CONDITIONING EVENT-BASED FLUVIAL MODELS

MICHAEL J. PYRCZ and CLAYTON V. DEUTSCH
Department of Civil & Environmental Engineering, 220 CEB,
University of Alberta, Canada, T6G 2G7

Abstract. A fluvial depositional unit is characterized by a central axis, denoted as a streamline. A set of streamlines can be used to describe a stratigraphic interval. This event-based (denoted as event-based to avoid confusion with streamline-based flow simulation) approach may be applied to construct stochastic fluvial models for a variety of reservoir types, fluvial styles and systems tracts. Prior models are calculated based on all available soft information and then updated efficiently to honor hard well data.

1 Introduction

Interest in North Sea fluvial reservoirs led to the development of object-based models for fluvial facies and geometries (see Deutsch and Wang, 1996 for a review of development). For these models conditioning is often problematic. These difficulties in conditioning spurred research in direct object modeling. Visuer et al. (1998) and Shmaryan and Deutsch (1999) published methods to simulate fluvial object-based models that directly honor well data. These algorithms segment the well data into unique channel and nonchannel facies and then fit channels through the segments. The channel center line is parameterized as a random function of departure along a vector and the geometry is based on a set of sections fit along the center line.

Yet, these techniques are only well suited to paleo valley (PV) reservoir types. The PV reservoir type geologic model is based on ribbon sandbodies from typically low net-to-gross systems with primary reservoir quality encountered in sinuous to straight channels and secondary reservoir rock based on levees and crevasse splays embedded in overbank fines (Galloway and Hobday, 1996; Miall, 1996).

More complicated channel belt (CB) fluvial reservoir types are common. Important examples include the McMurray Formation (Mossop and Flach, 1983, Thomas et al., 1987) and Daqing Oil Field, China (Jin et al., 1985, Thomas et al., 1987). These reservoirs include complicated architectural element configurations developed during meander migration punctuated by avulsion events. The application of the bank retreat model for realistic channel meander migration has been proposed by Howard (1992), applied by Sun et al. (1996) and Lopez et al. (2001)

to construct realistic models of CB type fluvial reservoirs. These methods lack flexibility in conditioning.

A event-based paradigm is introduced with (**1**) improved flexibility to reproduce a variety of fluvial reservoir styles with realistic channel morphologies, avulsion and meander migration and (**2**) a new efficient approach to condition to well data and areal reservoir quality trends. Fortran algorithms are available that apply this techniques, `ALLUVSIM` is an unconditional algorithm for the construction of training images and the `ALLUVSIMCOND` algorithm includes streamline updating for well conditioning. Greater detail on this work and the associated code is available in Pyrcz (2004).

This work was inspired by the developments of Sun et al. (1996) and Lopez et al. (2001), but it was conducted independent of Cojan and Lopez (2003) and Cojan et al. (2004). The reader is referred to these recent papers for additional insights into the construction of geostatistical fluvial models.

2 Event-based Stochastic Fluvial Model

The basic building block of this model is the *streamline*. A streamline represents the central axis of a flow event and backbone for architectural elements (Wietzerbin and Mallet, 1993). This concept is general and may represent confined or unconfined, fluvial or debris flows.

Genetically related streamlines may be grouped into *streamline associations*. Streamline associations are interrelated by process. For example, a streamline association may represent a channel fill architectural elements within a braided stream or lateral accretion architectural elements within point bar. Fluvial architectural elements are attached to streamlines and architectural element interrelationships are characterized by streamline associations. This is a logical technique for constructing fluvial models since all architectural elements are related to "flow events".

2.1 3-D STREAMLINES

The direct application of a cubic spline function to represent the plan view projection of a fluvial flow event is severely limited. As a function, a spline represented as $f^s(x)$ may only have a single value for any value x. In graphical terms, a function may not curve back on itself. This precludes the direct use of a spline function to characterize high sinuosity channel streamlines.

A streamline is modeled as a set of cubic splines. Each spline models the coordinates (x, y and z) with respect to distance along the spline (s). The advantages of this technique are: (**1**) continuous interpolation of streamline location in Cartesian coordinates at any location along the streamline, (**2**) relatively few parameters required to describe complicated curvilinear paths, (**3**) manipulation of splines is much more computationally efficient than modifying geometries and (**4**) other properties such as architectural element geometric parameters and longitudinal trends may be stored as continuous functions along the streamline. These issues are discussed in further detail below.

The control nodes of a 3-D spline may be freely translated. The only requirement is that the second derivatives of the spline location parameters is recalculated after modification. This operation is very fast. The calculation of complicated geometries generally requires a high level of computational intensity or simplification. In the event-based models the geometric construction is postponed to the end of the algorithm. This results in very fast calculation and manipulation of complicated geometric morphologies and associations represented as 3-D splines.

Any properties may be attached to the 3-D spline and interpolated along the length of the spline. In the fluvial event-based model, the channel width, local curvature, relative thalweg location and local azimuth are included in the 3-D spline. Other information including architectural element type and additional property trends may be included. These properties are calculated at the control nodes and then splines are fit as with the location parameters.

2.2 STREAMLINE ASSOCIATIONS WITHIN EVENT-BASED MODELS

A streamline association is a grouping of interrelated 3-D splines. Streamline associations are characterized by their internal structure and interrelationship or stacking patterns. The internal structure is the relation of streamlines within the streamline association. The external structure is the interrelationship between streamline associations. Streamline associations may be tailored to reproduced features observed in each fluvial reservoir style.

A variety of stacking patterns may exist in the fluvial depositional setting. Compensation is common in dispersive sedimentary environments such as proximal alluvial fans, vertical stacking with little migration is common in anastomosing reaches and nested channel belts often form in incised valleys. These patterns include important information with regard to the heterogeneity of a reservoir and should be included in fluvial models.

2.3 STREAMLINE OPERATIONS

A suite of streamline operations is presented that allow for event-based models to be constructed by the creation and modification of streamlines. These operations include (**1**) initialization, (**2**) avulsion, (**3**) aggradation and (**4**) migration.

The streamline *initialization operator* is applied to generate an initial streamline or to represent channel avulsion proximal of the model area. The disturbed dampened harmonic model developed by Ferguson (1976) is applied.

The *avulsion operator* creates a copy of a specific channel streamline, selects a location along the streamline, generates a new downstream channel segment with same streamline sinuosity and the same geometric parameter distributions. The geometric parameters (e.g. channel width) of the new streamline are corrected so that the properties are continuous at the avulsion location. The initial azimuth is specified as the azimuth of the tangent at the avulsion location. There is no constraint to prevent the avulsed streamline from crossing the original streamline distal of the avulsion location.

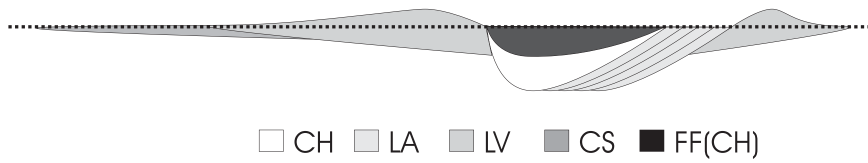

Figure 1. An illustration of the fluvial architectural elements applied in the event-based model.

Aggradation is represented by a incremental increase in the elevation of a streamline. The current implementation is to add a specified constant value to the elevation, z, parameter for all control nodes.

The streamline *migration operator* is based on the bank retreat model. The application of the bank retreat model for realistic channel meander migration has been proposed by Howard (1992), applied to construct fluvial models by Sun et al. (1996) and extended to construct meandering fluvial models that approximately honor global proportions, vertical and horizontal trends by Lopez et al. (2001).

Key implementation differences from the original work from Sun et al. (1996) include (**1**) standardization of migration steps, (**2**) integration of 3-D splines for location and properties, (**3**) application of various architectural elements. The meander migration along the streamline is standardized such that the maximum migration matches a user specified value. This removes the significance of hydraulic parameters such as friction coefficient, scour factor and average flow rate, since only the relative near bank velocity along the streamline is significant. Hydraulic parameters are replaced by the maximum spacing of accretion surfaces, which may be more accessible in practice.

2.4 FLUVIAL ARCHITECTURAL ELEMENTS

The available architectural elements include (**1**) channel fill (CH), (**2**) lateral accretion (LA), (**3**) levee (LV), (**4**) crevasse splay (CS), (**5**) abandoned channel fill (FF(CH)) and (**6**) overbank fines (FF) (see illustration in Figure 1). The geometries and associated parameters are discussed for each element in detail in Pyrcz (2004).

2.5 EVENT SCHEDULE

The event-based approach is able to reproduce a wide variety of reservoir styles with limited parametrization. This algorithm may reproduce braided, avulsing, meandering channels and may reproduce geometries and interrelationships of a variety of fluvial reservoir types. The algorithm is supplied with areal and vertical trends, distributions of geometric parameters, probabilities of events and architectural elements.

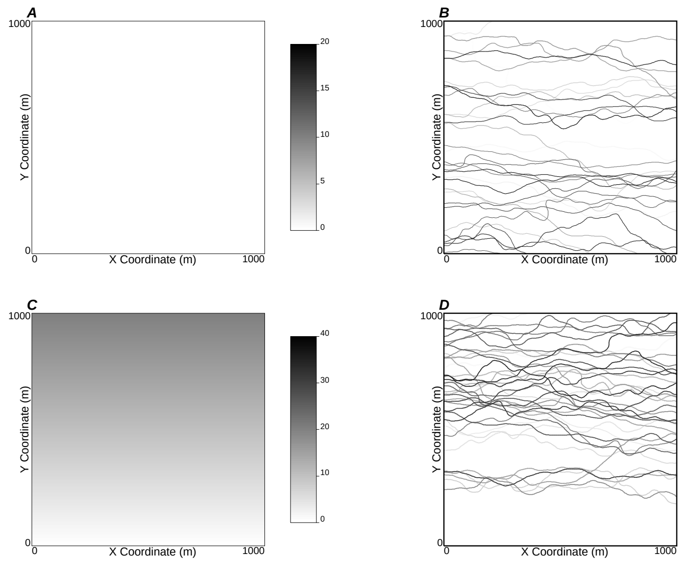

Figure 2. Example areal trends in channel density and the resulting streamlines. A and B - no areal trend supplied and C and D - a linear trend increasing in the y positive direction. Note areal trend is a relative measure without units.

2.6 AREAL CHANNEL DENSITY TRENDS

Analogue, well test and seismic information may indicate areal trends in reservoir quality. Although seismic vertical resolution is often greater than the reservoir thickness, seismic attributes calibrated to well data may indicate a relative measure of local reservoir quality. Well tests may provide areal information on the distribution of reservoir quality and may significantly constrain model uncertainty. Analogue information such as reservoir type may indicate a confined PV type or a more extensive and uniform SH type reservoirs. If the net facies are associated with CH, LV and CS elements then this areal trend information may be integrated by preferentially placing streamlines in areal locations with high reservoir quality.

The technique for honoring areal trends is to (**1**) construct a suite of candidate streamlines with the desired morphology, (**2**) superimpose each candidate streamline on the areal trend model and calculated average relative quality along the streamline and (**3**) for each streamline initialization drawn from this distribution of candidate streamlines (without replacement) weighted by the average quality index. This technique is efficient since the construction of hundreds or thousands of streamlines is computationally fast. This technique is demonstrated in Figure 2.

2.7 VERTICAL CHANNEL DENSITY TRENDS AND AGGRADATION SCHEDULE

Well data and analogue information may provide information on vertical trends in reservoir quality. Well logs calibrated by core are valuable sources of vertical trend information. Often, identification of systems tract and fluvial style will provide analogue information concerning potential vertical trends.

These trends may be honored by constraining the aggradation schedule. The current implementation is to apply the trend within a user defined number of constant elevation levels. Streamlines and associated architectural elements are generated at the lowest level until the NTG indicated by the vertical trend is reached for the model subset from the base of the model, to the elevation of the first level. Then the aggradation operator is applied to aggrade to the next level and the process is repeated through all user defined levels. For the highest level, the model is complete when the global NTG ratio is reached.

3 Conditional Event-based Simulation

There are a variety of available methods that may be applied to condition complicated geologic models; (**1**) dynamically constrain model parameters during model construction to improve data match (Lopez et al., 2001), (**2**) posteriori correction with kriging for conditioning (Ren et al.,2004), (**3**) pseudo-reverse modeling (Tetzlaff, 1990), (**4**) apply as a training image for multiple-point geostatistics (Strebelle, 2002) and (**5**) direct fitting of geometries to data (Shmaryan et. al., 1999 and Visuer et. al., 1998). Each of these techniques has limitations either in efficiency, robustness or the ability to retain complicated geometries and interrelationships.

An event-based model consists of associations of streamlines with associated geometric parameters and identified architectural elements. A prior model of streamline associations may be updated to reproduce well observations. The proposed procedure is: (**1**) construct the prior event-based model conditioned by all available soft information, (**2**) interpret well data and identify CH′ element intervals (where CH′ elements are channel fill elements without differentiation of CH, LA and FF(CH) elements), (**3**) update streamline associations to honor identified CH′ element intervals and (**4**) correct for unwarranted CH′ intercepts. This technique entails the manipulation of large-scale elements to honor small scale data; therefore, it is only suitable for settings with sparse conditioning data. Settings with dense data may be intractable.

3.1 INTERPRETED WELL DATA

The hard data from wells is applied to identified CH′ element intervals. CH′ elements are typically identified by erosional bases and normal grading. CH′ element fills often occur in multistory and multilateral configurations. CH′ elements often erode into previously deposited CH′ elements to form amalgamated elements (Collinson, 1996, Miall, 1996).

The geologic interpretation of well data is performed prior to the updating step. The input data includes the areal location for each vertical well and a list of CH′ element intervals with base and original top (prior to erosion). The geologic interpretation is often uncertain, especially with amalgamated CH′ elements. Alternate geologic interpretations may be applied to account for this uncertainty.

3.2 UPDATING STREAMLINE ASSOCIATIONS TO HONOR WELL DATA

The model is updated by modifying the position of streamline associations to honor CH′ element intercepts observed in well data. For each CH′ element interval the following steps are performed. (**1**) The horizontal position is corrected such that the CH′ element intercept thickness is within tolerance of the CH′ element interval thickness. (**2**) Then the vertical location is corrected such that the CH′ element intercept top matches the top of the CH′ element interval. Entire streamline associations are corrected to preserve the relationships between streamlines within a streamline association. For example, if a streamline association includes a set of streamlines related by meander migration, the entire set of streamlines representing a point bar is shifted. If individual streamlines were modified independently this may change the nature of the streamline association.

The CH′ element intervals are sequentially corrected. If there is no previous conditioning then streamline associations are translated (see A in Figure 3). If there is previous conditioning a smooth correction method is applied to the streamline association (see B in Figure 3). A step vector is constructed oriented from the nearest location on a streamline within the streamline association to the location of the well interval. The scale of the step of the sense is determined by an iterative procedure described below.

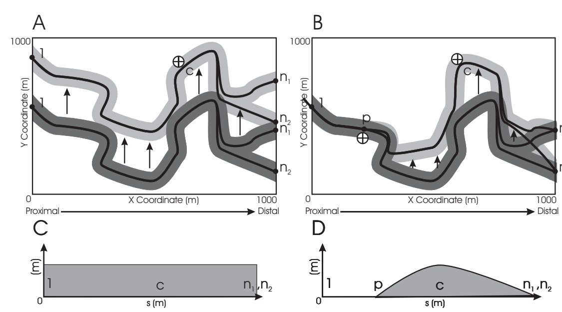

Figure 3. An illustration of methods for updating streamline associations with well data. For this example, there are two streamlines in the streamline association representing an avulsion event that are corrected to honor conditioning data (c). A - the case with no previous conditioning. B - the case with previous conditioning. C and D - the transverse correction with respect to location along the streamline.

3.3 ITERATIVE PROCEDURE FOR UPDATING STREAMLINE ASSOCIATIONS

Modifications of streamline associations has an impact on CH′ element geometry. It would be difficult to directly calculate the precise translation of a streamline to result in the correct interval thickness at a well location. A simple iterative method is applied to correct the well intercept thickness. The thickness of the CH′ element from a streamline association is calculated at the vertical well location. The error is calculated, if the thickness is less than indicated by the conditioning then the streamline association is shifted towards the well location. If the thickness is greater than indicated by the conditioning then the streamline association is shifted away from the well location. The procedure is repeated for all identified CH′ element intercepts.

3.4 CORRECTION FOR UNWARRANTED WELL INTERCEPTS

The correction for unwarranted CH′ element intercepts applies a robust iterative technique. For each unwarranted CH′ element intercept the associated streamline association is checked for conditioning. If the streamline association is not anchored to conditioning data then the streamline association may be translated in the direction transverse to the primary flow direction. If the streamline association is anchored to conditioning data then a smooth modifications is applied.

The streamline association is modified until the thickness of the unwarranted CH′ element intercept reaches zero. For each iteration the step size of the modification is increased and the direction is reversed. This method is robust since it does not become trapped with complicated streamline associations. This methodology is illustrated in Figure 4 with a complicated setting.

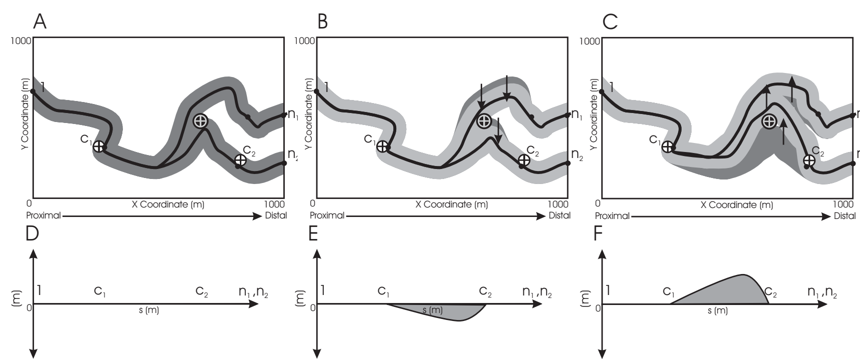

Figure 4. An illustration of the method for correcting streamline associations to remove unwarranted well intercepts. The two streamlines are related by avulsion in the streamline association and there are two previously conditioned locations (C_1 and C_2). A and D - the initial streamline association prior to correction. B and E - the first smooth modification (Oliver, 2002). C and F - the second iteration.

3.5 EXAMPLE CONDITIONAL EVENT-BASED MODELS

The ALLUVSIMCOND algorithm was applied to construct a conditional model. The streamlines include braided low to high sinuosity morphology. A single well is included with two CH′ element intervals identified. Cross sections and streamline plan sections of the prior and updated models are shown in Figure 5. The morphology of the streamlines is preserved while the well intercepts are honored.

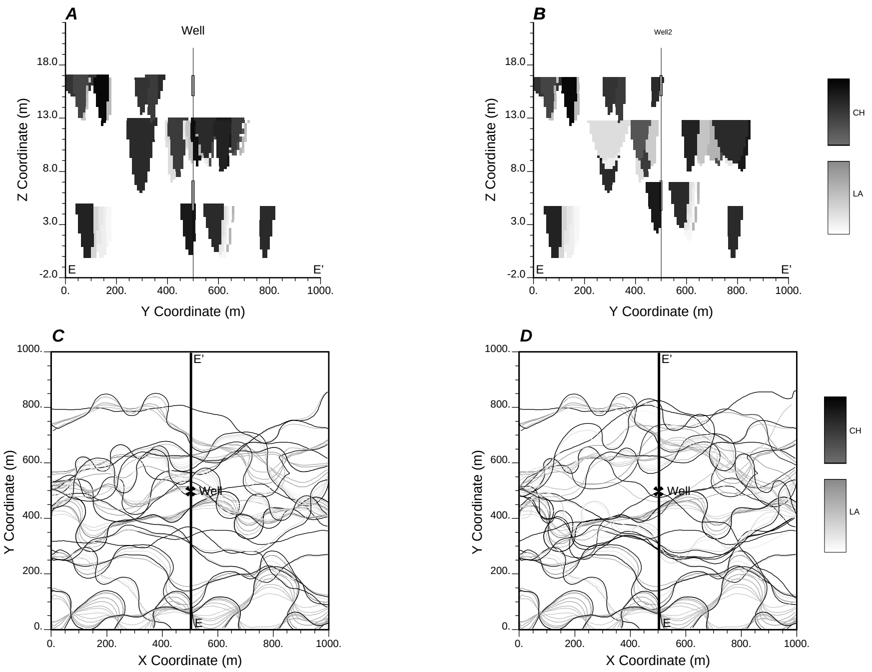

Figure 5. An example conditional event-based model from `ALLUVSIMCOND`. A and B - cross section of prior and updated model and C - D plan section of prior and updated model streamlines with cross section indicated.

4 Conclusions and Future Work

The event-based approach is a flexible and efficient tool for the construction of stochastic fluvial models. The building block approach allows for the modeling of a variety of fluvial reservoir styles, including the complicated architectures of CB type fluvial reservoirs. Event-based models may be constructed based on all available soft geologic information and then updated to honor hard well data.

Future implementation will address well observations of other architectural elements and the applications of the the event-based approach to a variety of depositional settings, such as deepwater (Pyrcz, 2004).

Acknowledgements

We would like to acknowledge the industry sponsors of the Centre for Computational Geostatistics at the University of Alberta and the National Science and Engineering Council of Canada for supporting this research.

References

Cojan, I. and Lopez, S., *Process-based Stochastic Modeling of Meandering Channelized Reservoirs*, AAPG Annual Meeting, Dallas, 2003, May

Cojan, I. and Fouche, O and Lopez, S., *Process-based Reservoir Modelling in the Example Meandering Channel*, Seventh International Geostatistics Congress, Banff, 2004 September

Collinson, J. D., *Alluvial Sediments*, *in* H. G. Reading, editor, *Sedimentary Environments: Processes, Facies and Stratigraphy*, Balckwell Science, 1996.

Deutsch, C. V. and Tran, T. T., *FLUVSIM: A Program for Object-Based Stochastic Modeling of Fluvial Depositional Systems*, Computers & Geosciences, vol. 28, 2002.

Ferguson, R. I., *Disturbed Periodic Model for River Meanders*, Earth Surface Processes, vol. 1, p. 337-347.

Galloway, W. E. and Hobday, D. K., *Terrigenous Clastic Depositional Systems*, Springer, 1997.

Howard, A. D., *Modeling Channel Migration and Floodplain Sedimentation in Meandering Streams*, *in* P. A. Carling and G. E. Petts, editor, *Lowland Floodplain Rivers*, John Wiley and Sons, 1992.

Jin, Y., Liu D. and Luo C., *Development of Daqing Oil Field by Waterflooding*, Journel Petroleum Technology, February, 1985, p. 269-274.

Lopez, S, Galli, A. and Cojan, I., *Fluvial Meandering Channelized Reservoirs: a Stochastic and Process-base Approach*, 2001 Annual Conference of the IAMG, International Association of Mathematical Geologists, Cancun, Mexico, 2001.

Miall, A. D., *The Geology of Fluvial Deposits*, Springer, 1996.

Mossop, G. D. and Flach, P. D., *Deep Channel Sedimentation in the Lower Cretaceous McMurray Formation*, Sedimentology, vol. 30, 1983, p. 493-509.

Oliver, D. S., *Conditioning Channel Meanders to Well Observations*, Mathematical Geology, vol. 34, 2002, p. 185-201.

Pyrcz, M. J. *Integration of Geologic Information into Geostatistical Models*, Ph. D. Thesis, University of Alberta, Edmonton, 2004.

Ren, W., Cunha, L. and Deutsch, C. V., *Preservation of Multiple Point Structure when Conditioning by Kriging*, Sixth International Geostatistics Congress, Banff, AB, 2004

Shmaryan, L. and Deutsch, C. V., *Object-Based Modeling of Fluvial/Deepwater Reservoirs with Fast Data Conditioning: Methodology and Case Studies*, SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers, Houston, TX, 1999.

Strebelle, S., *Conditional Simulation of Complex Geological Structures Using Multiple-Point Statistics*, Mathematical Geology, vol. 32, no. 9, 2002, p. 2937-2954.

Sun T., Meakin, P. and Josang, T., *A Simulation Model for Meandering Rivers*, Water Resources Research, vol. 32, no. 9, 1996, p. 2937-2954.

Tetzlaff, D. M., *Limits to the Predictive Ability of Dynamic Models the Simulation Clastic Sedimentation*, *in* T. A. Cross, editor, *Quantitative Dynamic Stratigraphy*, Prentice-Hall, 1990.

Thomas, R. G., Smith D. G., Wood, J. M., Visser, J., Calverley-Range, A. and Koster, E. H., *Inclined Heterolithic Stratification - Terminology, Description, Interpretation and Significance*, Sedimentary Geology, vol. 53, 1987, p. 123-179.

Viseur, S., Shtuka, A. and Mallet J. L., *New Fast, Stochastic, Boolean Simulation of Fluvial Deposits*, SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers, New Orleans, LA, 1998.

Wietzerbin, L. J. and Mallet J. L., *Parameterization of Complex 3D Heterogeneities: A New CAD Approach*, SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers, Houston, TX, 1993.