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Reservoir modeling with publicly available software☆

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Abstract

Numerical reservoir models are extensively used to determine in-place hydrocarbon resources and recoverable reserves. Geostatistical techniques are being increasingly used to construct such numerical models. The second edition of the GSLIB software together with other publicly available software provides the tools needed to construct realistic models of large and complex reservoirs.

This paper describes how to model lithofacies, porosity and permeability in sedimentary formations, particularly petroleum reservoirs, with publicly available software. Programs for postprocessing tasks such as scale up and management of multiple realizations are also presented. The relative merits of expensive commercial software are discussed. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Lithofacies modeling; Object-based modeling; Porosity; Permeability; Reservoir characterization; Scale up

1. Introduction

Numerical reservoir models have many uses. They provide a means to help understand the 3-D architecture of the reservoir for well placement and production development. Such reservoir models are also essential input to reservoir simulation, which is used for a variety of reservoir management tasks. Only large scale geologic features may be deterministically correlated with the available (usually sparse) well data. Most often there are reservoir heterogeneities that have an important effect on fluid flow, which cannot be modeled deterministically. This has led to an increasing application of geostatistical or stochastic methods for reservoir modeling.

This paper presents the essential methodology of reservoir modeling together with freeware/shareware for each step. The main steps of reservoir modeling are to (1) visualize the available data and prepare a stratigraphic framework for correlating lithofacies and petrophysical properties, (2) construct a lithofacies model that honors all hard and soft conditioning data, (3) fill each lithofacies type with porosity and permeability and (4) scale the detailed geological model to a resolution and appropriate format for flow simulation.

There are a number of commercial software packages available for reservoir modeling. These products are expensive (the ones with user support are between US$50,000.00 and US$100,000.00 per license). The cost is justified on the basis of the work effort to create and maintain the software combined with the relatively small market. The advantages of these products are (1) user support, training and regular upgrades are available through the vendor, (2) there are often seamless linkages from the raw seismic and geologic data through modeling to flow simulation and (3) the data visualization capabilities can be quite sophisticated. Notwithstanding these clear benefits, there are times when public domain software is suitable. The main reasons are cost, simplicity, flexibility, novelty and an audit trail.

The major energy producing companies of the world can easily afford such commercial software given the magnitude of their projects; however, the combined

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cost of the software, hardware (virtually all commercial software in this area is designed for high-end workstations), and support personnel is an impediment to many organizations. Regarding simplicity, commercial software often provides numerous options and capabilities not directly related to numerical reservoir modeling that make them difficult to use for straightforward reservoir modeling. Public software is often more compact and direct. Another advantage of public software is flexibility. The availability of source code allows the advanced user to easily implement a modification that permits better data integration or faster computation. Regarding novelty, universities and research institutions are regularly developing new algorithms that are not immediately implemented by commercial software vendors; often, such vendors will implement algorithms that have proven useful in public domain applications. Also, public software may be the only place to find new algorithms. Finally, the accessibility and ability to scrutinize the algorithms inside public software permits an audit trail that can be followed (or repeated with different modeling assumptions) by joint venture partners and other interested parties.

The techniques and software for each step is accessible in the published literature; however, there is no single paper or section in a book where they are described with attention to the specific software that could be used and the data transfer between steps (the paper Clayton (1995) describes some public software). All data files and noncommercial programs used in this paper are available by anonymous ftp from the Computers & Geosciences server, iamg.org.

Fig. 1 shows a common overall flowchart for geostatistical modeling. The first step *Establish Stratigraphic Layering/Coordinates* involves extensive work in defining the geometry and stratigraphy of the reservoir interval being modeled. This part of the work flow is largely outside the domain of geostatistics; however, some geostatistical tools are useful. The lithofacies (facies) are modeled by cell-based or object-based techniques within each stratigraphic interval. The porosity and permeability are then modeled with geostatistical methods for continuous variables.

A characterisitic of geostatistics is the ability to create multiple realizations by repeating the entire process with a different random number seed. Each realization is equally probable for the particular 'geostatistical model' being used.

There are a number of references on geostatistics and numerical modelling that may be helpful including Goovaerts (1997), Hohn (1988), Isaaks and Srivastava (1989) Journel and Huijbregts (1978) and Journel (1989).

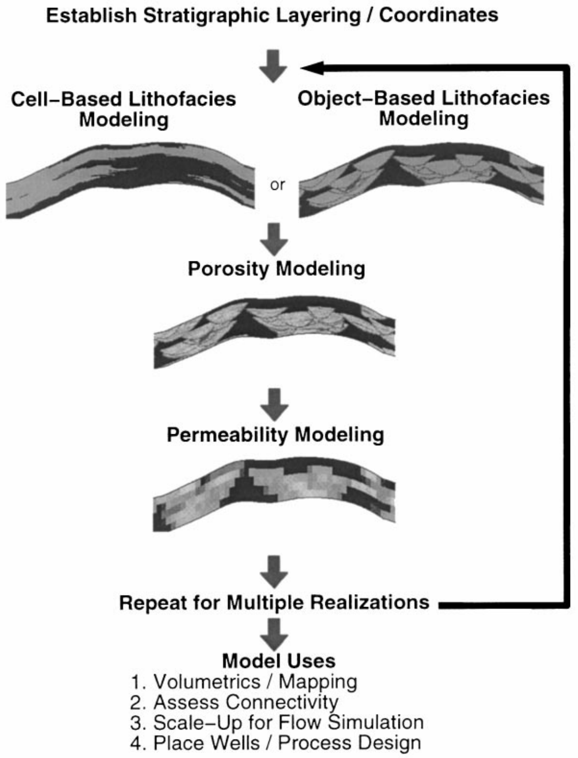

Fig. 1. High-level geostatistical reservoir-modeling flow chart: the structure and stratigraphy of each reservoir layer must be established, lithofacies modeled within each layer, and then porosity and permeability modeled within each lithofacies.

2. Data visualization/stratigraphic framework

It is important to understand the 3-D architecture of the reservoir and display graphics that aid the geologist in establishing the stratigraphic correlation structure. The stratigraphic correlation structure must be quantified by a series of structural grids defining (1) the existing layer structure, (2) restored stratigraphic surfaces for correlation and (3) fault surfaces.

Each stratigraphic layer is modeled independently with a relative stratigraphic coordinate derived from four stratigraphic grids (1) the existing top z_{et} (2) the existing base z_{eb} (3) the restored top z_{rt} and (4) the restored base z_{rb}

$$z_{\mathrm{rel}} = \frac{z - z_{\mathrm{rb}}}{z_{\mathrm{rt}} - z_{\mathrm{rb}}} \cdot T. \tag{1}$$

The coordinate z_{rel} is 0 at the stratigraphic base and T at the stratigraphic top. T is a thickness constant chosen to yield reasonable distance units for the z_{rel} coordinate; most commonly, T is the average thickness of the layer using the z_{et} and z_{eb} surface grids.

Fig. 2 shows a schematic illustration of this coordinate transformation with two wells. The numerical

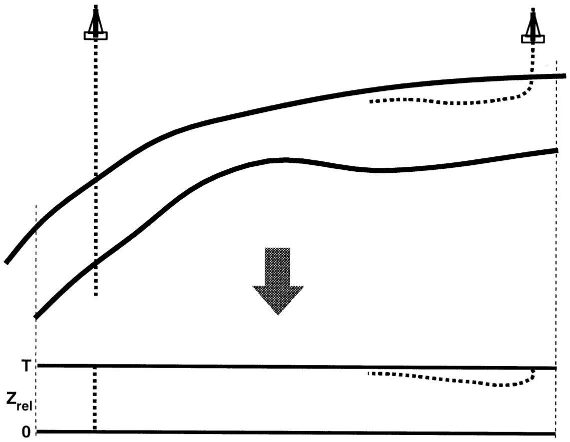

Fig. 2. Illustration of $z_{\rm rel}$ coordinate calculation for proportional stratigraphic correlation.

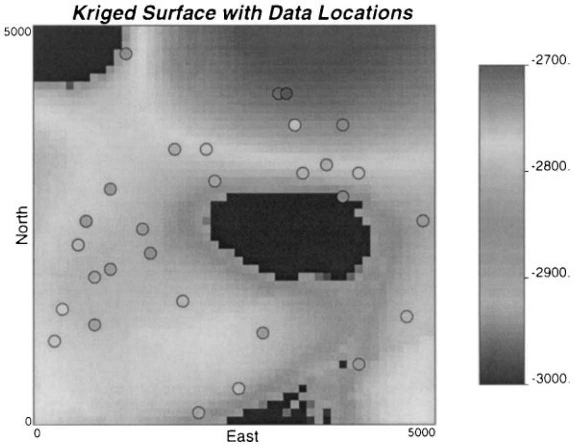

Fig. 3. Color scale map of kriged structural surface with well locations posted on map. Created by combining PostScript output of `pixelplt` and `locmap`. Negative kriging weights make it possible to estimate surface at lower elevations than smallest data value.

geological model is constructed with the $0 \rightarrow T$ vertical coordinate; the model can be back transformed and assembled into a final model for scale up and formatting (see later).

There is little software needed in this step; most of the work involves interpretation. Kriging can be used to create smooth elevation maps from available control points/wells. In particular, the GSLIB programs `kt3d/kb2d` (Deutsch and Journel, 1998) can be used to interpolate smoothly structural/stratigraphic surfaces and layer thickness or isochore maps. For such surface modelling, a 'default' variogram with a near-zero nugget effect (0.01% of the arbitrary sill for matrix stability), Gaussian shape (implying smooth variations), and long range ($\frac{1}{2}$ of the field size) works fine. One can impose geometric anisotropy to capture directional trends in the structure.

The GSLIB program `pixelplt` (Deutsch and Journel, 1998) can be used to display a 2-D surface (or a 2-D view through a 3-D model). The GSLIB program `locmap` can be used to post the data on areal maps or cross sections. These programs create maps at exactly the same scale; therefore, the data may be posted on top of the surface map. See Fig. 3 for an illustration of a surface and posted well locations.

The program `secview` creates a PostScript cross section through a set of stratigraphic surfaces. This program will display the gridding scheme or petrophysical properties. Fig. 4 shows example cross sections through a three-layer reservoir. The reservoir top is the left (western) edge of the grid shown on Fig. 3. A suitable number (say five) of cross sections in different directions provides a reasonable picture of spatial variations in the stratigraphic framework.

3. Data checking/facies selection

Reservoir volumes and dynamic performance call for a 3-D model of the spatial variations in porosity, permeability and saturation functions such as relative permeability and capillary pressure. The most important control on each of these petrophysical properties is the facies, or more correctly *lithofacies*, type. In some cases the variability in petrophysical properties is

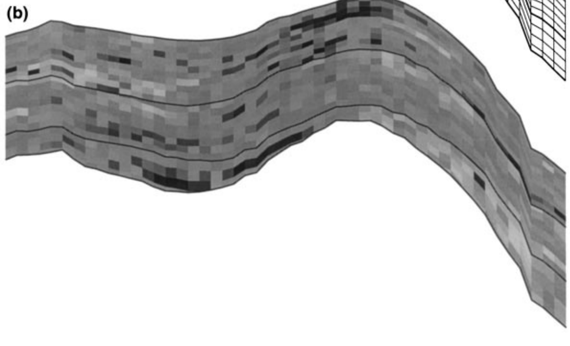

Fig. 4. Example output from `secview`: (a) gridding scheme-note 'erosion' at top of middle layer and 'onlap' at the bottom of bottom layer and (b) color coded according to petrophysical property such as porosity.

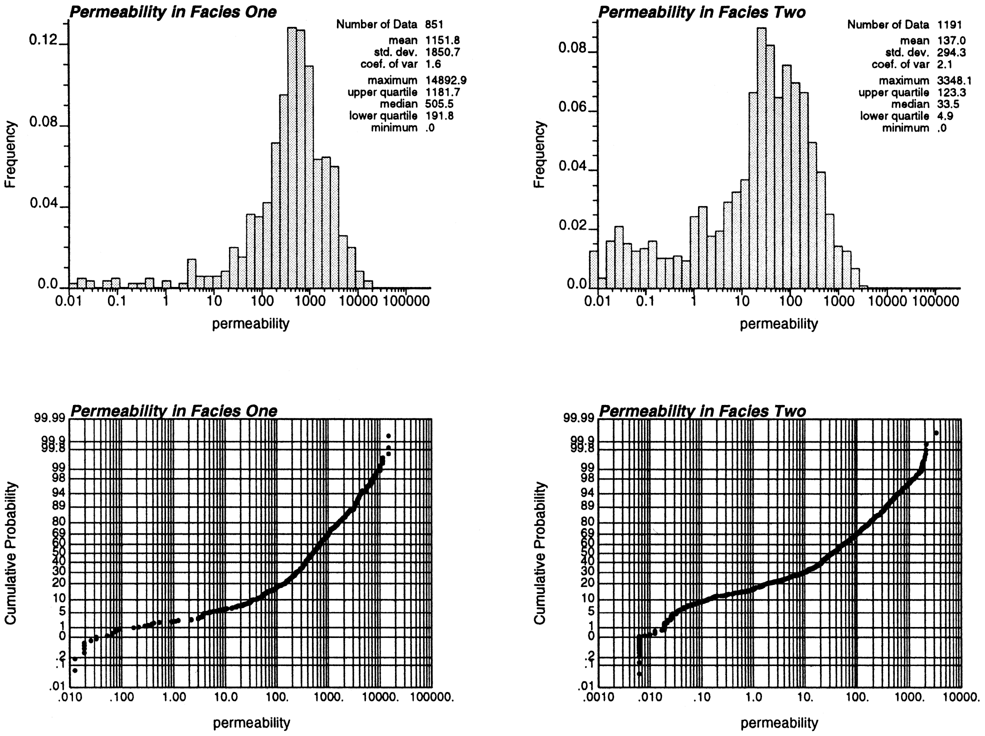

Fig. 5. Example histograms and probability plots for two facies types within same reservoir layer.

almost entirely *between* lithofacies and constant petrophysical properties can be used within each facies type. In other cases, there is significant overlap in the petrophysical properties between facies and it is necessary to model spatial variations in the continuous properties (porosity, permeability, ...) as well as the facies tpyes. Prior to facies/petrophysical modelling, basic statistical displays and summary statistics are used to identify problem data and to choose the optimal number of facies for detailed 3-D modelling.

Histograms and probability plots are essential statistical displays that are routinely used for understanding data better. Fig. 5 shows histograms and probability plots of permeability in two facies within the same reservoir layer. The `histplt` and `probplt` from GSLIB (Deutsch and Journel, 1998) were used for the displays. A cross plot of porosity and permeabilty, using the `scatplt` from GSLIB, is also useful to highlight the differences in properties between facies, see Fig. 6.

Other GSLIB programs such as `qpplt` can also be used to compare the distribution of properties in different facies types. Cross validation in an estimation or simulation mode can be carried out with the `kt3d` program for Gaussian methods, the `ik3d` program for indicator methods, and `sasim` for annealing methods. The program `accplt` (described in Appendix A and available with this paper) computes summary measures of accuracy, precision, and uncertainty. Alternative choices of facies separations, algorithms, or implementation options can be compared.

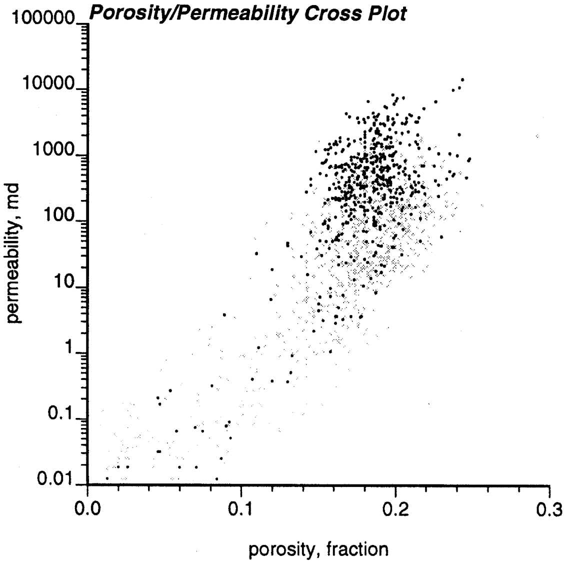

Fig. 6. Cross plot of permeability versus porosity for two facies types shown in Fig. 5.

4. Facies modeling

Geological rock types or *facies* must be modeled within the stratigraphic framework already established. There are two main approaches that people follow: (1) object-based whereby parametric objects are embedded within a 'matrix' facies type and (2) cell-based where the facies are assigned on a cell-by-cell basis statistically correlated with data and other cells.

The basic idea of placing geometric objects within a matrix is coded in the `ellipsim` program from GSLIB. This program, however, does not honor local conditioning data and only considers simple ellipsoidal shapes, which may be appropriate for remnant shales embedded within a sand matrix. In general, a different object-based program must be used for each depositional environment. Fluvial reservoirs have been the subject of much study because of their importance and the inadequacy of cell-based methods (see Bratvold et al., 1994; Gundesø and Egeland, 1990). The publicly available program `fluvsim` is available for object-based modeling of certain fluvial and deep water depositional settings (Deutsch and Wang, 1996; Deutsch and Tran, 1999).

A common approach to cell-based facies modelling is indicator simulation, as coded in the sisim program from GSLIB. This approach is particularly useful for situations when there is a significant diagenetic control on the facies, that is, the spatial distribution of facies is more 'stochastic' with little high order connectivity (see Alabert and Massonnat, 1990). Indicator simulation allows the construction of facies models that are constrained to indicator variograms, locally varying proportions of facies and, in special cases, locally varying directions of continuity.

Another approach to cell-based facies modelling is truncated Gaussian simulation, as coded in the `gtsim` program from GSLIB. The key idea is to simulate a continuous/Gaussian variable and then truncate it at various thresholds to construct a categorical facies model, see Matheron et al., 1987. In general, there is less flexibility than the indicator simulation methods since only one variogram (i.e. one degree of continuity) can be used for the underlying Gaussin variable. Truncated Gaussian presents a clear advantage when there is a natural nesting of the facies types. Indicator simulation cannot straightforwardly impose a specific ordering of facies whereas the truncated Gaussian *always* imposes an ordering of the facies.

The `pixelplt` program from GSLIB generates a gray or color scale 2-D slice through a 3-D facies (or continuous property) model. The 2-D slices must be aligned with one of the principle axes. This is not a consequential limitation since the stratigraphic coordinate transform, discussed above, removes the need for oblique sections. The publicly available `isoview` program (published for the first time with this paper) creates an isometric view of a 3-D model.

One characteristic feature of cell-based facies models is the presence of unwanted short scale spatial variations in the facies types. These variations are more often an artefact of the simulation program than a 'real' geological feature. Low-pass filtering them makes the result more aesthetically pleasing, improves the accuracy of scaled up block properties and improves the CPU performance of flow simulators by limiting high permeability contrasts. The publicly available `maps` program provides a flexible solution for image cleaning. The trans program in GSLIB is another alternative; however, it is only suited to binary systems (two facies types).

Fig. 7 shows some views, created with `isoview` and `pixelplt`, of object-based and cell-based facies models: (a) `fluvsim` object-based facies model, (b) horizontal slice through an sisim indicator simulation, (c) cross section through a facies model created by truncated Gaussian, `gtsim`, technique and (d) cross section through realization after 'cleaning' with maps.

5. Petrophysical property modeling

Continuous variables such as porosity and permeability are modeled within homogeneous facies types. In some cases it is acceptable to assign constant properties within certain facies, e.g. constant low porosity and permeability within shales. The assignment of spatially varying porosity and permeability is not critical when the facies have significantly different properties; however, in many cases there is significant overlap in the properties between facies. In such cases the spatial variations can be important.

Gaussian-based techniques for modelling spatial variations in continuous properties are widely used due to their simplicity and flexibility. The `sgsim` program from GSLIB is regarded as a 'workhorse' program for petrophysical property modeling. Some features of `sgsim` (or any comparable program) that are particularly useful: (1) the histogram and variogram of the Gaussian transform are honored by construction, (2) trends can be accounted for with locally varying means and (3) simple linear correlations with secondary variables, e.g. porosity/seismic or permeability/porosity can be accounted for with a form of cokriging.

Fig. 8 shows a Gaussian simulation of porosity in a system with three facies. This illustrates how, most often, continuous properties are put in different facies types with a 'template' approach.

Another class of techniques for continuous variable modelling is indicator techniques. The key feature of indicator techniques is that the range of variability is divided by a series of thresholds and estimation/simu-

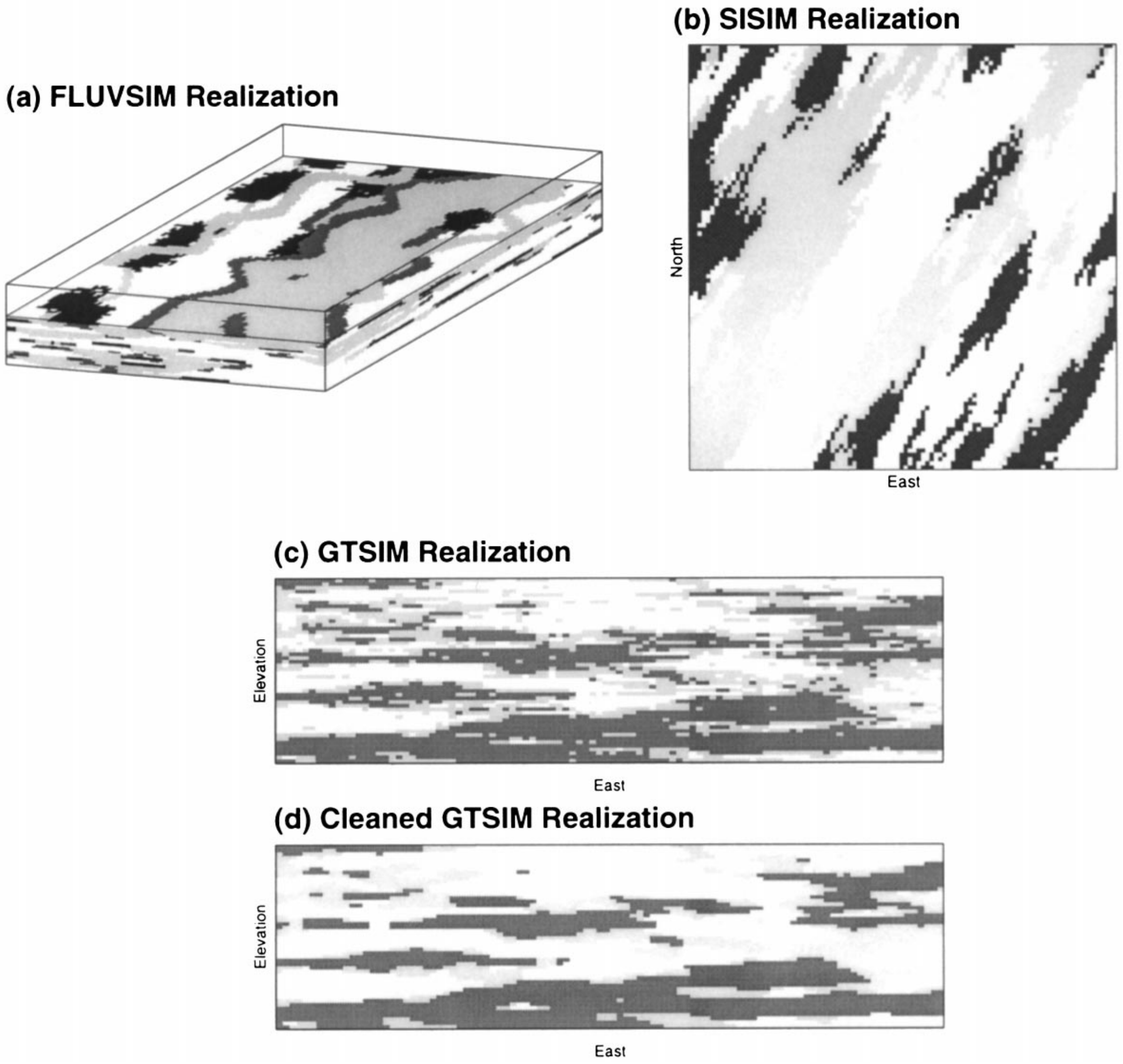

Fig. 7. Examples of facies modelling: (a) isometric view (generated with isoview) of fluvsim object-based facies model, (b) horizontal slice through sisim indicator simulation, (c) cross-section through facies model created by truncated Gaussian, gtsim, technique and (d) cross-section through realization after 'cleaning' with maps.

lation proceeds by considering the spatial patterns at each threshold in turn. The advantages of this approach are that (1) it is straightforward to consider different measures of variability (variograms) for extreme values and (2) it is also convenient to integrate soft secondary data that is not linearly related to the variable being considered. The sisim program in GSLIB implements indicator simulation.

A third class of techniques for continuous variable modelling is annealing-based methods, as coded in sasim from GSLIB. The essential feature of these techniques is considering the model-building problem as an optimization problem. The objective function is written to allow the integration of data not easily handled in conventional kriging-based simulation programs. While very powerful, the successful application of these methods depends on the delicate adjustment of a number of 'tuning parameters'.

6. Scale up/formatting/postprocessing

Geostatistical models are created at a higher resolution than is acceptable to most flow simulation programs. This discrepancy is not unusual because it (1) allows for small scale geological details to be accounted for in the reservoir model and (2) accounts, in some sense, for the discrepancy in scale between cores/logs and the geological modeling cell size. Programs are available to scale high resolution geosta-

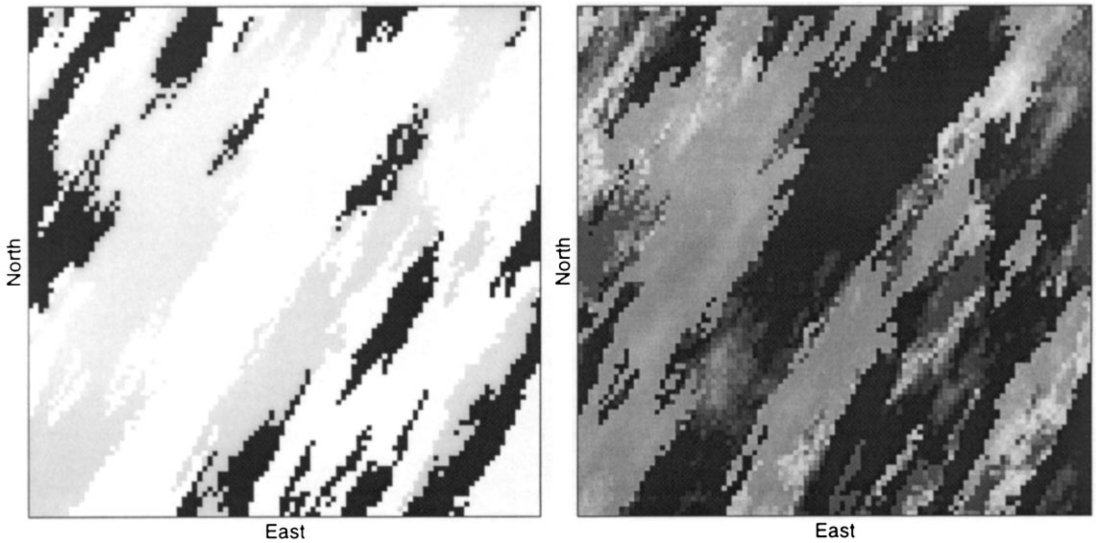

Fig. 8. Facies model and corresponding porosity model. Porosity values in each facies type were generated independently with `sgsim` program.

tistical models to coarse flow simulation models when the gridding is not too complex, e.g. regular Cartesian grids. Such code could be modified to account for local grid refinement and flexible grids.

Most often, scale up is performed separately within each major straigraphic layer. This allows the stratigraphic boundaries to be preserved in flow simulation. The program `flowsim` (published for the first time in this paper) is a program for flow-based scale-up of porosity and permeability within a stratigraphic layer. The problem amounts to taking a fine scale 3-D Cartesian grid of porosity/permeability and scaling it to a coarser 3-D Cartesian grids of effective properties. The arithmetic average is calculated for porosity scale up. The geometric and harmonic averages are also reported for effective permeability. The effective permeability in each direction is also calculated by solving the steady-state single-phase flow equations with no flow boundary conditions.

The simple ASCII input/output files may be reformatted for input to any public domain or commercial flow simulator. The `addcoord` program from GSLIB is a particularly useful starting point to work with the facies, porosity, and permeability grids created with the programs mentioned above.

3-D reservoir models are used for visualization, reservoir volume calculations and flow simulation. At times, it is convenient to calculate measures of connectivity to assist with well placement and ranking realizations. Ranking is used to limit the number of realizations used in full flow simulation, that is, the realizations are ordered from 'low' to 'high' on the basis of some measure of connectivity. This ranking allows fewer realizations such as a 'low', 'median' and 'high' realizations to be chosen. There are a number of public programs available for connectivity and ranking calculations. A program `geo_obj` is available to calculate the connected geo-objects from 3-D lithofacies, porosity and permeability models. Relevant summary statistics such as the number of geo-objects, their sizes and their tortuosities are reported. The connected volumes may be used for ranking geostatistical realizations; the program `rank_obj` is available for this purpose. It may also useful to rank realizations according to the connectivity to one particular location (e.g. a well location) or between two locations (e.g. injector–producer pair); programs `rank_loc` and `rank2loc` are available.

7. Conclusions

Reservoir modeling proceeds sequentially. One reservoir model is built at a time with a unique random number seed to create a family of multiple equiprobable stochastic reservoir models. Each major reservoir layer bounded by chronostratigraphic surfaces is modeled independently and then combined in a final reservoir model. Within a layer, the distribution of facies types is constructed to honor all available well and seismic data. Finally, within each facies type, porosity and permeability are modeled. Publicly available software has been presented for these tasks of reservoir modeling. These tasks are important and widely available in powerful commercial software solutions.

There are advantages to commercial products that make them attractive to the major energy producing companies of the world: (1) user support, training and maintenance/upgrades, (2) there are often seamless linkages of data along the workflow from raw seismic and geologic data through modeling to flow simulation and (3) the data visualization capabilities are more sophisticated. Notwithstanding these benefits there are reasons to consider publicly available software.

The obvious advantage of publicly available software is cost. The software can also be simpler to use since there is no cumbersome user interface designed around a large/complex package. The availability of source code permits flexibility and customization that is awkward with commercial software. The latest algorithms developed in academia are often available as publicly available software before incorporation in commercial products. A last advantage of publicly available software is the clear audit trail that it provides.

Appendix A. Software notes

The GSLIB software and documentation is available in the book by Deutsch and Journel, 1998. The software is also publicly available by anonymous ftp to `markov.stanford.edu`; however, the text cannot be made available electronically. Many of the supplementary programs used in this paper were written by the author and are available from the Computers & Geosciences server. These programs were written to 'look and feel' like GSLIB programs, i.e. they use the same data file format and run from a prepared parameter file. A short description of each program with some notes:

ACCPLT	takes the output of cross validation (`kt3d` for Gaussian methods, `ik3d` for indicator methods and `sasim` for annealing methods) and computes summary statistics and measures of accuracy, precision and uncertainty.
GEO_OBJ	calculates the connected 3-D regions/objects within a 3-D facies/petrophysical model.
ISOVIEW	creates a 3-D isometric block view of a 3-D facies or petrophysical property model.
FLOWSIM	scales up porosity and permeability from a geological grid to a coarser flow simulation grid. The effective permeability calculation is based on solution to the pressure equation with no flow boundary conditions.
FLUVSIM	creates an object-based model of a sinuous sand-filled channels, lobe shaped crevasse sands and levee sands in a channelized fluvial or deep water geological setting.
MAPS	removes short scale spatial variations from cell-based facies models, i.e. 'cleans' images. Often such short scale variations are unrealistic and increase the difficulty of flow simulation.
RANKOBJ	ranks realizations according to summary measures of geo-object connectivity, e.g. connected pore volume in largest connected region.
RANKLOC	ranks realizations according to connectivity to a well location(s).
RANK2LOC	ranks realizations according to connectivity *between* multiple well location(s).
SECVIEW	creates a PostScript file with a section through a series of stratigraphic layers. The user will need to extract the 1-D stratigraphic surfaces and 2-D property models from the respective 2-D and 3-D grids.

The only sure way to understand/debug these programs is to dig into the source code, which is provided. The source code also provides a starting point for custom programs that perform similar tasks.

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