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Compartmentalization Analysis using Discrete Fracture Network Models

Paul R. La Pointe*, Thorsten Eiben*, William Dershowitz*, Eugene Wadleigh*

* Golder Associates Inc., 4104 - 148th Ave. N.E., Redmond, WA, 98052

* Marathon Oil Company, Mid-Continent Region Production U.S., P.O. Box 552,
Midland, TX 79702

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ABSTRACT

This paper illustrates how Discrete Fracture Network (DFN) technology can serve as a basis for the calculation of reservoir engineering parameters for the development of fractured reservoirs. It describes the development of quantitative techniques for defining the geometry and volume of structurally controlled compartments. These techniques are based on a combination of stochastic geometry, computational geometry, and graph theory. The parameters addressed are compartment size, matrix block size and tributary drainage volume. The concept of DFN models is explained and methodologies to compute these parameters are demonstrated.

1. INTRODUCTION

In fractured reservoirs, the low permeability rock matrix holds the storage for the hydrocarbons while the high permeability fracture system provides the pathways to produce them. The amount of hydrocarbon that can be produced therefore is a function of the fracture network connectivity and geometry.

For fractured reservoirs the quantity and rate of fluid movement between the rock mass and a well often significantly departs from what a porous continuum model of the system might indicate (La Pointe and Dershowitz 1994). High initial production (IP) rates may drop dramatically over the first months of production. Estimates of recoverable hydrocarbons based upon dynamic and mass balance calculations may differ substantially. A key parameter in this context is reservoir compartmentalization, i.e. the division of the reservoir in not or only poorly connected regions. A petroleum reservoir that is compartmentalized either increases the cost of production or reduces the quantity of oil that is ultimately recovered. This economic cost has spawned renewed interest in understanding reservoir compartmentalization and methods to engineer compartmentalized reservoirs (e.g. Ortaleva, 1994).

Compartmentalization may arise due to a variety of structural and depositional geological processes (Ortaleva, 1994). One process which has not been well-studied but occurs widely is compartmentalization due to the finite extent of poorly connected fracture networks. One reason that this compartmentalization process has not been studied more thoroughly is that tools have only recently become available.

Recently, a new method to study flow and transport in fractured rock has evolved to the point that it provides a useful way to study fractured reservoir compartmentalization. This method is based upon Discrete Fracture Network (DFN) models. DFN models are three-dimensional stochastic or combined stochastic/deterministic realizations of the fractures in a rock mass. Fracture properties such as orientation, size, intensity, location and transmissivity can be conditioned to match either observed fracture statistics or structural models related to folding, faulting or in-situ stress.

The DOE/NIPER research project "*Fractured Reservoir Discrete Fracture Network Technologies*", undertaken by Golder Associates, Marathon Oil Co. and The Massachusetts Institute of Technology, will develop and demonstrate technologies for improving recovery from fractured oil reservoirs. The project focuses on applying DFN-technology to tertiary recovery processes. The research is designed to use information gathered during a field trial of Thermally-Assisted-Gravity-Segregation (TAGS) at the Yates field in West Texas.

This paper presents some preliminary results of this research showing how DFN models might be used for the analysis of reservoir compartmentalization.

2. DFN MODELS

DFN models, like all models, idealize the fracturing in a reservoir. While conventional dual-continuum models simplify fracture geometry in order to better model transient multiphase flow behavior, DFN models focus on realistic fracture geometries while simplifying the flow physics (Figure 1).

Each type of modeling strategy has its strengths and weaknesses, and there is some useful overlap in these modeling approaches. However, when fracture networks dominate rock mass permeability, DFN models will significantly out-perform conventional models based on effective continuum properties (La Pointe et al., 1996b). This is because network geometry and the connectivity structures that result control the scale at which wells can communicate with each other, how much matrix can be accessed by a well, and the rate of advective flow, mass transport and heat conduction. The effects of multiphase flow or other physical processes, though also important, are second-order effects for these applications.

DFN models are stochastic or a combination of deterministic and stochastic fractures. Large-scale faults are easily identified from seismic profiles, geological mapping, lineament analyses and well logs/core. These large-scale faults are either significant flow conduits or act as barriers due to stratigraphic offset or mineralization. Since large-scale

faults are known and because they are important, they are treated as deterministic features. This means that the DFN model will have each large-scale fault represented in the location that it occurs, and with the geometry and fluid flow characteristics that have been measured or inferred. Every stochastic realization of the entire DFN model will have these deterministic features whose properties will remain unchanged throughout all of the realizations.

However, there are many medium- and small-scale faults and joints that are not detected by seismic or remote sensing imagery, or encountered in wells. Yet these faults and large joints form important flow conduits through the rock mass. It is possible to derive statistical distributions necessary for the construction of DFN models for these smaller faults and joints, as detailed for example in Dershowitz et al. (1996). These fractures constitute the stochastic portion of the DFN model, since their locations, orientations, etc. are assigned as a random sample from the statistical distributions for each realization.

The statistical distributions of fracture properties may vary in different regions. Structural models abound that relate fracture intensity, orientation, permeability and location according to the structural geology of folds, faults or in-situ stress fields thought to have produced the fractures (e.g. Stearns 1971, Stearns and Friedman 1972, Suppe 1983, Mitra 1993). Advanced DFN modeling software (Dershowitz et al., 1996) incorporates this type of conditioning.

Because the resulting DFN models contain a stochastic component, it is possible to generate multiple statistical realizations of the faults and joints. These realizations can then be used to calculate the statistics for any parameter, such as compartment size and shape, and also to carry out sensitivity studies to determine what factors control compartment size. This makes the DFN approach particularly useful for economic decision analysis.

3. METHODOLOGIES FOR CALCULATING RESERVOIR ENGINEERING PARAMETERS FROM DISCRETE FRACTURE NETWORKS

Once a DFN realization has been created, the calculation of practical reservoir engineering parameters is a straightforward, although numerically sophisticated, process. First, it is necessary to determine which fractures intersect to form networks, and to determine whether these networks intersect a well. Elementary graph theory algorithms can be used to identify completely isolated fracture networks or networks that are weakly connected to other networks. This intersection information can be stored as either an *adjacency matrix* or an *adjacency list* (Sedgewick, 1990).

Based on the intersection information various parameters can be computed. In the current stage of the project there are three parameters calculated from the DFN model:

Compartment size is defined only by the fracture network geometry. It gives the oil in place which is associated with a connected fracture system. In combination with a recovery factor it can serve as a rough quantitative measure of how much oil or gas can be produced by a well.

Matrix block shape and size also is a purely geometrical parameter. It gives a measure of the typical undisturbed volume of rock matrix in a fractured reservoir. Fluid flow within such a block will be purely dependent upon the matrix properties.

Drainage volume is a more precise quantity and important for the ultimate recovery of hydrocarbon from a producing well and for the rate of movement and shape of the heat front during steam injection. It describes the estimated volume of matrix that a fracture system intersected by a well can access. The drainage volume therefore is related to both compartmentalization and matrix block size.

4. COMPARTMENT SIZE

4.1 EFFECT OF COMPARTMENTALIZATION ON FIELD DEVELOPMENT PLANNING

The "size" of a compartment formed by a fracture network may be defined in different ways, depending upon the reservoir engineering application. For example, the horizontal cross-section of each compartment relates to how efficient a particular well pattern will be in accessing potentially recoverable oil. The number of wells, representing an economic cost, needs to be balanced against the estimated ultimate recovery (EUR) that can be produced from those wells. If many compartments are missed by a proposed well pattern, then potentially recoverable hydrocarbons are being left in the ground. Alternatively, a well pattern that already produces from most of the reservoir compartments will not benefit from an infill drilling program.

Compartmentalization as it relates to economically efficient well patterns can be assessed by computing the horizontal dimensions and area of all of the fracture compartments in a series of DFN realizations. From these Monte Carlo realizations of a model, it is possible to compute a cumulative probability graph for compartment cross-sectional area. Such a graph provides an estimate of the mean acreage of the reservoir which a well could access. This acreage provides an indication whether a particular well pattern spacing will probably miss intersecting a number of compartments, whether each compartment is typically intersected by numerous wells (and thus may be economically inefficient), or whether the number of wells balances compartment access with drilling costs.

While it is usually possible to identify large-scale fault-bounded reservoir compartments from seismic or production histories, it is far more difficult to assess the compartmentalization due to joint network geometry and connectivity, for which seismic information is of little use. Joint network compartmentalization is often suspected when static and dynamic calculations of recoverable oil or gas do not agree, and there is no evidence for fault-offset or other types of fault-related compartmentalization.

Figures 2 and 3 illustrate the effect compartmentalization has on the connectivity within a reservoir. Figure 2 shows the DFN of a compartmentalized and intensively fractured rock mass. By looking at the figure one would expect all areas of the reservoir to be well connected. Figure 3, however, displays the same fracture network but only shows that portion of the network which is connected directly or indirectly to one of the 5 wells.

4.2 COMPARTMENTALIZATION ANALYSIS

The computation of the volume and horizontal extent of joint network compartments is a three-step process:

- Step 1. Identify individual fracture networks within the DFN model
- Step 2. Compute the bounding surface for each identified network
- Step 3. Calculate the volume within the bounding surface and the horizontal extent of the network

While it would be possible to compute the "bounding box" for a network, and use this box volume and horizontal cross-section as surrogates for compartment volume and horizontal extent, this would lead to an overestimation in most cases of both volume and cross-section. This in turn would produce overestimates of the ultimate recovery from wells, and suggest greater well spacings and recovery efficiencies than would actually be the case. To reduce the potential for overestimates, it is necessary to calculate a bounding surface that better approximates the outer limits of the network. A convex hull meets these requirements.

A convex hull is essentially a bounding surface with certain advantageous mathematical properties. For points with three-dimensional spatial coordinates, the convex hull is a convex polyhedron, which has the minimum volume of all possible convex polyhedra that bound the point set. Figure 4 shows such a three-dimensional convex hull calculated using the QuickHull algorithm and the Qhull software package (Barber et al., 1995) for the central well shown in Figure 3. In Figure 5, the horizontal projection of the hull is

shown. The resulting data can easily be used to compute the volume and cross-sectional area of each hull.

5. MATRIX BLOCK SIZE

The fracture surface area of matrix blocks within a simulation grid cell influences the rate and quantity of fluids that can move between the matrix and the fracture system. The Z-dimension of matrix blocks influences gravity drainage mechanisms. The shape of the matrix blocks influences the choice of sugar cube, matchstick or slab idealization. A realistic description of block size and shape in a way that can be implemented in existing dual porosity simulators will benefit not only the thermal simulation TAGS processes, but also non-thermal simulations of injection or production in fractured reservoirs.

5.1 BLOCK SIZE ANALYSIS

Two DFN algorithms have been developed to compute matrix block shape and size that are :

1. Based on geologically realistic three-dimensional fracture systems, and
2. Provide output in the form required by conventional dual-porosity simulators.

The first algorithm is a fast computational method to compute blocks based upon fracture spacing distributions in several directions. Its main advantage is that the calculation is computationally fast. Its disadvantage is that it assumes that block x, y and z dimensions are uncorrelated. This algorithm is referred to as the *multidirectional spacing distribution algorithm* (Figure 6).

For each realization of the discrete fracture model, a series of randomly-located lines in selected directions are generated. The location of fractures intersected by each line is recorded. This leads to a spacing frequency distribution in several directions. Typically, the directions include the vertical direction, in order to calculate the vertical dimension of blocks for gravity drainage considerations, and in two or three orthogonal directions that relate to simulator grid layering geometry and the fracture system.

The spacing probability distributions are multiplied together using Monte Carlo sampling techniques to produce a frequency distribution of block volumes and surface areas. This is carried out by selecting X, Y and Z spacing values at random with selection probability proportional to their frequency, and multiplying them together to create a prismatic block volume.

The second algorithm is based upon graph theory and, again, uses convex hulls. This algorithm is therefore referred to as the *convex hull algorithm*. It is based upon computing the convex hull of points lying on fractures bounding or partially bounding a matrix block.

The convex hull algorithm is more computationally intensive, but measures the actual dimensions of the blocks, rather than reconstructing blocks stochastically from spacing frequencies. Thus, any correlation among block dimensions or non-prismatic block shapes are considered appropriately. The algorithm's accuracy is governed by two factors: whether in fact the matrix blocks are convex; and how many points are required to accurately characterize the convex block. The algorithm as implemented allows the user to specify the number of points for characterizing the convex block.

Test cases (La Pointe et al., 1996b) suggest that both the multi directional spacing (MDS) and convex hull (CH) algorithms provide reliable and consistent estimates of fracture surface area, at least for simple fracture geometries. The CH algorithm appears to provide better estimates of the mean volume of matrix blocks when block dimensions are partially correlated. Since jointing in many sedimentary rocks is characterized by pseudo-periodic spacings (e.g., La Pointe and Hudson, 1985), it may be preferable to use the CH algorithm to estimate block volumes. On the other hand, the geometric construction of a convex hull from a sparse data set creates hulls with slightly greater average Z-dimensions than the MDS algorithm. In both test cases 1 and 2, the MDS algorithm provided more accurate estimates of the Z-dimension. Thus, both algorithms have proven useful and necessary to provide estimates of matrix block parameters, and neither alone is completely satisfactory.

6. DRAINAGE VOLUME

The tributary drainage volume for a well is that volume of the matrix that can be drained by the fracture network connected to a well or heated up by steam injection. The drainage volume takes into account both the geometry of the fracture network and the physical processes of advective flow, transport, diffusion and heat conduction. Tributary drainage volume is related to both block size and compartmentalization.

6.1 DRAINAGE VOLUME ANALYSIS

The algorithm developed to compute the tributary drainage volume is divided into two steps:

Step 1. Identify the fracture networks connected to the well or perforated zone of interest

Step 2. Estimate the volume of matrix within the network that could be produced

While the procedure for step 1 is the same as for the compartmentalization analysis, step 2 can become extremely complex. The task is to predict which portion of the matrix volume is close enough to a fracture, given the pressure drawdown within the matrix block, to be able to contribute to production.

Different ways could be used to accomplish step 2. If the fracture network is very dense, then the volume of the matrix accessed by the fracture network will be closely approximated by the volume of the convex hull enclosing the network. In essence, this means that the tributary drainage volume is equal to the compartment volume. The same conclusion applies if the matrix permeability is sufficiently large to allow production to take place from all of the matrix volume.

In less dense fracture networks where the typical matrix block size is large, some or maybe most of the volume inside the convex hull will be too far from any of the fractures to be easily produced. For these cases, the user can specify an average drainage percentage. It is possible to compute this percentage with the help of the blocksize information

derived earlier. The average drainage percentage is then used to reduce the convex hull volume.

Another approach to exclude matrix that might not be efficiently produced through pressure depletion drainage is to surround each fracture in the network with a polygon that is calculated from the area of the fracture and the distance away from the fracture over which drainage might be effective (Figure 7). This leads to a prism that encloses the fracture. For pressure depletion mechanisms, the fracture forms the midplane of the prism. An obvious problem with this algorithm is to avoid double-counting the volume where there is overlap between the prisms. Calculations based upon solid geometry to compute the volume while accounting for the overlap are highly time-consuming for the number of fractures that might commonly be encountered in a fracture network. A simpler method has been devised which is much more efficient, though not as numerically exact (La Pointe et al. 1996b).

Computing the drainage volume is a critical reservoir engineering parameter. For computing the ultimate recovery, it is necessary to combine the static parameters like compartment volume and block size with the dynamics involved in the flow of fluids from the matrix into the fracture system. Because of the time dependent pressure distribution within a matrix block the drainage volume will also be time dependent. This corresponds to the step from volumetric oil in place estimation to dynamic ultimate recovery calculation using reservoir simulation.

Nonetheless, the measures described above will provide an estimate of the recoverable reserves from a reservoir. They offer an advantage, however, that a large number of realizations can be run, and so the uncertainty relating to simplification can be quantified in a clear and straightforward manner. The alternative of carrying out hundreds of numerical fluid flow simulations requires substantially greater, and perhaps prohibitive, computing times.

7. SUMMARY AND OUTLOOK

The ongoing DOE/NIPER research project "*Fractured Reservoir Discrete Fracture Network Technologies*" is developing technologies for improving recovery from fractured oil reservoirs. This paper illustrates some preliminary results of this effort. The work thus far has concentrated on the development of methodologies and algorithms which can be used to extract valuable parameters from fracture network information for the use in reservoir engineering tasks. It has been shown how Discrete Fracture Network models can be used to calculate parameters like compartment size, matrix block size and tributary drainage volume.

At the time of the submission of this paper, the methods described are undergoing an intense verification process (La Pointe et al. 1996b). In the next step, the methods will be used on field data from the Yates field.

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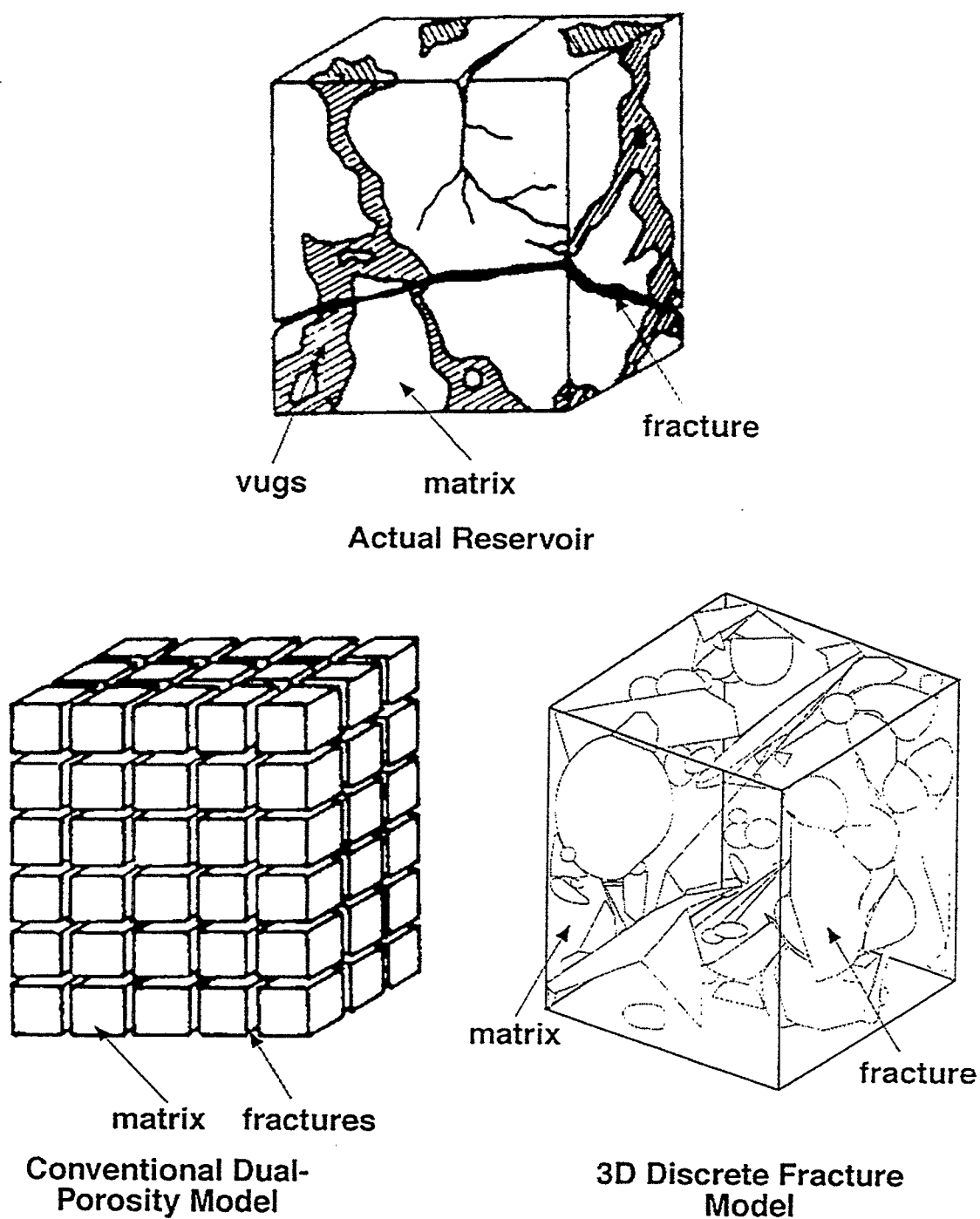


Fig. 1: Discrete Fracture Network model approach for a fractured rock mass

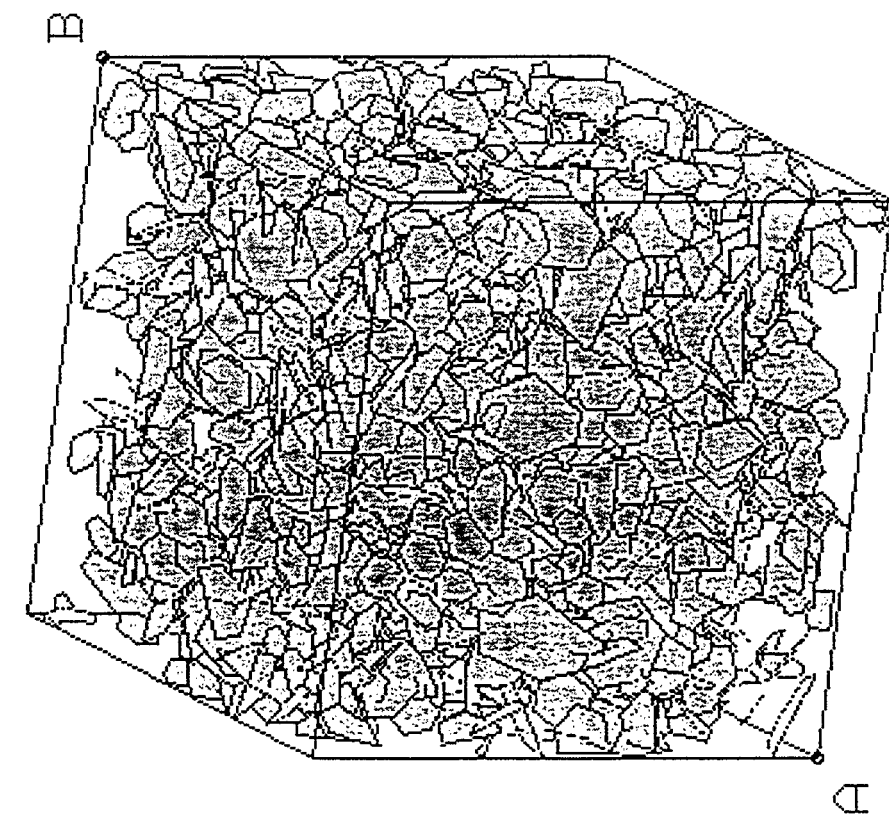


Fig. 2: DFN model of compartmentalized intensively fractured
rock mass

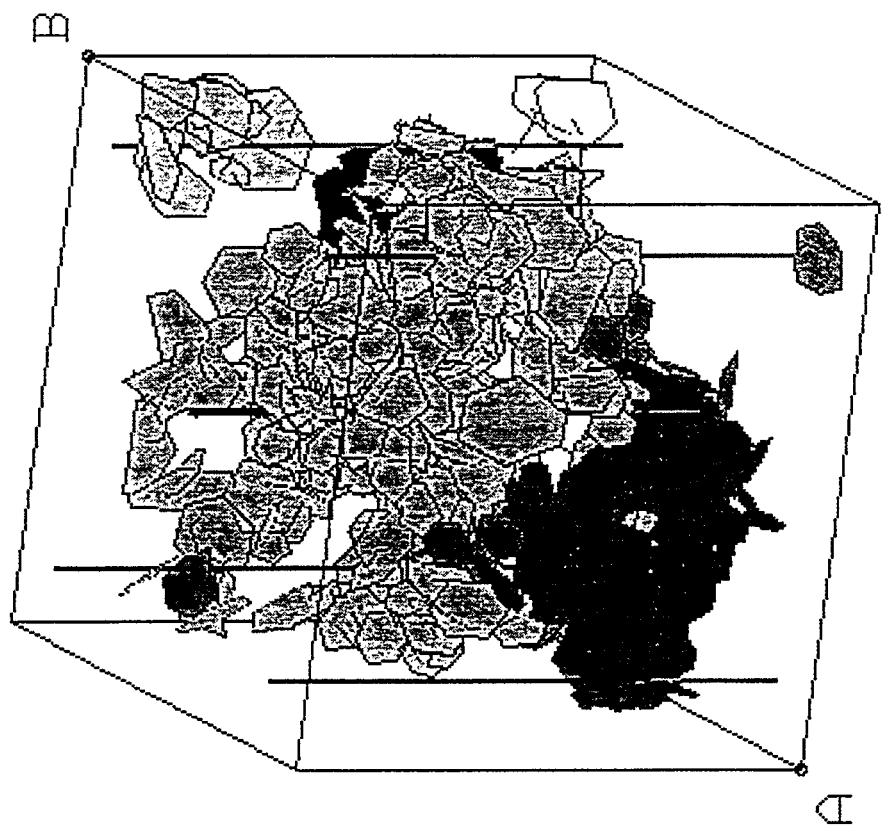


Fig. 3: Production from compartmentalized intensively frac-
tured reservoir

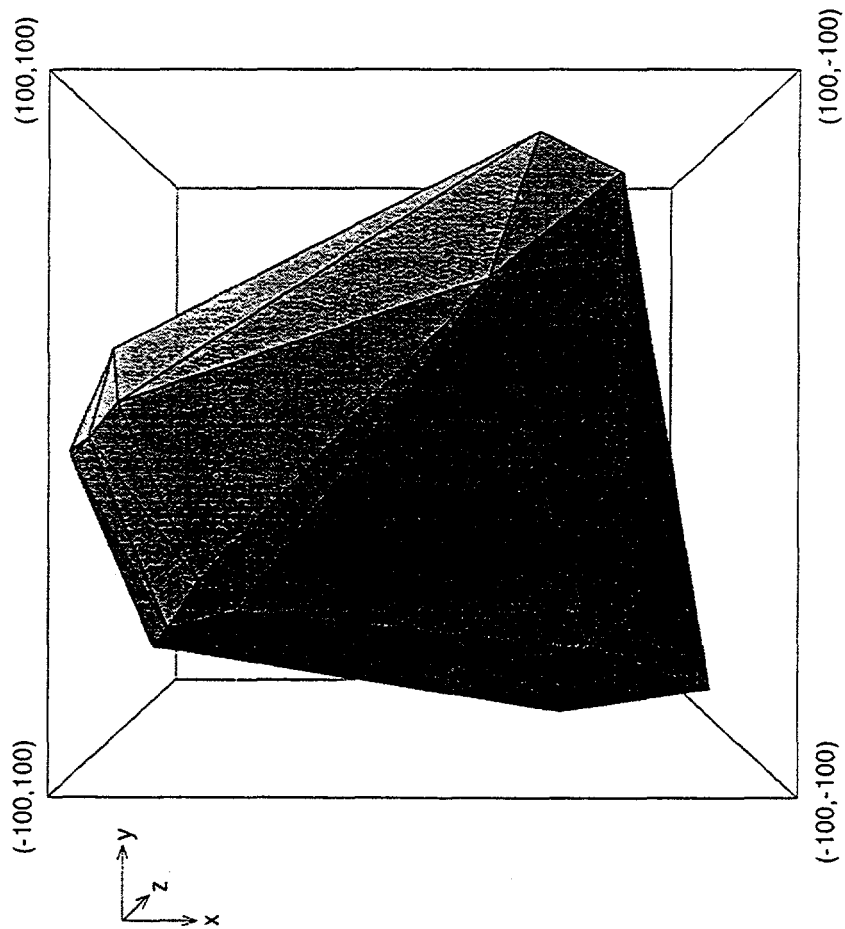


Fig. 4: Convex hull of fracture network connected to center well

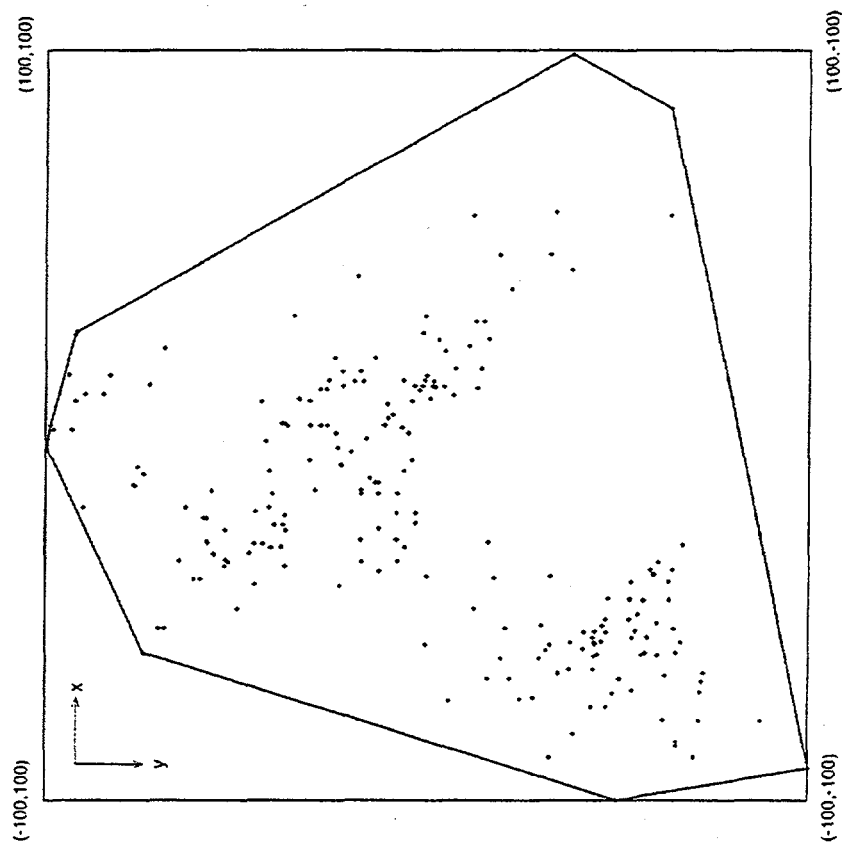


Fig. 5: Horizontal projection of convex hull connected to center well

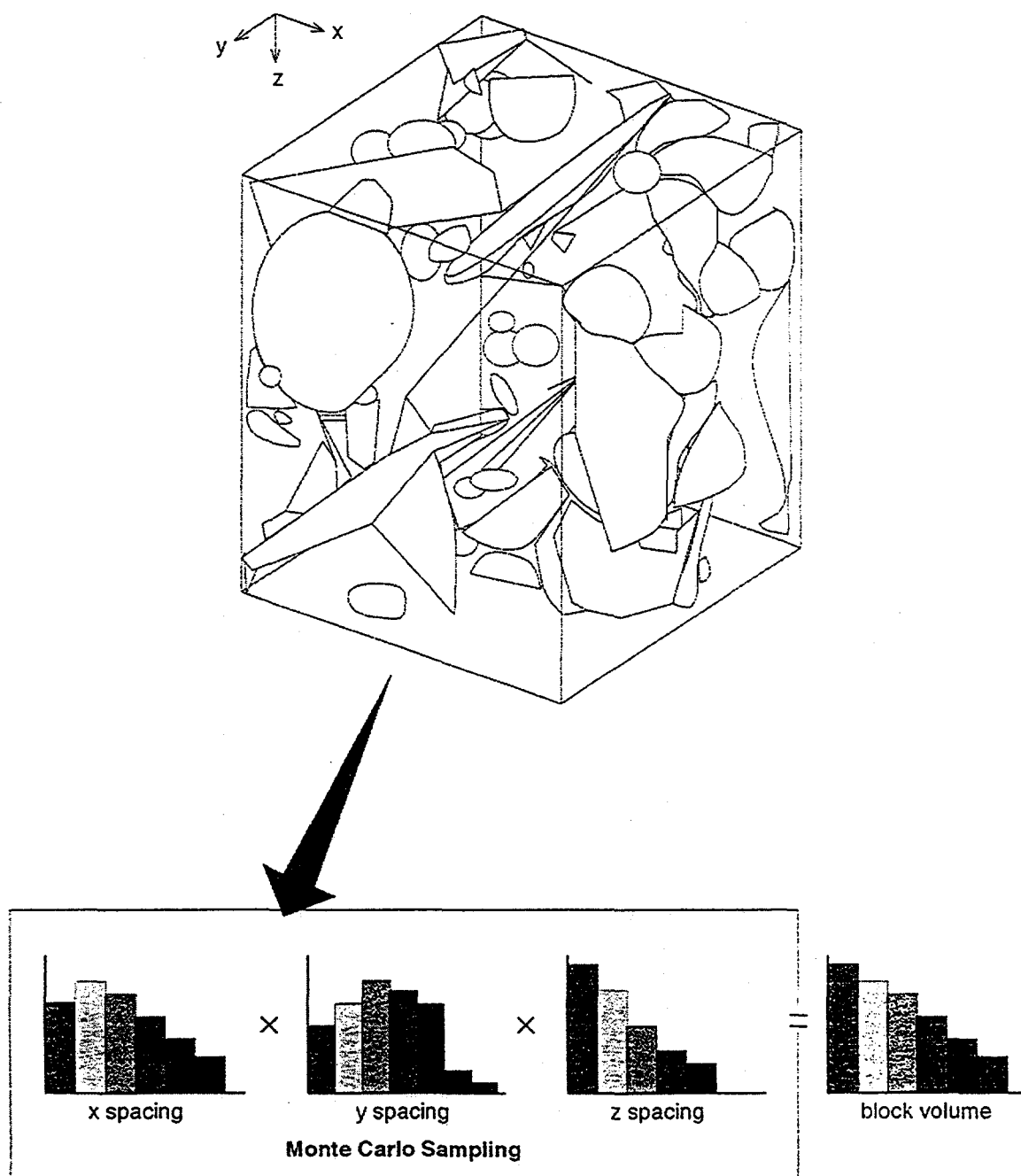


Fig. 6: Multi-Directional Spacing Algorithm