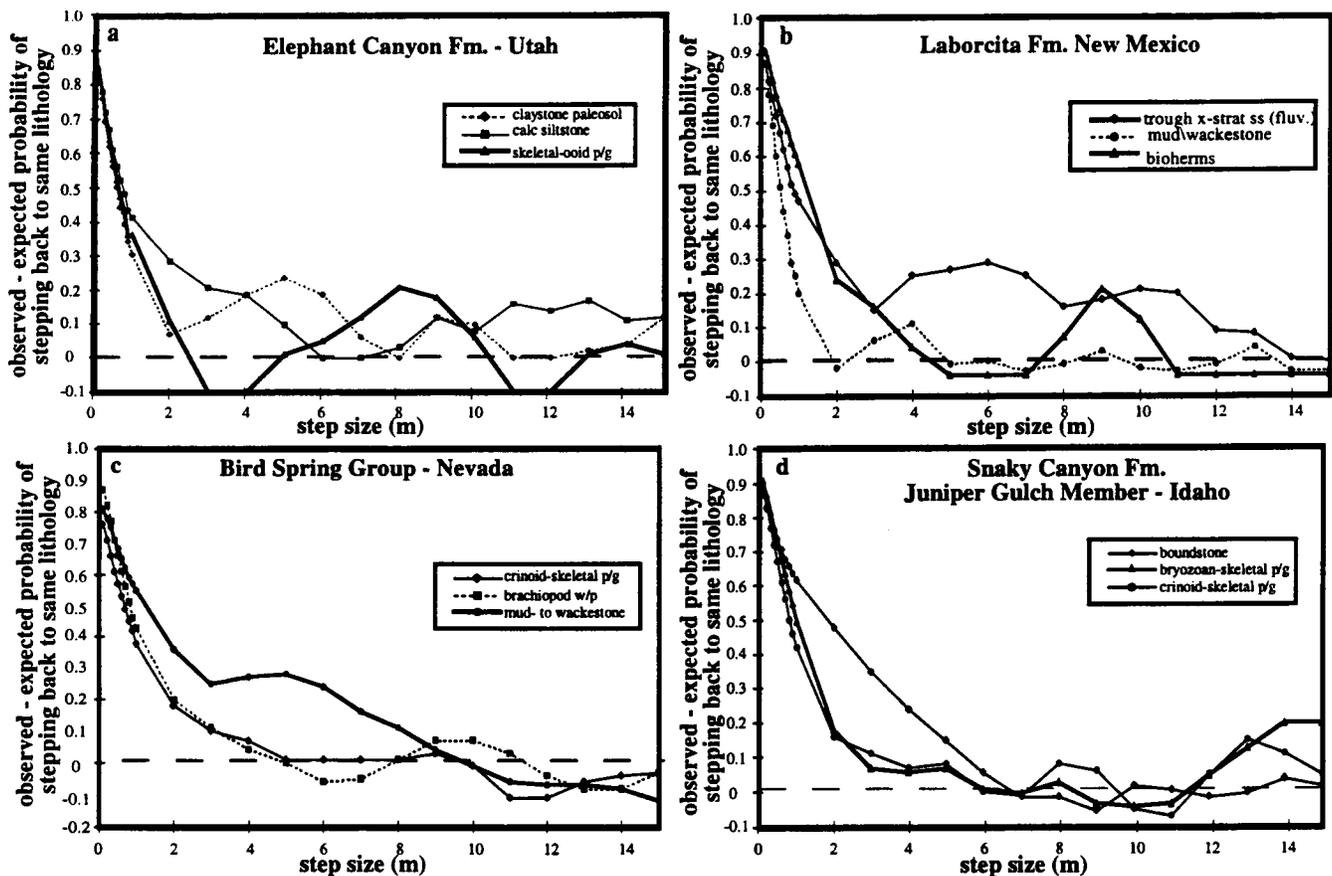


Figure 1. Vertical recurrence probability plots. These plots graph the probability of stepping from one facies back to itself at a given step size normalized to the average probability of that facies occurring in the succession. A value of zero indicates that the probability of stepping from a facies back to the same facies is the same as in a random section. Sections with regular, predictable thickness patterns will show pronounced probability peaks at certain step sizes. Note that the Elephant Canyon and Laborcita sections (in inner shelf locations) both show pronounced probability peaks, whereas the other, middle shelf (Bird Spring Group) and shelf-edge (Juniper Gulch Member) sections do not. The sections with pronounced probability peaks are also characterized by high, non-random vertical predictability of facies transitions, based on Markov chain analysis (Figure 2), possibly indicating a similar causal mechanism. Also note that marine facies (carbonate, bioherms) have thicker recurrence intervals than terrestrial facies (fluvial sandstone, claystone paleosol).

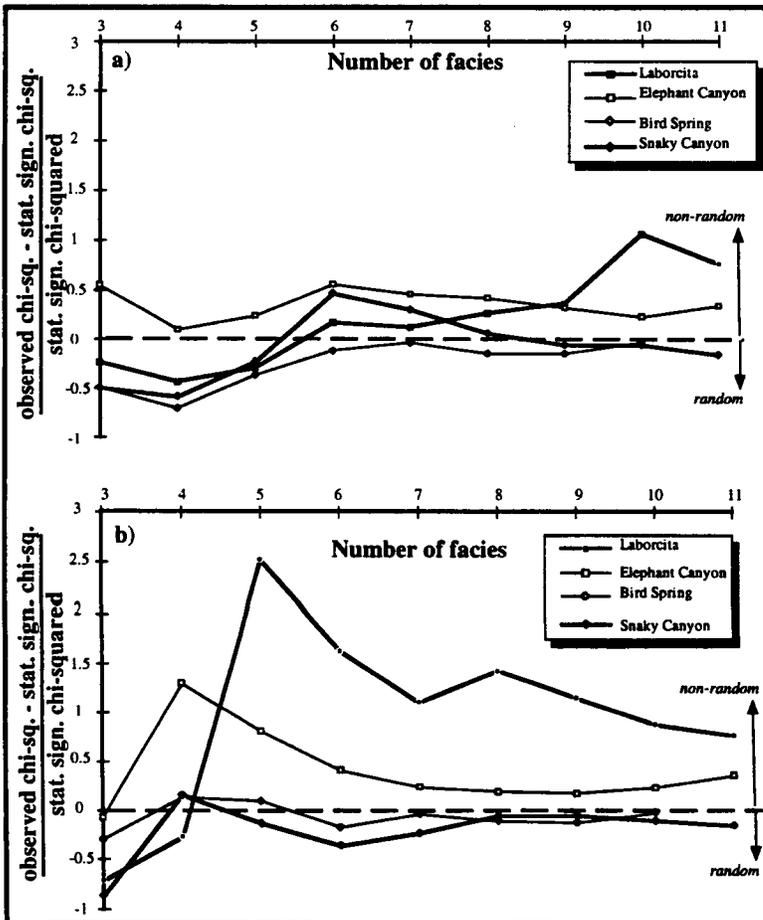


Figure 2. Effects of 'lumping' on Markov chain analysis in several time-equivalent units. The x-axis is the number of facies; the y-axis is the (observed chi-squared - the statistically significant chi-squared with n states) normalized to the statistically significant chi-squared with n states (95% C.I.). A negative value indicates that the calculated chi-squared is less than the statistically significant chi-squared, and that a null hypothesis of randomness cannot be rejected. A positive value reflects calculated chi-squared greater than statistically significant chi-squared, and statistically significant predictability.

a) 'Lumps' based on two facies with highest mutual substitutability
b) 'Lumps' of "most similar" facies selected on the basis of lateral facies changes.

'Lumping' similar facies can be thought to remove autogenic processes such as lateral facies changes. Note that the level of predictability among sections varies almost two-fold with 11 facies defined, and even when the sections are simplified to four states (Figure 2b), the difference in chi-squared between most- and least-predictable sections is 310%. These differences show that any common external forcing mechanism (ie. eustasy) is manifest differently in different settings, even when sections are 'simplified' by 'lumping.'



Stochastic Modeling of Dakota Sandstone (Rocktown Channel Member) in Central Kansas using Architectural-Element Analysis

Timothy Ray, John Holbrook (*c127sce@semovm.semo.edu*), **Yuzhi Cui, and M.D. Raghunath**, *Southeast Missouri State University, Cape Girardeau, MO*

Architectural-element analysis provides a system for describing depositional units in terms of three dimensional geometric building blocks for simulation of aquifer heterogeneity. We predicted the probable growth pattern(s) of the Rocktown channel section by using stochastic modeling to assess the most likely stacking arrangement for component architectural elements.

Detailed architectural-element analysis of the Rocktown channel member at twenty-nine outcrops in the central-Kansas Saline River valley revealed that these upper Dakota strata are dominated by four elements, each with distinct geometries. These are, in order of abundance, channel-fill (=F744%, ribbons), overbank-fine (=F727%, tabular), sandy-bedform (=F717%, prismatic), and lateral-accretion (=F712%, lobate) elements. The Rocktown channel member was deposited from a meandering stream system. Our stochastic model uses these field data to predict elements between data points. The initial model lattice contains the observed outcrop data. The lattice is then partially filled by using Monte Carlo methods to place additional elements according to the abundance percentages listed above. The rest of the lattice is then filled by allowing each existing element to grow according to its shape and size constraints, taking into account surrounding elements, growth likelihood probabilities, and other geological factors.

This architectural approach frees us from facies models, allowing us to define deposits in terms of three-dimensional, genetically significant units. This method has the advantage over geostatistic techniques of being able to incorporate boundaries into the model, while still accounting for the chaotic aspects of natural systems.

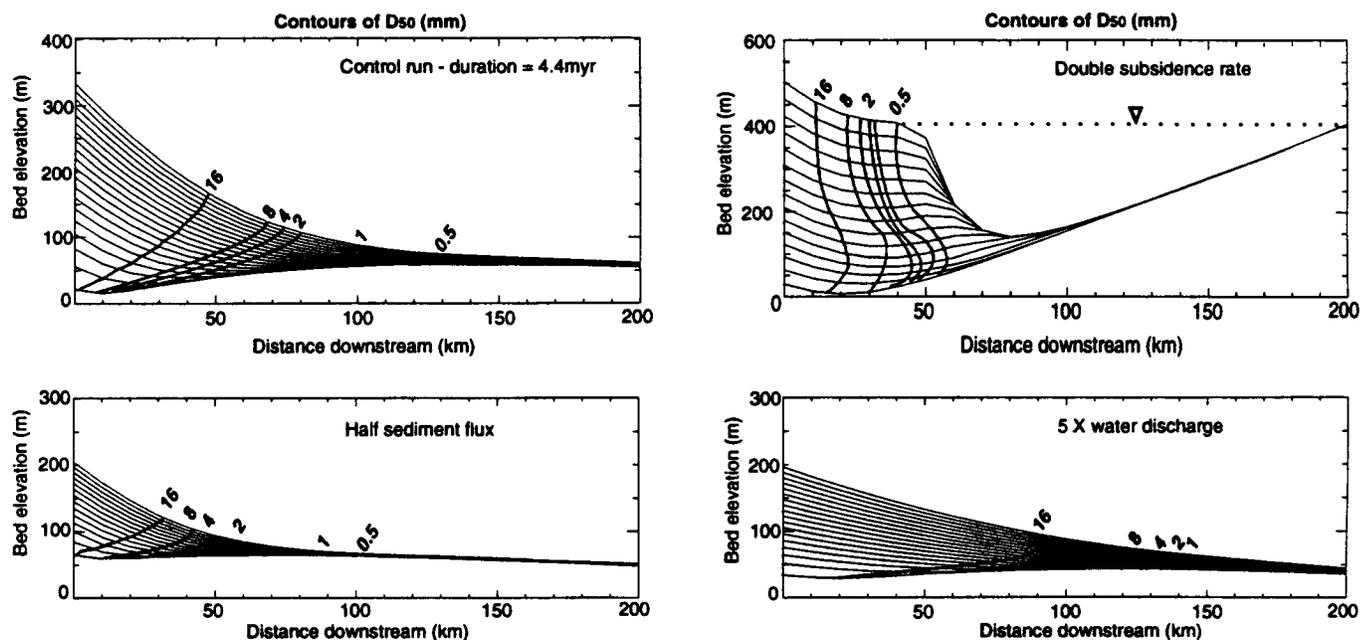


Figure 1. Longitudinal profiles of an alluviating river, showing bed elevation through time. **A.** Control run. Grey lines represent median (D_{50}) grain-size contours (mm). Subsidence profile is exponential in **A**, **C**, and **D**, and linear in **B**. Sediment feed size distribution is bimodal. All profiles have increasing channel width and discharge downstream. **B.** Doubling subsidence rate has the greatest effect on downstream fining rate. **C.** Halving sediment flux slightly increases fining rate due to reduced bed slope and improved sorting. **D.** Five-fold increase in water discharge increases the downstream fining rate by almost half.

Table 1. Basin-filling and sediment transport models

Authors	Modeling Approach
Bitzer and Pflug (1989)	simplified 3-D fluid flow - no hiding
Carlson and Flemings (in review)	diffusion-based - Einstein transport - hiding - two grain sizes
Hoey and Ferguson (1994)	1-D fluid flow - Parker transport equation - hiding - multiple sizes
Kendall et al. (1991)	large-scale basin fill & deformation - sediment transport approx.
Lawrence et al. (1990)	large-scale basin fill & deformation - sediment transport approx.
Lee and Harbaugh (1992)	quasi-3D fluid flow - sediment transport approximation - four grain-size intervals - no hiding
Paola et al. (1992)	diffusion-based transport - perfect sorting
Parker (1991)	1-D fluid flow - Einstein-based transport - hiding - multiple sizes
Syvitski and Alcott (1995)	probabilistic hydrographs - slope & discharge-based transport - four grain-size intervals - no hiding
van Niekerk et al. (1991)	1-D fluid flow - Bagnold-based transport - hiding - multiple sizes and densities - probabilistic turbulence

Sediment Transport in Stratigraphic Simulation Models: Getting it Right

Ruth A.J. Robinson (*ruth@geosc.psu.edu*) and **Rudy L. Slingerland** (*sling@geosc.psu.edu*), *Department of Geosciences, Pennsylvania State University, University Park, PA 16801*

Accurate stratigraphic simulation requires accurate prediction of sediment transport rates over heterogeneous size-density beds. Recent theoretical formulations, observations of modern rivers, and flume studies have convincingly demonstrated that these rates depend upon the “small-scale” processes of entraining and depositing individual grains as well as the “large-scale” processes of along stream-varying water discharge, accumulation rate, hydraulic geometry, and abrasion. Since existing stratigraphic simulation models (for example, Table 1) are highly variable in their treatment of these processes, the question arises: which, if any, of these processes can be ignored in modeling grain-size and facies belt distributions of fluvial deposits?

In an attempt to provide a working hierarchy of all the important variables that influence grain-size trends in the fluvial system of a foreland basin, we have conducted numerous sensitivity tests using a 1-D physically-based multiple grain-size sediment transport model (MIDAS) and geologically realistic values for input parameters, to test how sensitive grain-size trends, and thus facies distributions, are to different magnitudes of these mechanisms and processes. Our results suggest that grain-size trends, and thus facies distributions, reflect in decreasing order: 1) magnitude and spatial variation of subsidence rate, 2) magnitude and size distribution of sediment feed, and 3) magnitude of water discharge and along-stream variations (Figure 1). Of lesser, but non-negligible importance are relative mobility criteria and river planform response to excess shear stress. Depending on sediment lithology, abrasion may rank as more or less important than any of the three large-scale mechanisms.

This hierarchy is tested against a grain-size dataset collected from within the Lower Castlegate Sandstone, which outcrops in the Book Cliffs and Wasatch Plateau areas of east-central Utah. Two depositional dip transects of this Upper Campanian fluvial deposit define vertical and lateral grain-size trends and stacking patterns that reflect different accumulation histories, downstream fining trends, facies distributions and provenance. The northern transect reflects more rapid downstream fining consistent with our interpretation of higher accumulation rate. The facies resolution of the sedimentologic data serve as a detailed template that can test the sensitivity of the Castlegate fluvial system to both large- and small-scale processes.

References

- Carlson, J., and Flemings, P.B., in review, Transport and deposition of heterogeneous-sized sediments in a non-marine sedimentary basin: *Journal of Sedimentary Research*.
- Hoey, T.B., and Ferguson, R., 1994, Numerical simulation of downstream fining by selective transport in gravel bed rivers: Model development and illustration: *Water Resources Research*, 30, p. 2251-2260.
- Kendall, C.G.St.C. and others, 1991, Simulation of sedimentary fill of basins: in *Sedimentary modeling: Computer simulations and methods for improved parameter definition*, Franseen, E.K., Watney, W.L., Kendall, C.G.St.C., and Ross, W. (Eds.), *Kansas Geological Survey Bulletin*, 233, p. 9-30.
- Lawrence, D.T., Doyle, M., and Aiger, T., 1990, Stratigraphic simulating of sedimentary basins - concepts and calibrations: *AAPG Bulletin*, 74, p. 273-295.
- Lee, Y.H., and Harbaugh, J.W., 1992, Stanford's SEDSIM project: Dynamic three-dimensional simulation of processes that affect clastic sediments: in *Lecture Notes in Earth Sciences*, 41: *Computer Graphics in Geology*, Pflug, R. and Harbaugh, J.W. (Eds.), Springer Verlag, 298 p.
- 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*, 4, p. 73-90.
- Parker, G., 1991, Selective sorting and abrasion of river gravel. I. Theory: *J. Hydraulic Eng.*, 117, p. 150-171.
- Rivenæs, J.C., 1992, Application of a dual-lithology, depth-dependent diffusion equation in stratigraphic simulations: *Basin Research*, 4, p. 133-146.
- Syvitski, J.P.M., and Alcott, J.M., 1995, RIVER3: Simulation of river discharge and sediment transport: *Computers and Geosciences*, 21, p. 89-151.
- van Niekerk, A., Vogel, K.R., Slingerland, R.L., and Bridge, J.S., 1992, Routing of heterogeneous sediments over movable bed: model development: *J. Hydraulic Eng.*, v. 118, p. 246-262.

Testing Different Relative Sea Level Curves on Sedimentation in Three Basins Using Stratigraphic Modeling: US Gulf of Mexico, Texas Offshore; Paradox Basin, SE Utah and South Caspian Sea, Azerbaijan

Linda Smith-Rouch (*Rouch_Linda/DAL10_LSROUCH//US/MOBIL/BB2@dal.mobil.com*),
Consultant for Mobil Oil Corporation, University of Texas at Dallas, 15725 Terrance Lawn
Circle, Dallas, TX 75248

Experiments in stratigraphy using computer simulations provide a tool to test different sea level curves and their consequences on sedimentation. Three basins were chosen for the tests; East breaks, Gulf of Mexico-Pliocene to Recent; Paradox Basin, SE Utah-Desmoinesian and South Caspian Sea, Azerbaijan-Pliocene. Input parameters were derived for each basin and kept the same for each sea level iteration.

The Gulf of Mexico experiments were conducted using a Marco-Polo Curve and the Haq et al curve for the Pliocene to Recent (5.1 my to 0 my). Comparison graphs between the models show the Marco Polo Curve matches the thickness digitized from the seismic profile. The Haq et al curve produced significantly thicker shelf sequences and dominantly thinner intra-slope basin sequences, except for two. Overall shelf and intra-shelf basin lithofacies were sandier in the Haq et al test. Also extreme underfill in Recent shelf margin deposition resulted from the Haq et al curve.

With a relatively small data set, stratigraphic modeling has quantified several physical variables that provide a quantitative gauge to interpret the Pliocene depositional systems in the South Caspian Basin. The simulation began at 6.3 my and ended at 2.47 my. All the variables were the same except the sea level curves. Subsidence rates were kept simple for these models. A general subsidence profile that increased from the shelf into the basin was developed from formation thicknesses across the profile. A climate curve (curve 1) and a modified Mamedov Curve (curve 2) were used to test South Caspian Sea-Pliocene depositional sequences. Geologic ages were assigned from climate data, isotopes, sea level curves and paleontology. Although climate oscillations generally precede a change in relative sea level, this curve provided an initial quantitative data set. The modified T. Mamedov curve was developed from a seismic profile located on the east coast of the South Caspian. The climate sea level curve test produced a series of stacked sand/silt/shale lithofacies. Four major transgressions are visible in the more shale rich sequences. Major sand rich prograding sequences are the Kalinsky, Pereryva, top Balakhansky, and two middle Surkhansky. The modified Mamedov curve clearly defines six major transgressions and regressions. Major transgressions are identified by the shaley sections and shoreface backstepping. Regressions show massive sand rich progradation into the basin. Simulations showed that the modified Mamedov curve was the best fit, however 2 or 3 higher order cycles should be added to this curve for comparisons to well lithofacies.

Simulations allowed us to test the effects of amplitude and frequency variations from three sea level curves derived for the lower Ismay Stage, Desmoinesian, Paradox Basin, SE Utah. The frequencies and amplitudes of these cycles have a profound effect on facies development

and diagenesis of carbonate rocks. Previous sea level curves were developed by assigning water depths to a specific lithofacies (Goldhammer and others, 1991 and Gerhard, 1991). This study has derived a curve from the petrographic work, isotope data, stratigraphic onlap and backstripping out the tectonic component. Three stratigraphic simulation models were run using the different sea level curves along the same profile (Honaker Trail to Aneth Field). Quantitative data produced from the models provided optimum values for carbonate growth rates, subsidence rates, sea level amplitudes, and specific water depths along the profile at each time slice.

A few cautions should be mentioned before analyzing sedimentation patterns from different sea level curves. In the Gulf of Mexico examples, subsidence rates were calculated by running a 2-D backstripping program across an interpreted seismic profile. Paleowater depths were defined by locating the seismic inflection point for each horizon and assigning water depths along the profile at the time of deposition. Maximum flooding surfaces were correlated by bioevents and times of maximum flooding on the Marco Polo curve. This may bias subsidence rates to the Marco Polo Curve. The best test would be to back strip the seismic profile tying ages for maximum flooding surfaces and paleowater depths to each curve.

References

Gerhard, L.C., 1991, Reef modeling: Progress in simulation of carbonate environments; *in* Sedimentary Modeling: Computer Simulations and Methods for Improved Parameter Definition: Kansas Geological Survey, Bulletin 233, pp. 345-358.

Goldhammer, R.K., Oswald, E.J., and Dunn, P.A., 1991, Hierarchy of stratigraphic forcing: Example from Middle Pennsylvanian shelf carbonates of the Paradox basin; *in* Sedimentary Modeling: Computer Simulations and Methods for Improved Parameter Definition: Kansas Geological Survey, Bulletin 233, pp. 361-413.

Modeling Facies with Physics of Sedimentation and Building Stratigraphy with the Results: Toward an Analytical Theory of Stratigraphy

Donald J. P. Swift (*djs100F@Ludwick.NAECO.ODU.EDU*), **Yong Zhang**, *Department of Oceanography, Old Dominion University, Norfolk, VA, 23508*, **Alan Wm. Niedoroda** and **Christopher W. Reed**, *Woodward Clyde Consultants, 376 Hartfield Rd., Tallahassee FL 32303*, and **Julian A. Thorne**, *Chevron Oilfield Research Company. La Habra, CA 90633*

Two critical problems facing stratigraphic modelers are 1) capturing the mathematics of the complex mix of small-scale, deterministic and chaotic-deterministic processes that build sedimentary deposits, and 2) generalizing these insights to stratigraphically significant time and space scales with minimal loss of predictive power.

The first problem is now relatively tractable. Our understanding of the fluid dynamics of sediment transport has expanded dramatically over the past decade, and it is possible to go beyond classical facies descriptions to *analytical* facies models, in which conceptualizations are underpinned by equations describing the physics of facies formation. Using the abundant fluid dynamical data sets now available from modern continental margins, we have taken initial steps towards a shallow marine facies model; still largely qualitative but backed by computation, and simplified by separation of fundamental variables from varietal ones. In the model, we distinguish between a *dispersal system*, defined as an assemblage of flow-linked depositional environments (2-D surfaces) aligned along a fluid power gradient, and a *depositional system*; an assemblage of process related facies (3-D volumes). One-dimensional event stratigraphic columns are built by selecting successive storm events from probability density functions describing wave, current, and flooding regimes, and building the resulting event beds with boundary layer physics (Fig. 1). The 1-d models are "chained" to form 2-d cross-sections, through which multiple grain size classes of sediment undergo differential transport during successive transport events.

Progressive sorting results, in which the accumulating sediment is packaged as event beds at each station in the dispersal system. The coarsest particles introduced during each event are sequestered in the sole of the resulting event bed; erosion during the next event preferentially bypasses finer sediment to the downstream stations, so that stratification and grain size, the two critical facies parameters vary systematically from proximal to distal stations. Facies bodies are generated with control of the "Sloss variables" (rate of sea level change, rate of sediment input, sediment grain size, sediment transport function), depositional environments (surfaces) move through space as these variables change, and sweep out the volumes that become sedimentary facies. Retrograde motion of surfaces along these trajectories cuts the erosional bounding surfaces that characterize systems and sequence stratigraphy.

It is possible to build a numerical dispersal system with continental shelf geometry (or with many other geometries) and manipulate the Sloss variables, so that accommodation is created and a sediment pile (depositional system) accumulates. These exercises that provide rules of combination for a systems stratigraphy, that, as time and space scales expand, coalesces into the better known patterns of "sequence stratigraphy."

Solution of the second problem, expanding time and space scales, is best done in steps, coordinated by dynamical calibration. Morphodynamics is an important behavioristic tool here, allowing stratigraphers to generalize a dynamical stratigraphy, just as thermodynamics has allowed chemists to generalize a dynamical chemistry. In our case, we can resort to the morphodynamics of the shelf surface, describing the transport of multiple grain size classes across an equilibrium surface, shaped by supply and accommodation, by means of an advection-diffusion equation in which the time-averaged wave field is accounted for. With such an approach, facies arrange themselves with respect geomorphic surfaces (shoreface; shelf floor, edge), sequence stratigraphic bounding surfaces are generated, and response times can be computed. Since the hydraulic history is known, the growing sedimentary pile can be numerically "cored" to resolve its event stratigraphy (Fig. 2). In this manner we can provide sediment dynamical insights with which to fill the basins modeled for us by students of lithospheric dynamics.

Figure Captions

Fig. 1. Growth of synthetic event stratigraphic column in 250 yr time steps. Note ephemeral stratigraphy of zone or resuspension; short return period beds do not pass into zone of permanent burial.

Fig. 2. Continental margin stratigraphic section with numerical cores revealing event stratigraphy.

Figures from Swift et al.

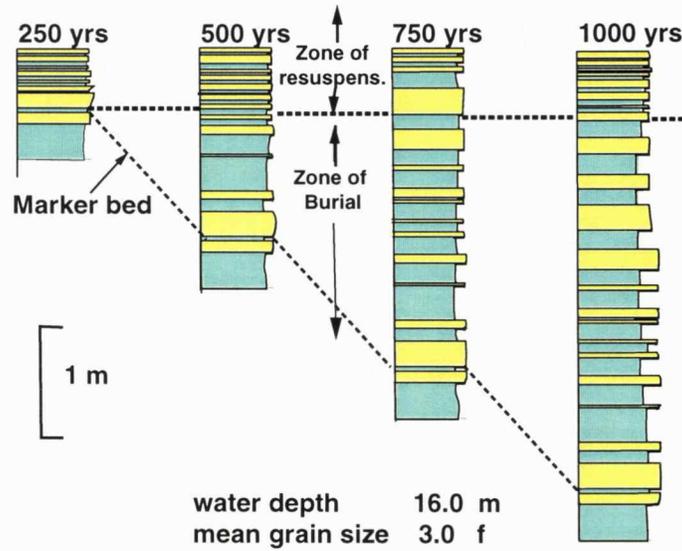


Fig. 1. Growth of synthetic event stratigraphic column in 250 yr time steps. Note ephemeral stratigraphy of zone of resuspension; short return period beds do not pass into zone of permanent burial.

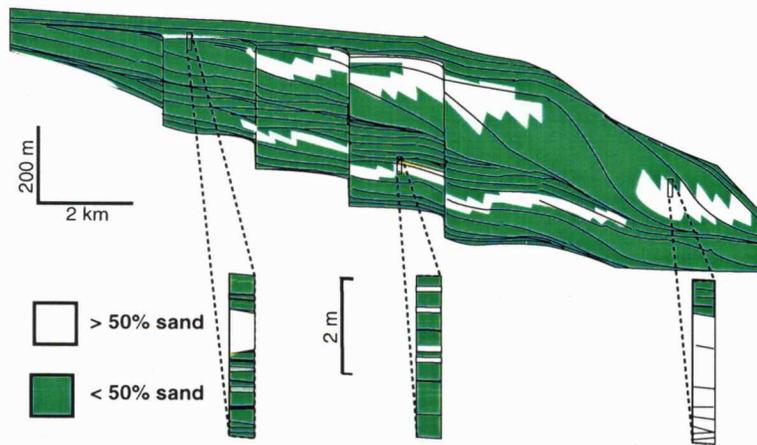


Fig. 2. Continental margin stratigraphic section with numerical cores revealing event stratigraphy.

Predicting Sediment Delivery and Stratigraphy on Marginal Slopes and Shelf Basins for the Navy

James P. Syvitski (*james.syvitski@colorado.edu*), *Institute of Arctic and Alpine Research & Dept of Geological Sciences, University of Colorado at Boulder, 1560 30th Street, Campus Box 450, Boulder CO, 80309-0450*

The U.S. Navy has interest in understanding and predicting the acoustic complexities of continental margins, so as to strengthen their preparedness for operating within the littoral zone (<2000 m water depth). Mine counter-measures, anti-submarine warfare and transport and deployment of troop-carriers all demand a detailed understanding of the 3-dimensional nature of sedimentary deposits comprising continental margins. As a consequence, oceanographers, geologists, engineers and geophysicists have recently been asked to combine their expertise to explain continental margins as a dynamic feature evolving in response to sediment delivery and removal and major events such as sea-level change. This 1994 ONR initiative has been termed STRATAFORM. A major task of this initiative is to develop a broad landscape-stratigraphic model, capable of predicting complex fine structure within a larger framework, delineating stratal geometries, lateral and vertical variability, and geometry of the discrete depositional units, given variations in sea level, terrestrial sediment delivery, subsidence rate, and other relevant factors, and to simulate seismo-acoustic features observed on geophysical records & geotechnical properties observed in cores.

My contribution to this effort is to use semi-independent basin-scale models to simulate fluvial delivery of a multi-sized sediment load onto and across a continental margin, including bedload dumping at the river mouth, transport and deposition of turbidity currents generated near a delta front, sedimentation under buoyant river plumes, current and wave erosion and transport, and debris flows generated from slope instabilities. The over-riding aim is to link sediment transport & marine process studies to geophysical & sediment observations, using numerical techniques. ONR interests include ability to predict the acoustic signature of slope margins based on a region's geological history.

Four research objectives are addressed:

- 1) Simulate sediment delivery by rivers to continental margins to include the influence of seasonal effects of river flooding, climate trends, random catastrophic events, and the effects of fluctuating sea-levels on sediment input.
- 2) Test *sediment delivery model* with observations made on STRATAFORM & other river sites that have large sediment inputs and conduits across the shelf that may act as shelf-slope transport pathways from these point-source origins.
- 3) Develop a *multi-process sedimentation model* to help understand how external forcing mechanisms affect the events that control the slope morphology and stratigraphy, including:
 - + simulations of fluvial delivery of sediment onto continental margins;
 - + simulations of submarine failure & mass movements including debris flow & turbidity current runout.

4) Using results from the multi-process sedimentation model, simulate the seismo-acoustic features of continental margins at a scale directly comparable with very-high resolution (e.g. Chirp and Huntex) seismic records and geotechnical properties observed on cores (i.e. at the scale of individual beds).

Early accomplishments include development of a climate-driven drainage basin simulator to accept data from meteorological station data, or output from a Global Circulation Model, and to predict realistic return periods of river flooding, and longer-term climate trends. HYDROTREND can predict river mouth velocity & discharge, and sediment load concentrations of 5 grain sizes, every day. HYDROTREND successfully predicts the range in magnitude and return interval of peak discharge events and sediment loads. E.g. predicted parameters for the 400 year Eel River flood that occurred in 1964.

A world-wide data set on river floods & loads, covering 75% of landmass that drains into the world oceans, was acquired. SE Asian rivers have sediment loads so high that 9 rivers are able to generate underflows at least once per year. Elsewhere, small-medium size rivers trigger marine underflows at longer return intervals (10 to 1000 yr floods). Larger rivers are not able to generate hyperpycnal underflows. A method to predict the return interval of turbidity currents generated at river mouths (hyperpycnal discharges) was designed to assist engineers in their assessment of shelf hazards offshore of gauged and ungauged river basins.

A method is developed that allows rating coefficients for gauged and ungauged rivers to be predicted. Sediment loads of rivers on a daily basis can be estimated to within 30% of their measured values, although predictions can be made over a 5 order-of-magnitude range in discharge, and over a wide range of hinterland conditions.

Using empirical relationships between hydrometric, morphometric and climatic data for 279 rivers, sea-level fluctuations are shown to influence river discharge and sediment loads, and frequency of underflows generated at river mouths: e.g. during sea level lowering, turbidity current activity decreases where rivers merge and giant rivers form; in contrast, hyperpycnal activity may increase for smaller rivers, particularly in tectonically active areas.

A 2-D buoyant *plume* model wherein a river's sediment load is advected by the river-induced velocity field and diffused by turbulence was developed. This 2DH buoyant PLUME model solves the plume generated from a river's discharge as a non-dimensioned inventory of a 2D (x,y) grid: sedimentation is governed by a first-order removal rate scheme for each grain size. PLUME predictions were verified against field observations on river plumes in Alaska, British Columbia and Norway. PLUME model was incorporated into a multi-process sedimentation model DELTA and linked to the HYDROTREND model. Together these models allow the multi-process sedimentation model to simulate sediment accumulation rates on continental margins on a daily basis and for time periods 1 to 10,000 yr or longer. The influence of flood deposits on shaping the development of continental margins and influencing mass sediment failures can now be properly examined.

A psuedo-2DH model SURGE was developed to predict the run-outdistance, the shape and properties of surge turbidity currents including the transition from debris flows. SURGE model analyzes the rheological transition of a debris flow (visco-plastic scheme) to a turbidity current (Newtonian scheme). The approach includes the influence of seafloor

erosion, and bedform & sediment deposition from surge-type currents. Model tested favourably against observations of the 1979 Nice (Var River) submarine slide, including offshore location of sedimentary structures, erosion features and extensiveness of the sand deposit.

A numerical model INFLOW was developed to simulate the hyperpycnal flow dynamics at river mouths, including run-out distance, shape and properties of deposits laid down by these sediment laden river floods. Simulations compare well with seismic and core observations that characterize seafloor deposits resulting from the 1663 Saguenay River flood.

A numerical scheme (FACIES) was developed to track the properties of sediment deposits affected by multi-transport pathways so as to predict lithologies of offshore sediment core sites. Linked to DELTA, FACIES can track the ever-changing properties of offshore deposits affected by a variety of marine processes over long simulation periods. Bin-averaging routines allow the study of data loss at specified spatial resolution schemes.

CYNTHIA, using a Fast-Fourier Transform scheme, allows for the sediment property predictions of FACIES to be used to produce a synthetic acoustic response from a given seismic-source signature. Simple attenuation schemes allow reasonable seismic profile records to be produced.

STRATAFORM publications

Syvitski, J.P.M. and Nicholson, M. (in prep.) HYDROTREND: Simulation of trends in river discharge and sediment transport from climate normal and GCM predictions: Computers and Geoscience. Code is now available.

Syvitski, J.P.M., 1995, Advances in the numerical simulation of river-delta sedimentation: Geological Assoc. Canada, Abstracts, Victoria, Ca., May 17-19, p. 267.

Syvitski, J.P.M. and Nicholson, M., 1995, Providing sediment flux models as a link between GCM's and the paleorecord: Abstracts of the Paleoclimate of Arctic Lakes and Estuaries meeting, Feb. 4-7, 1995, Seattle, Washington, p. 27.

Mulder T. and Syvitski J.P.M., 1995, Turbidity currents generated at river mouths during exceptional discharge to the world oceans: *Journal of Geology*, 103: 285-298.

Mulder T., Savoye B. et Syvitski J.P.M., 1995, Origine des courants de turbidité enregistrés l'embouchure du Var en 1971, C.R. Acad. Sci.: *Marine Geology* (in press).

Mulder Th., Savoye B. et Syvitski J.P.M. (in review) La mise en évidence de courants de turbidité hyperpycniaux dans la tête du canyon du Var: données hydrologiques et observations de terrain (*Bull. de la Soc.Géol. de France*).

Savoye B. Mulder Th. et Syvitski J.P.M. (in prep.) Evidence for hyperpycnal plumes at the Var River mouth.

Syvitski, J.P.M. and Mulder, T. (in prep.) Estimating the sediment loads of rivers during floods for both gauged and ungauged river basins: *Journal of Geology*.

Mulder Th. et Syvitski J.P.M. (in prep.) Climatic and morphologic relationships for rivers. Implications during eustatic changes: *Journal of Geology*.

Syvitski, J.P.M., Nicholson, M., & Skene, K., 1995, Application of hydrologic model RIVER4.1 to Eel River Basin, California, a flood-dominated basin: AGU 1995 Fall meeting EOS supplement, p. 240.

Syvitski, J.P.M., Skene, K. and Nicholson, M. (in review) PLUME: A 2-D generator of river plumes flowing into the sea based on advection and diffusion: *Computers and Geoscience*.

Syvitski, J.P.M. and Alcott, J.M., 1995, DELTA6: Numerical simulation of basin sedimentation affected by slope failure and debris flow runout. In: Pierre Beghin International Workshop on Rapid Gravitational Mass Movements, Grenoble, France, p. 305-312.

Mulder, T., Savoye, B. and Syvitski J.P.M. (in review) Numerical modelling of the sediment budget for a mid-sized gravity flow: the 1979 Nice turbidity current: *Sedimentology*.

Syvitski, J.P.M. and Alcott, J.M. (in prep.) FACIES: Display of a process-oriented numerical simulator as an aid to understanding sequence stratigraphy: *Computers and Geoscience*.

Syvitski J.P.M. and Schafer, C.T., 1995, Evidence for an earthquake-triggered basin collapse in Saguenay Fjord, Canada: *Sedimentary Geology*. (in press).

Mulder, T. and Syvitski J.P.M. (in press) Modelling of erosion and deposition by sediment gravity flows generated at river mouths: *Jour. Sedimentary Research*.

Skene, K., Paul, R., Mulder, T., and Syvitski, J.P.M. (in prep.) INFLOW: Predictions of erosion and deposition from hyperpycnal river floods flowing into coastal marine basins: *Computers and Geoscience*.

Courtney, R., Syvitski, J.P.M., Nicholson, M. (in prep.) CYNTHIA: Generating synthetic seismic profiles from process-driven sedimentation models: *Computers and Geoscience*.

Probabilistic Estimates from Reservoir-Scale Sedimentation Models

Daniel M. Tetzlaff (*dan.tetzlaff@houston.aws.waii.com*) and Eliseo Rodriguez, *Western Atlas Logging Services, 10205 Westheimer Road, Houston, TX 77042*

Sedimentary process models have been used successfully to explain and predict overall characteristics of basin fill over spatial scales of hundreds of kilometers or more. Few have been used in drilling decisions at the reservoir scale. This is so in part because sedimentary systems, when observed at scales of a few hundred meters, often exhibit chaotic behavior, i.e. they settle into a succession of states that is neither steady nor strictly cyclic. A meandering river, for example, continuously changes course throughout time. Even extremely accurate knowledge of initial and boundary conditions (“model inputs”) is insufficient to determine the exact state of the system at a given time. Conventional inversion techniques cannot be applied to these systems, and we lack practical tools for their quantitative application. On the other hand, very imperfect knowledge of initial and boundary conditions (approximate slope, sediment type, and flow regime) and intuitive mental models are successfully employed by geologists to predict channel-set geometries and make useful drilling decisions.

This paper attempts to show how sedimentary process models that incorporate physical principles of sedimentation as well as probabilistic estimates can be made rigorous and quantitative. A simple hypothetical but realistic problem is used as an illustration: A well “A” intersects a fluvial channel. Paleogeographic and paleoclimatic variables are known, but are

affected by statistically quantified uncertainty. The goal is to find the probability that another well drilled at an arbitrary location B will intersect the same channel (Figure 1). Varying the position of B would then yield a map of probabilities of intersecting the channel, given it is present at A. The map could be used for performing risk analysis and determine, for example, bids for leases in the vicinity of the existing well.

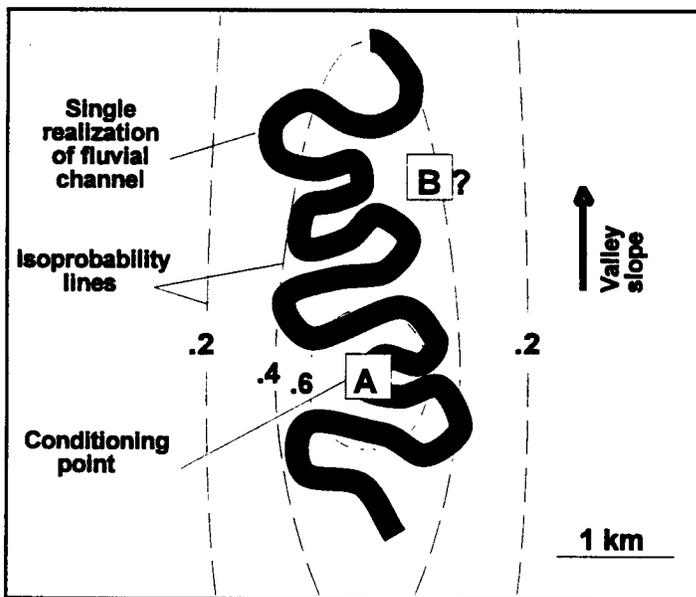


Figure 1: Well A is known to intersect a fluvial channel. Probability of intersecting channel at any other point is desired, given uncertain knowledge of paleogeographic conditions.

Problems of this type are routinely solved through geostatistical techniques. Traditional geostatistics, however, are shown to be inadequate in this case due to their inability to incorporate paleogeographic and paleoclimatic information and accurately

reproduce sedimentary features. Boolean geostatistical techniques fare better in their ability to reproduce realistic patterns, but their link to sedimentary processes is still done by intuitive comparison.

Two alternative solutions to the problem are proposed. The first is a Monte Carlo technique, in which a deterministic forward model is run repeatedly with input conditions drawn from a statistical population representing input uncertainty. Conditioning is achieved by selecting those outcomes that honor the data. This works well for a fast forward model, and a small set of conditioning points. The model used is a simplified fluvial-channel model that exhibits chaotic behavior. The method is feasible with more complicated sedimentation models, but may be impractical due to the lengthy run times involved.

The second method is a statistical technique of conditional simulation that utilizes more information than a variogram, thereby reproducing more complex features than those generated by conventional geostatistics. The proposed technique requires a large number of analogs from which to extract spatial variability information. While these would be difficult to obtain from field examples, they are readily available from repeated runs of a deterministic simulation model. Conditioning to honor data is straightforward. While the method is not fast, it requires much fewer runs of the model than the Monte Carlo technique (Figure 2). Other advanced geostatistical techniques may also be useful for this approach.

Examples produced with these two groups of methods indicate that, although presently computationally lengthy, they represent a viable means of obtaining quantitative statistical predictions from chaotic forward models at the reservoir scale.

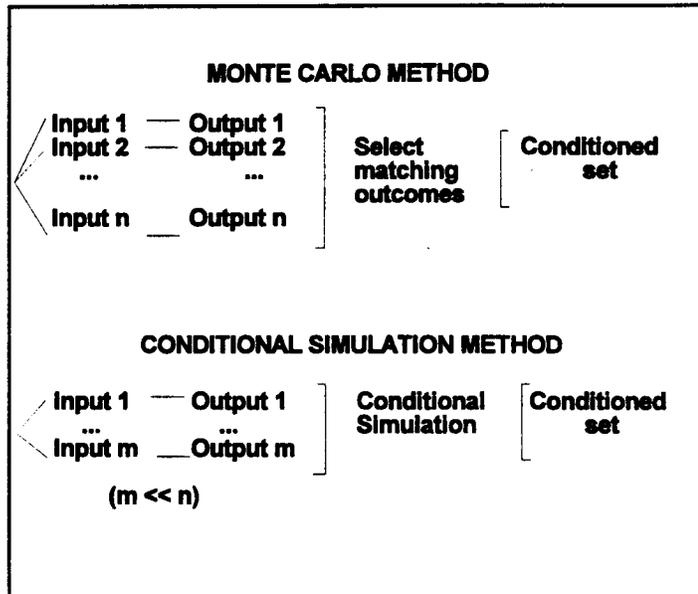


Figure 2: Schematic table comparing both methods. Monte Carlo method is more rigorous but requires far more runs of deterministic model.

The Effect of Rift Shoulder Erosion on Stratal Patterns at Passive Margins: Implications for Sequence Stratigraphy

Ronald van Balen (*balr@geo.vu.nl*), *Inst. of Earth Sciences, Tectonics/Structural Geology Group, Vrije Universiteit, Amsterdam, The Netherlands*

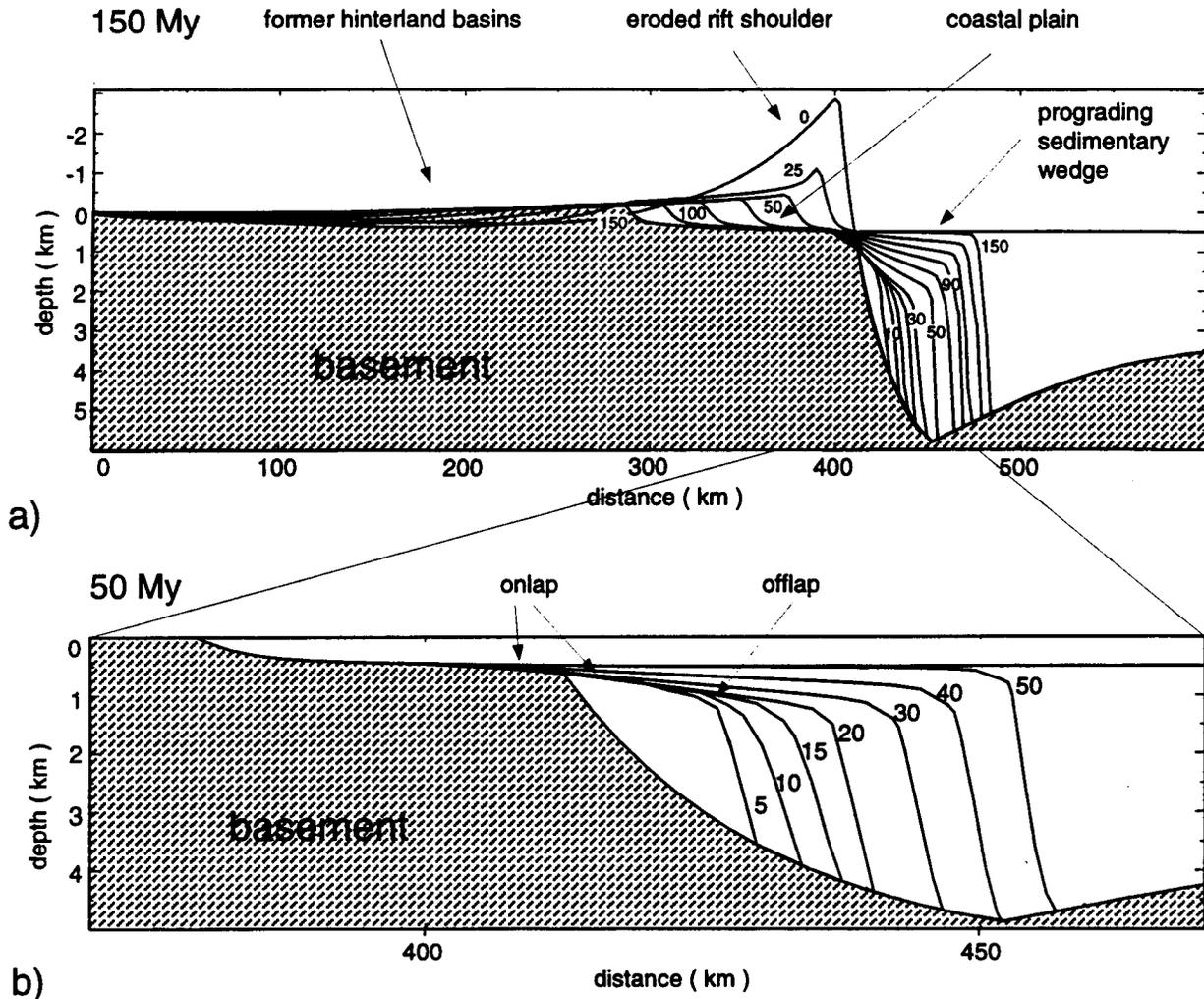
Uplifted flanks are a common feature of young rifts. The rift flank morphology is typically asymmetric and consists of a steep slope facing the rifted basin and a gentle slope extending in a landward direction away from the 2-3 km high flank summit. Modern examples include the Gulf of Suez, the northern Red Sea, the Transantarctic Mountains and the East African rift systems. Apatite fission track studies have revealed that large amounts (3-4 km) of basement rocks have been eroded from the present-day coastal plains of the South African, South American, U.S. east coast and southeastern Australian passive margins, providing evidence for uplift and erosion of rift flanks at these margins. At present, the passive margins of South America, South Africa and southeastern Australia are associated with an erosional escarpment located about 100 km landward of the shore-line.

Numerical modelling indicates that the erosion of uplifted rift flanks at passive margins has a profound effect on offshore stratigraphic patterns (figure). Flexural uplift, due to isostatic rebound in response to erosion, extends far into the basin and causes uplift of the shelf. As a result, the contemporaneously deposited sedimentary wedge displays a characteristic offlap pattern. When the rift shoulder is largely eroded, onlap promoting mechanisms, related to cooling of the lithosphere, enable sediments to onlap onto the basin margin. The initial offlapping and subsequent onlapping strata form one complete second order depositional sequence comprising a shelf-margin-, transgressive- and highstand systems tract, see figure. The modelling inferences are in broad agreement with stratal patterns and basin geometries observed at the U.S. east coast, southeastern Brazilian and southeastern Australian passive margins as well as the Transantarctic Mountains-Ross Sea Shelf system.

Coastal onlap is traditionally interpreted to be a general feature of passive margin stratigraphy by basin evolution models and sequence stratigraphy. It is considered to be a continuous feature, punctuated by tectonics and eustatic sea level changes. In the derivation of the global eustatic chart, it is assumed that passive margins show a continuous smooth and slow relative sea level rise due to thermal and sediment loading processes. In contrast, our modelling results and data from a number of rifted passive margins indicate that the first part of the post-rift phase will be in general characterized by a relative sea level fall and stratigraphic offlap.

Related Publication

Van Balen, R.T., van der Beek, P.A., and Cloetingh, S.A.P.L., 1995, The effect of rift shoulder erosion on stratal patterns at passive margins: implications for sequence stratigraphy: *Earth and Planetary Science Letters*, v. 134, p. 527-544.



The effect of rift shoulder erosion on stratal patterns at a passive margin

a) Large-scale result of the numerical erosion/sedimentation model. The left-hand part of the figure shows the evolution of the hinterland basin and the retreat of the rift shoulder. The right-hand part displays the resulting stratigraphy in the offshore extensional basin (passive margin). The numbers indicate ages (m.y.) of morphological and depositional surfaces.

b) Close-up of the stratigraphy in the extensional basin after 50 m.y. of margin evolution. The stratigraphy clearly demonstrates the offlapping nature of the first post-rift sediments. At 15 m.y. a total offlap of 15 km is observed in the modelling result. The offlap is caused by 500m of flexural uplift in response to rift shoulder erosion.

Controls on Sediment Provenance and Dispersal from Compositional Data: Inverse Modeling Strategies for Improved Parameter Estimation

Gert Jan Weltje (gjweltje@omega.earth.ruu.nl), *Faculty of Earth Sciences, Utrecht University, P.O. Box 80.021, NL 3508 TA Utrecht, The Netherlands*

The temporal and spatial variation of sediment composition in ancient basin fills contains extremely valuable information for stratigraphic and sedimentologic modeling studies. The lack of appropriate numerical-statistical tools available to sedimentary petrologists has thus far hampered integration of provenance studies with the mainstream of basin analysis. Recent progress in numerical-statistical modeling of sediment provenance and dispersal allows to make much better use of the detrital record. Principles and applications of an inverse method, termed end-member modeling, are illustrated here.

Compositional variation within or among sandstone suites is often considered to reflect mixing of sediments from different sources, but the exact nature of the mixing process is unknown. The forward model of a mixing process can be described as a system of constrained linear equations if (1) the effects of selective transport are eliminated by defining sediment composition in terms of ratios of grains of similar size, shape, and density (e.g., a single size class of sand grains, excluding platy micaceous grains and so-called heavy minerals), and (2) the variation of sediment composition is assumed to reflect the mixing of a limited number of end-member assemblages of fixed composition.

Recasting the observed compositional variation into a linear mixing model in the absence of prior knowledge about the end members requires a solution of the *bilinear (or explicit) mixing problem*. The solution of this inverse problem involves the estimation of both mixing proportions and end-member compositions from the data. The bilinear unmixing solution is intrinsically non-unique, unless additional constraints on the model parameters are introduced. In cases where the errors associated with the data are unknown, the concept of an "optimal" solution may be used. This concept is based on the trade-off between mathematical and geological feasibility, two apparently contradictory but equally desirable requirements of the unmixing solution.

A general solution of the bilinear mixing problem is a powerful tool for reconstructing the areal extent of major morphotectonic units and drainage systems in orogenic hinterlands. An application of the method illustrates how spatial patterns of compositional heterogeneity may be used to predict dispersal patterns of sands and the location of source areas in a complex geotectonic setting. The Po Delta and adjacent beaches of the Northern Adriatic Sea are an ideal natural laboratory for this experiment. Compositions of coastal sands, which serve as input for the model, indicate a "recycled orogen" or "mixed" provenance. The present situation and late Holocene evolution of the area are well-documented, enabling a rigorous testing of model predictions.

Test results show that the performance of the end-member modeling algorithm is quite satisfactory. Three out of four modeled end members closely approximate the compositions

of sediments supplied by fluvial drainage basins in the area. A fourth end-member assemblage, whose contributions are poorly represented in the material studied, shows a distinct lack of fit to its "actual" source composition. The lack of fit is attributable to the conservative estimation procedure adopted to maximize the geological feasibility of the unmixing solution. The modeled alongshore variation of beach sands, expressed as proportional end-member contributions, is in general agreement with present-day dispersal patterns and historical records of delta evolution.

Use of Sedimentary Process Simulation in Reservoir Characterization

Johannes Wendebourg (*johannes.WENDEBEOURG@ifp.fr*), *Institut Français du Pétrole, 1 et 4, avenue de Bois-Préau, BP 311 - 92506 Rueil-Malmaison Cedex, France*

Subsurface fluid flow is critically dependent on the 3-D distribution of petrophysical properties in rocks. In sequences of sedimentary rocks these properties are strongly influenced by lithology and facies distribution that stem from the geologic processes that generated them. In contrast to conventional geological models, sedimentary process simulators do not require closely spaced subsurface data, but process-related input data.

Two different approaches have become popular in the last few years: hydrodynamic and diffusion-based simulators. The latter can be used to model geometries and gross sediment distribution on a parasequence scale whereas hydrodynamic simulators can be used to model sediment variability as a function of local topography within an individual sedimentary sequence. Simulations result in sediment distributions that can be compared directly with maps and sections based on well data and/or seismic surveys. Results of hydrodynamic simulators can also be transformed into estimates of porosity and permeability, thereby placing them in form for direct use with subsurface flow simulators.

Applications of hydrodynamic process simulators in generating descriptions of hydrocarbon reservoirs or groundwater aquifers suggest that comparisons between actual and simulated 3-D sequences should be done using their statistical descriptions rather than the sequences directly. Statistical parameters derived from simulations can then be used as input to stochastic simulators in cases where limited data does not allow them to be determined directly. Such a procedure combines the advantages of stochastic simulators that can condition simulations to subsurface data, with the advantages of process simulators that treat geometric forms and flow properties of sequences interdependently and represent the development of sedimentary facies through space and time.



Development of a Coupled 2-Dimensional Sedimentological-Diagenetic Model of Carbonate Platform Evolution

Fiona Whitaker, Peter Smart (*smartpl@gma.bris.ac.uk*), *Department of Geography, University of Bristol, Bristol BS8 1SS, England* and **Yvette Hague, David Waltham**, (*dave@gl.rhbnc.ac.uk*), **Daniel Bosence**, *Department of Geology, Royal Holloway, University of London, Egham, Surrey TW20 OEX, England*

Numerical models simulating depositional facies and the architecture of developing sedimentary sequences have provided a useful framework for the identification of relationships between rates of sediment supply, subsidence and eustatic sea-level which together control basin-scale sequence stratigraphy. These same factors, together with regional climate, also represent the major controls determining the diagenetic evolution of a sedimentary sequence. Here we present a progress report on the development of a coupled 2-dimensional numerical computer model of carbonate platform sedimentation and diagenesis. Simulation of the controls on, and feedbacks between, sedimentological and diagenetic processes enables for the first time quantitative examination of the distribution and temporal evolution of porosity and carbonate mineralogy in a range of platform, geometries.

The existing stratigraphic simulation model of Bosence et al (1994) has been adapted to incorporate sediment texture as well as the internal architecture of carbonate platforms in response to varying rates of carbonate production, subaerial and submarine erosion, sediment redeposition and sea-level change. These sea-level changes, together with platform geometry and regional climate also control the distribution of hydrological zones within the platform. The model considers five hydrological zones: the vadose, fresh water, mixed, marine and sea-floor flushed zones. These are defined in 2-dimensional space from theoretical and empirical studies of the hydrology of carbonate islands and platforms and provide the framework for diagenetic modelling. Within each zone the processes of mineral precipitation, transformation and dissolution are assumed to operate at a rate which may be spatially uniform, or vary in response to hydrological flux and/or concentration of reactant or product. The model output includes estimates of spatially distributed mineralogy and porosity derived from initial depositional facies modified by diagenetic processes operating over time.

The rate of operation and controls on the diagenetic process within the different hydrological zones are specified by geochemical theory, modern process-based studies and historical studies of Holocene and Pleistocene diagenesis. Where these factors are well known, a model such as this has predictive value in the analysis and forward modelling of carbonate sequences, as already demonstrated by stratigraphic models. However, where the controls and operation of a diagenetic process are the subject of ongoing debate, the particular utility of such a model may lie in its ability to determine available time for reaction and the geometry and continuity of resulting diagenetic bodies in relation to the platform geometry, sea-level and climate.

The operation of the model is exemplified by comparison with 2-dimensional results of previous one dimensional forward modelling by Matthews and Froelich (1987). This used high frequency glacio-ecstatic sea-level fluctuations in a subsiding basin and hydrological zones of fixed thickness, generated a complex diagenetic stratigraphy that could not be readily deciphered by traditional stratigraphic and sedimentary methods. Using the same relative sea-level and rate parameterisation (Figure 1) our two-dimensional model generates a stacked sequence of distinct diagenetic zones formed during each low sea stand which are readily recognized because of their lateral continuity. The model also shows trends in diagenetic evolution from platform interior and marginal sediments, a consequence of the inclusion of variable depth hydrological zones (Figure 2). As accommodation space becomes limiting at low subsidence rates platform progradation increases. In such cases the increasing island width exposed during low sea stands leads to progressively greater sediment volumes subject to meteoric diagenesis, emphasizing the importance of explicitly coupling diagenetic and sedimentary processes.

References

Bosence, D.W.J., Pomar, L.P., Waltham, D.A. and Lankaster, T.H.G., 1994, Computer modelling of a Miocene carbonate platform, Mallorca, Spain: American Association of Petroleum Geologists Bulletin, v. 78, p. 247-266.

Matthews, R.K. and Froelich, C., 1987, Forward modelling of bank-margin carbonate diagenesis: Geology, v. 15, p. 673-373.

Figures

Figure 1. Relative sea-level curve resulting from interaction between constant basin subsidence and Pleistocene ecstatic sea-level fluctuations. Dashed line is predicted platform surface. Numbers represent oxygen isotope stages and substages, which also distinguish stratigraphic units and subaerial unconformities in the resultant stratigraphic column.

Figure 2. Simulated 2-dimensional distribution of aragonite, calcite and dolomite abundance for platform top deposits. Calcite (C) and dolomite (D) dominated diagenetic zones are numbered for sediment sequences defined by unconformities. Unconformities (wavy lines) are number according to oxygen isotope stage.

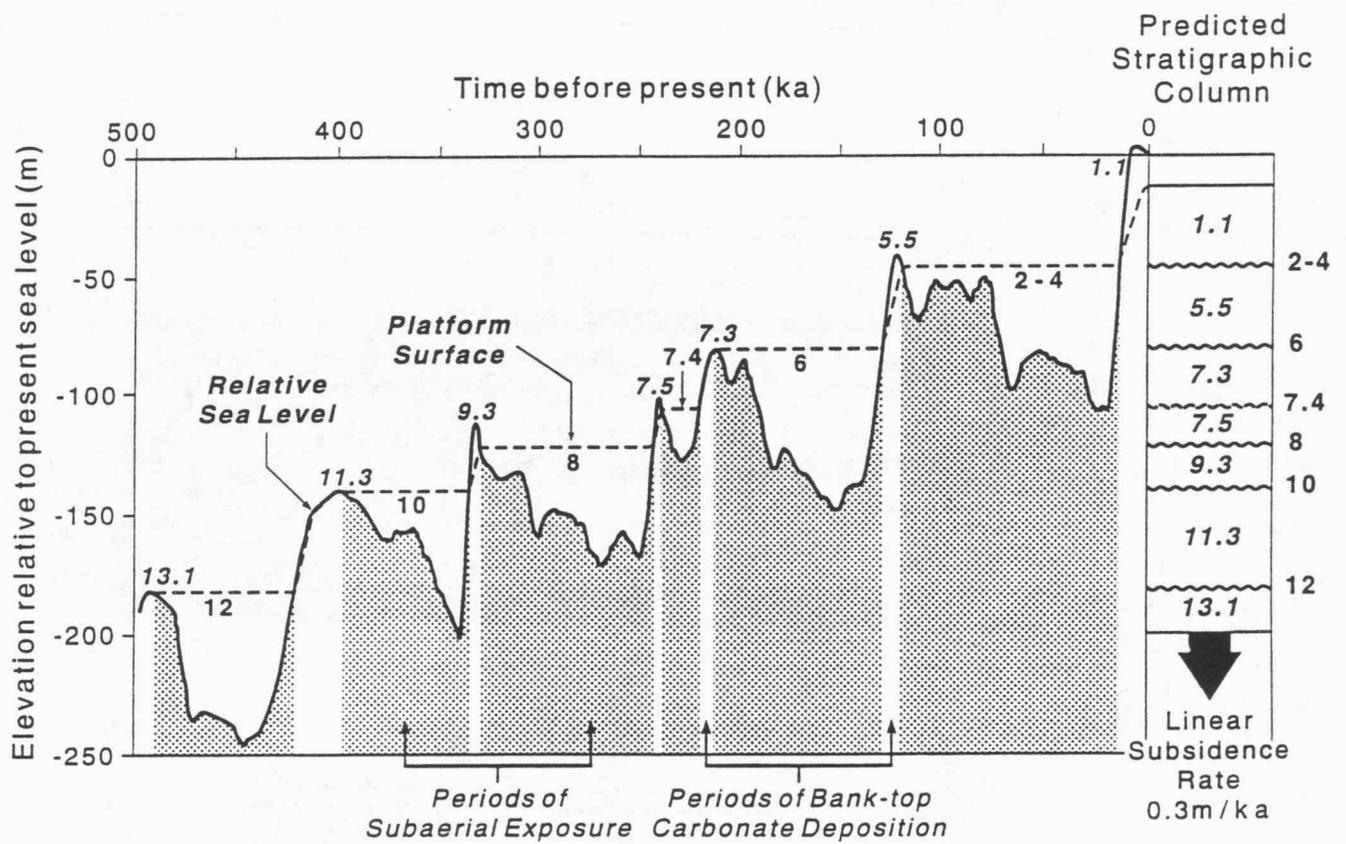


Figure 1.

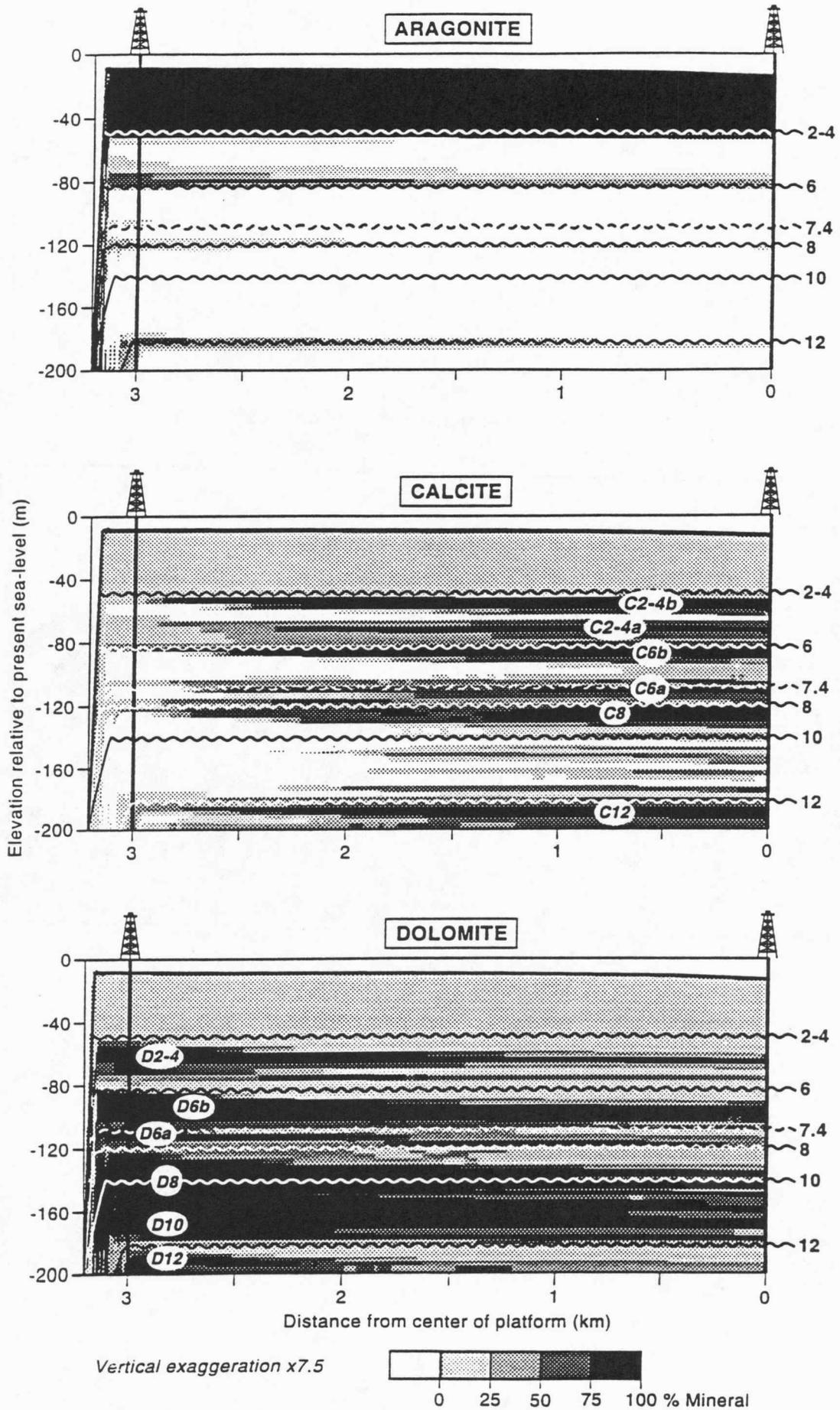


Figure 2.

Evaporite and Bauxite Proxy Formation Models Forced by a Global Climate Model

Christopher N. Wold (*chrisw@ncar.ucar.edu*), *National Center for Atmospheric Research, Climate Change Research, P.O. Box 3000, Boulder, Colorado 80307-3000*

A Proxy Formation Model (PFM) simulates the physical, chemical, and/or biological conditions necessary for the formation of a Climate-Sensitive Sediment (CSS). A proxy formation model may be forced by the monthly-mean climate data that are typically stored from a Global Climate Model (GCM) simulation. PFMs are used to simulate the conditions under which a variety of CSS may form. Two PFMs have been developed, one for evaporites and one for bauxites. These models can be applied at any resolution and for any time when evaporites or bauxites existed during Earth's history.

A database of present day evaporites (Wold et al., in preparation) and bauxites was compiled to test and validate the PFMs. The database of modern evaporites includes: marginal marine salinas and sabkhas, non-marine saline lakes, saline pans and saline mudflats. The bauxite database is preliminary but future adjustments will be minor.

Figure 1 shows the distribution of evaporites and the PFM predicted regions of potential for gypsum formation. The PFM for evaporites predicts the rate of evaporation from a dense, salty brine. The meteorological forcing fields (including precipitation) were derived from a GENESIS (Global Environmental and Ecological Simulation of Interactive Systems; version 1.02a) simulation for the present. The contours in Figure 1, represent an excess of evaporation over precipitation, the highest values having the highest potential for gypsum formation. There is generally good agreement between the PFM-predicted and observed evaporite locations. The most notable exceptions are in the northern-most regions. Saline lakes occur dominantly at these latitudes and their high salinity may be derived primarily from the dissolution by rivers and groundwater of older evaporite deposits. The results from a PFM simulation for evaporites during the Late Cretaceous (Wold and DeConto, submitted) using the new version of GENESIS (version 2.0; Pollard and Thompson, 1995; Thompson and Pollard, 1995) will also be discussed.

The PFM for bauxite is based on thermodynamic laws for the stability of gibbsite, $\text{Al}(\text{OH})_3$, in the $\text{Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ system. The input data include the surface air temperature and relative humidity. The compiled present day bauxite locations are shown in Figure 2 (black circles) and the PFM-predicted bauxite locations are indicated by the open squares. Most of the compiled bauxite locations were predicted by the PFM for bauxite with a few exceptions. Most notably in western Africa, northern India and northern Australia. These could be due to insufficient mean-annual relative humidity as simulated by GENESIS (version 2.0), or to deficiencies in the PFM. The next step is to drive both PFMs using observed climate data. Another way that the PFM-predictions could be improved is to force the models using only seasonal climate data. The PFM for bauxites could be forced only using data for monsoon seasons. The results shown in both figures were calculated using input from simulated mean-annual climate.

Proxy formation models are useful for quantitative validation of GCM simulation results. In the future, PFMs could serve as a link between GCM simulations of paleoclimate and forward stratigraphic modeling.

References Cited

Pollard, D., and Thompson, S.L., 1995, Use of a land-surface-transfer scheme (LSX) in a global climate model (GENESIS): The response to doubling stomatal resistance. *Global and Planet. Change*, 10, 129-161.

Thompson, S.L., and Pollard, D., 1995, A global climate model (GENESIS) with a land-surface-transfer scheme (LSX). Part 1: Present-day climate. *J. Climate*, 8, 732-761.

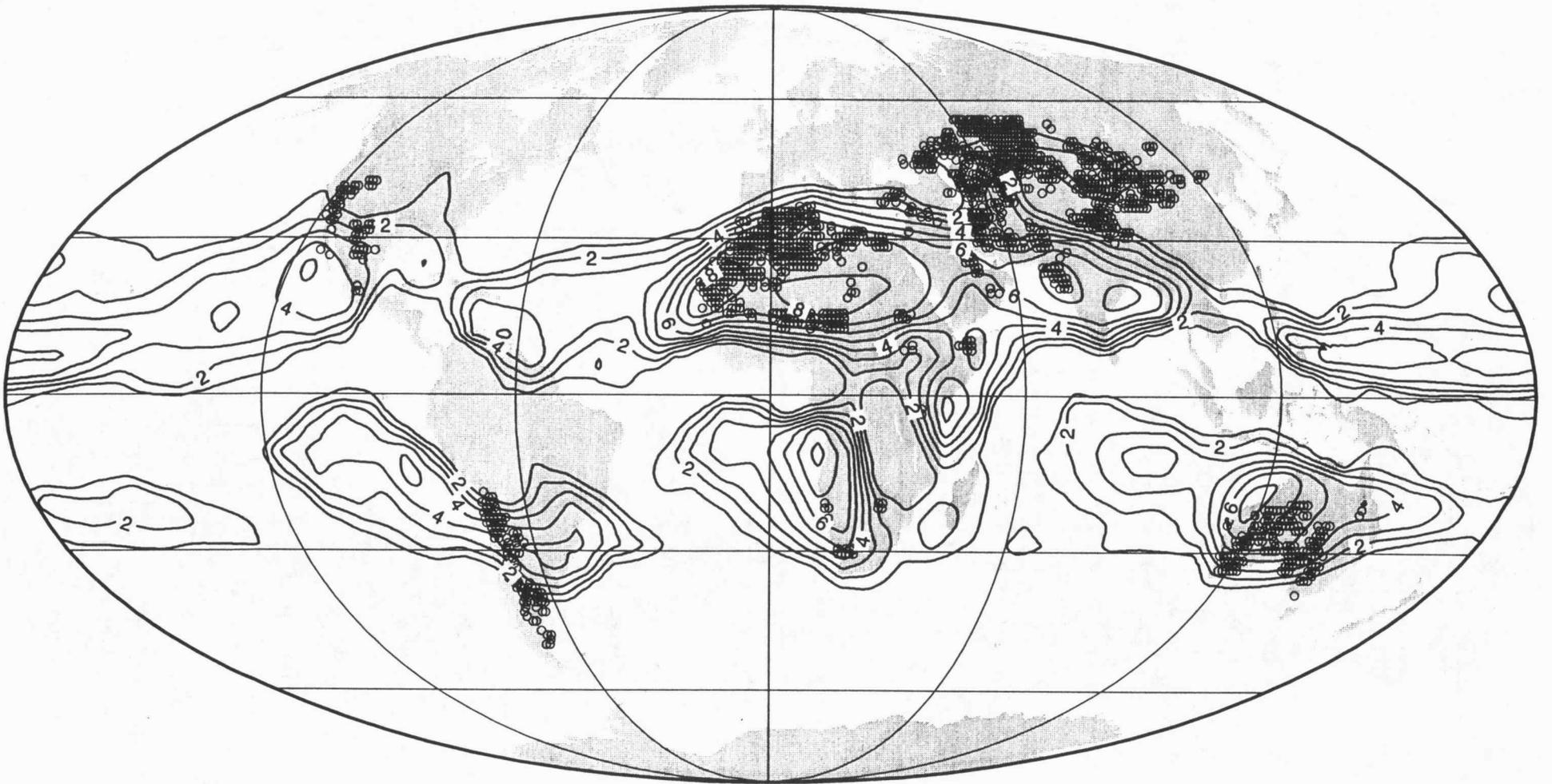
Wold, C.N., and DeConto, R.M., submitted, 1995. Proxy formation model used to predict the locations of Late Cretaceous evaporites. In: Barrera, E., and Johnson, C., eds., *The Evolution of Cretaceous Ocean/Climate Systems*, Geological Society of America Special Publication.

Wold, C.N., Schwartz, G.J., and Morrill, C., in preparation, 1996. Digital database of present day evaporites on land. *Geological Society of America Bulletin*.

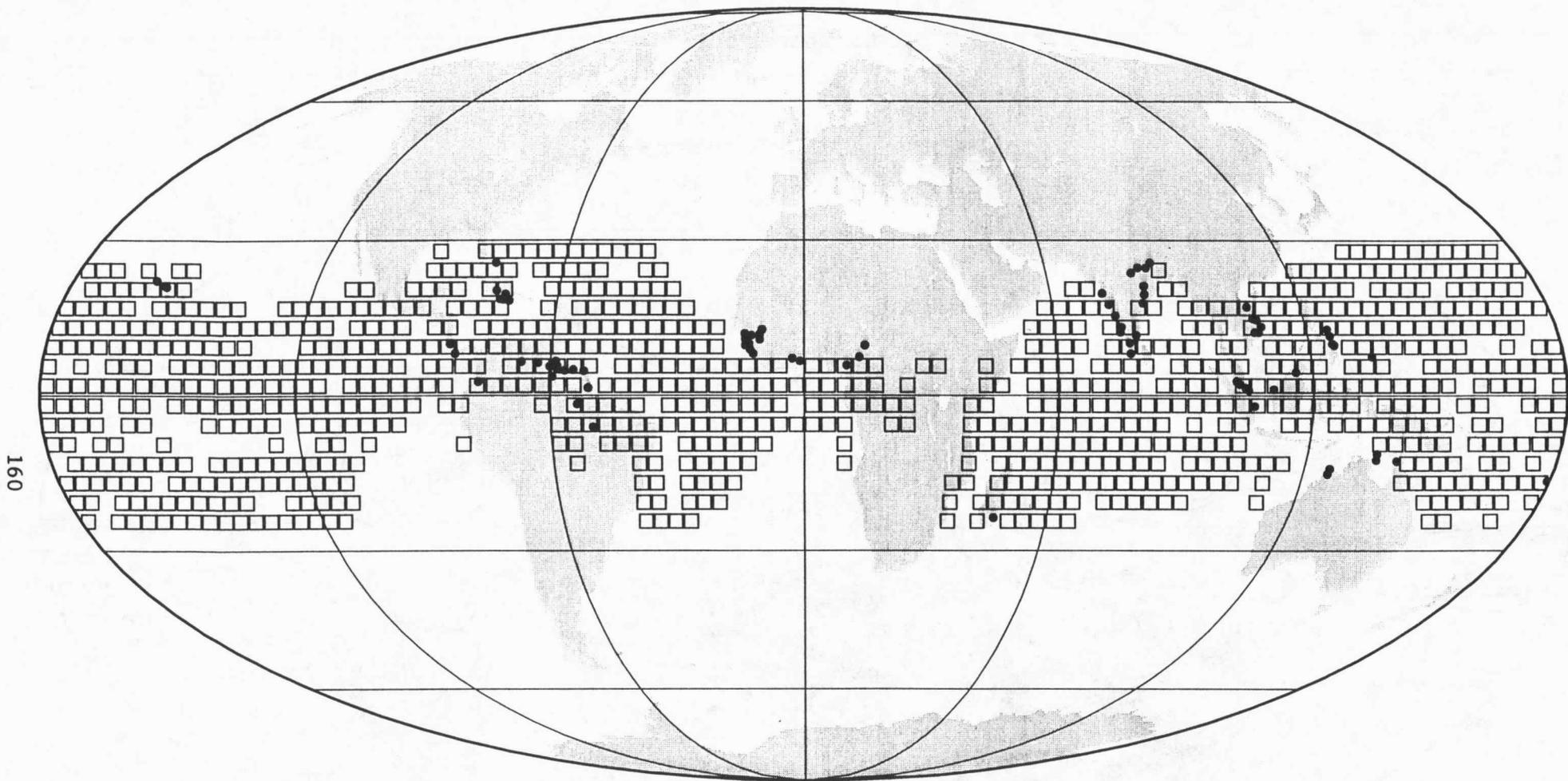
Figure Captions

Figure 1. Present day distribution of evaporite-forming environments (open circles) including marginal marine sabkhas and salinas, non-marine saline pans and saline mud flats, and saline lakes. The contours represent simulated Evaporation minus Precipitation (E-P) expressed in mm/day. The rate of precipitation is from a GENESIS (version 1.02a) simulation. The rate of evaporation was calculated using a Proxy Formation Model (PFM) for evaporites with a brine dense enough to precipitate gypsum (initial salinity = 175). The contours are only drawn where E-P is positive, the highest values indicate the highest potential for gypsum formation.

Figure 2. Present day distribution of bauxites (black circles). These occur all the way from Hawaii to Fiji and between 30 degrees north and 30 degrees south latitude. The PFM for bauxite is based on the relative stability of gibbsite in the Al_2O_3 - SiO_2 - H_2O system and is sensitive to temperature and relative humidity. The open squares are regions where the PFM predicted gibbsite would be stable under mean-annual climate conditions.



C. N. Wold, Figure 1



C. N. Wold, Figure 2



Modeling Event Stratigraphy on the Continental Margin

Yong Zhang and Donald J.P. Swift (*djs100F@Ludwick.NAECO.odu.edu*), Department of Oceanography, Old Dominion University, Norfolk, VA 23529-0276 and Alan W. Niedoroda and Christopher W. Reed, Woodward-Clyde Consultants, Tallahassee, Florida 32303

Rare but energetic events, such as storms and floods, dominate deposition on the continental margins, and result in distinctive stratal successions. These episodic but geologically common events, characterized by randomness, create event beds during a few hours or days. Meanwhile, they make contributions, either positive or negative, towards the preservation of preceding beds. We have developed a numerical model, consisting of process-oriented submodels for event bed formation and preservation, to simulate and predict lithofacies on the Northern California shelf.

The process that forms event strata on continental margin can be decoupled into two basic components, *event bed generation* and *event bed preservation*. Both can be viewed as random processes. An event bed forms at the sediment-water interface as a response to a storm or a river flood. A submodel that simulates the cross-shelf sediment transport during storm on the Northern California shelf is developed. This model calculates the erosion depth, bed thickness, net accumulation, and mean grain size of the storm bed. A river plume model is used to simulate the Eel River flood deposition. Both storm and flood events behave randomly, so that the storm climate and flood climate control the event bed generation. The probability of event bed generation, defined as the *bed generation potential*, is given by the probability density distribution of storms and floods respectively.

The bed sequence is a biased record of the event series. The initial event bed may be totally destroyed, partly modified, or entirely preserved by subsequent events, particularly by storms. A flood bed usually plays a positive role with respect to the preservation of underlying beds since it covers, rather than erodes them. A storm can create an initial storm bed. At the same time, it will destroy or modify the previous deposited beds by erosion. The degree of storm erosion with respect to the preservation of previous beds depends not only on the storm power itself, but also on the previous time series of events. For any storm event frequency distribution (storm climate), there are many different realizations. Each realization of storms can produce a unique bed sequence. Thus, combined with the effect of random realization of river floods, event bed preservation on continental margin behaves a complicated, highly random process which is significantly influenced by the combined effects of random realizations of storms and floods. It is hard to determine its probability density distribution because the recorded event strata constitute only one sample (a combination of one realization of storms and one realization of floods in history) in sample space. But the mode of this process can be estimated. We propose *bed preservation potential* as a parameter to describe the probability of an event bed to which degree it will be buried in bed sequence. By estimating the preservation potentials, the most probable event bed sequence may thus be predicted for various depths on continental shelf.

These simulations of event strata reflect the diversity of the sedimentary lithofacies on the continental shelf. The mathematical description of the facies patterns is not only necessary for comparing stratigraphic simulations with the observation, but for a more accurate, process-related classification of lithofacies as well. Four facies parameters, such as mean bed thickness (M), standard deviation of bed thickness (SD), sand bed percentage (SP) and bed rhythmicity (BR), have been constructed to quantitatively describe the lithofacies on the Northern California shelf (Fig. 1).

Our model simulates single event bed formation in terms of the shelf sediment dynamics on a deterministic domain. It then predicts the preserved bed sequences in terms of the bed preservation potentials on a domain that is stochastic as a consequence of the randomness of the event bed preservation process. The modeled bed sequences are parameterized by four facies parameters, giving a high resolution, process-oriented, and quantitative description of the stratigraphy. The facies model can be easily extended to longer time-scale simulations of sequence stratigraphy by introducing geological variables such as sea level change, storm or flood climate (including fluvial sediment discharge) change, without loss the high resolution (event scale) simulation that is based on the fundamental physics behind sediment transport on the continental margin.

Figure Caption

Fig. 1. Predicted Facies Parameters.

Figure from Zhang et. al

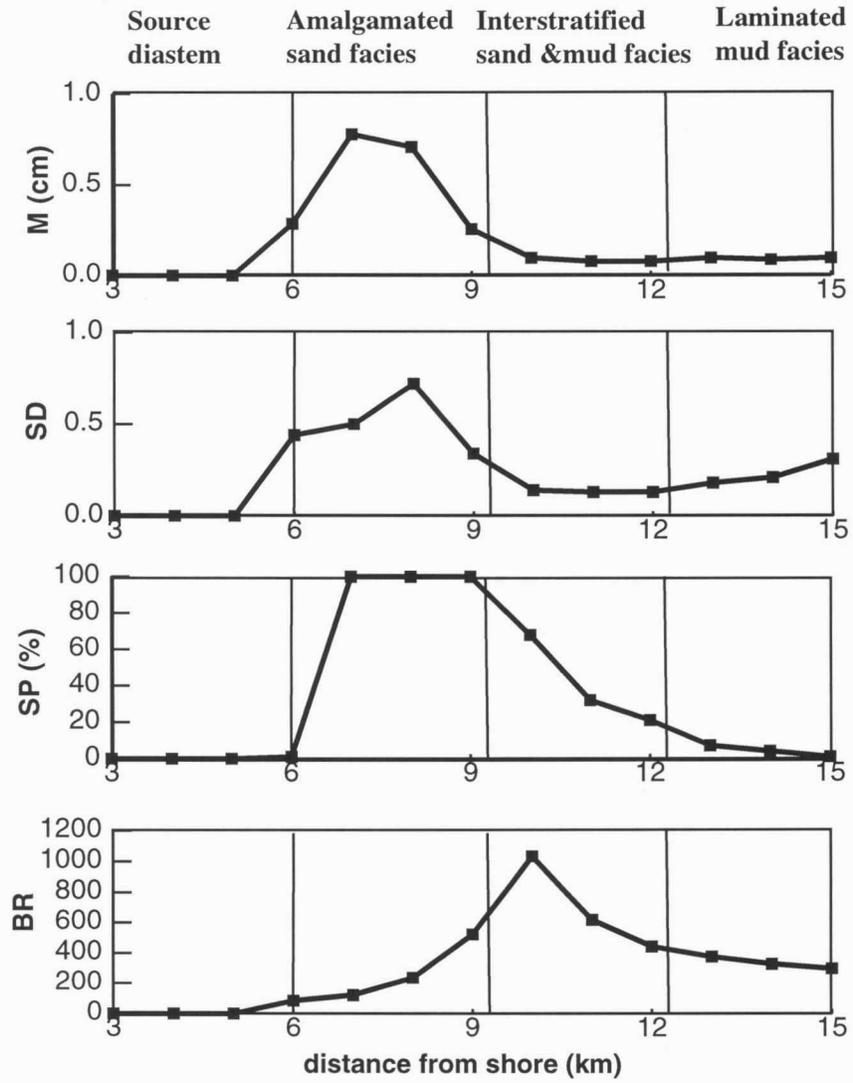


Fig. 1. Predicted facies Parameters

Simulation of the Genesis of Wavy-Bedded Tempestite Cycles in Chalk

J(Hans). J.P. Zijlstra and Poppe L. de Boer (*pdeboer@earth.ruu.nl*), *Inst. of Earth Sciences, P.O. Box 80.021, NL 3508 TA Utrecht, The Netherlands*

Mesozoic and Early Tertiary sediments of NW Europe are fine-grained, planar-parallel bedded sediments, which have been deposited in broad shallow-marine basins that covered a large part of a low relief continent.

Despite the shallow marine depositional environment, these sediments are comparable to recent deeper marine deposits as far as it concerns low rates of deposition and great lateral extent of facies. The reconstruction of basin morphology and facies distribution is hampered by the poor exposure with respect to the large-scale depositional systems and possibly by a post-depositional differential lateral displacement of the faulted lithosphere along grabens.

Attention is therefore being focused on a detailed sedimentological analysis of small sequences and the reconstruction of local variations of subsurface motion, hydrodynamic energy and deposition rates. As an example, Late Cretaceous Chalk sequences in the SE Netherlands, eastern Denmark and SW France were investigated and compared.

Chalk is a shallow subtropical marine, porous, fine-grained, well sorted, detrital, skeletal carbonate, characterized by a regular succession of dm-m thick, laterally continuous beds. The bedding is caused by a rhythmical vertical variation of grain size, structures and early-diagenetic mineral concentrations (e.g. smectitic glauconite, pyrite, carbonate cement and silica).

The rhythmicity is considered the result of precession-induced climate cycles and, in particular, of a periodic variation of storm frequency and intensity. Times of storm-energy increase were characterized by sediment winnowing, a decrease of deposition and burial rate, and an increase of early diagenetic mineral concentration in specific zones of bacterial metabolism below the sediment surface.

A numerical model has been developed that simulates the genesis of rhythmically bedded sequences. Simulated cycles are well comparable to Chalk sequences observed in the field. Thus an impression can be obtained of the relative magnitude of variations of subsidence rate, sea level, storm-induced hydrodynamic energy, deposition rates and the degree and type of early diagenetic mineralization.

Of particular interest are complex sequences, such as the wavy-bedded Cretaceous-Tertiary boundary sequence of Stevns Klint (Denmark). The model suggests that wavy-bedded tempestite cycles are formed by means of the interaction of storm erosion and lithification, when the accommodation space, formed by an (exceptionally) rapid increase of subsidence rate, is filled during the decrease of storm frequency and intensity.

The numerical model operates under Microsoft Windows and is equipped with a graphical user interface that allows the definition of environmental parameters, or the selection of some predefined cases, so that the genesis of various Chalk sequences can be simulated, understood and classified.