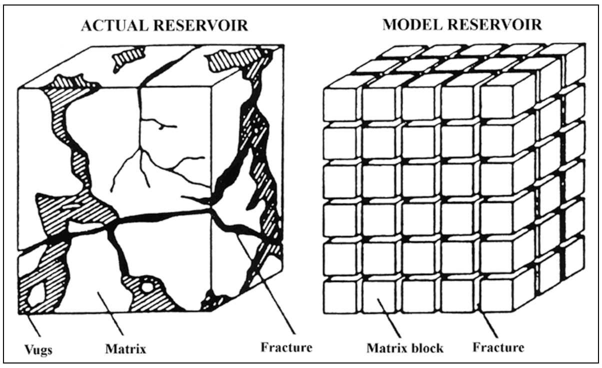
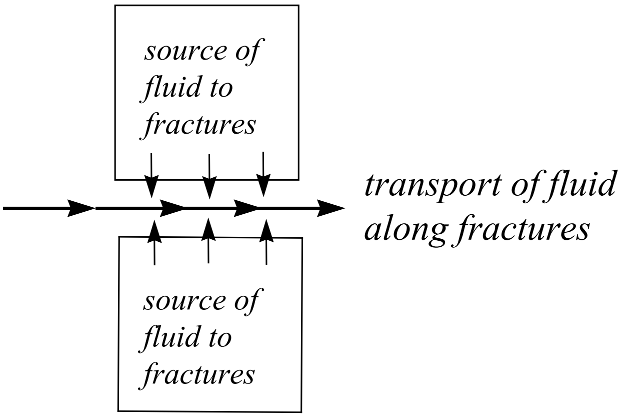
INTRODUCTION TO FRACTURED RESERVOIR SIMULATION

Based on the theory of fluid flow in fractured porous media developed in the 1960's by Barrenblatt *et al.*, Warren and Root introduced the concept of dual-porosity models into petroleum reservoir engineering. Their idealized model of a highly interconnected set of fractures which is supplied by fluids from numerous small matrix blocks, is shown below.



In the North Sea, the Ekofisk Area contains several fractured reservoirs. Ekofisk itself is highly fractured, and Phillips Petroleum estimates that the average matrix bloc size is 30 cm by 30 cm by 30 cm. Thus, the Ekofisk reservoir may contain in the order of 10^{11} grid blocks (!), and it is of course impossible with current computers to model each matrix block and its interaction with fractures individually. Hence the need for dual porosity models.

In a conventional dual porosity model, the main transport of fluids takes place through the fractures, while the matrix blocks supply the fluids to the fractures. This is illustrated below.



In one dimension, and for one phase flow, the equation for flow along the fracture system may be written as

$$\frac{\partial}{\partial x}\left(\frac{k}{\mu B}\frac{\partial P}{\partial x}\right)_f + q'_{mf} = \frac{\partial}{\partial t}\left(\frac{\phi}{B}\right)_f$$

Here, the index *f* is used to denote fracture system. Thus, the permeability and porosity represent relative values for the combined matrix block-fracture system. The flow term in the equation, q_{mf}, represents the fluid exchange between matrix blocks and fracture system. We may also write an equation for the matrix block system, as

$$-q'_{mf} = \frac{\partial}{\partial t}\left(\frac{\phi}{B}\right)_m .$$

This equation is really only a material balance equation, since there is no flow term included. The nature of this flow term will of course be process dependent. In multi-phase flow, the rate of exchange under capillary imbibition will, for example, be completely different from the rate of fluid exchange under gravity drainage. Conventional dual porosity models represents the exchange term by

$$-q'_{mf} = \sigma\lambda\left(P_m - P_f\right)$$

where σ is a geometric factor, λ is the mobility term, and P_m and P_f represent matrix and fracture pressures, respectively.

The assumption of no fluid flow between matrix blocks may be questioned, and therefore the dual porosity, dual permeability model is preferred:

$$\frac{\partial}{\partial x}\left(\frac{k}{\mu B}\frac{\partial P}{\partial x}\right)_f + q'_{mf} = \frac{\partial}{\partial t}\left(\frac{\phi}{B}\right)_f$$

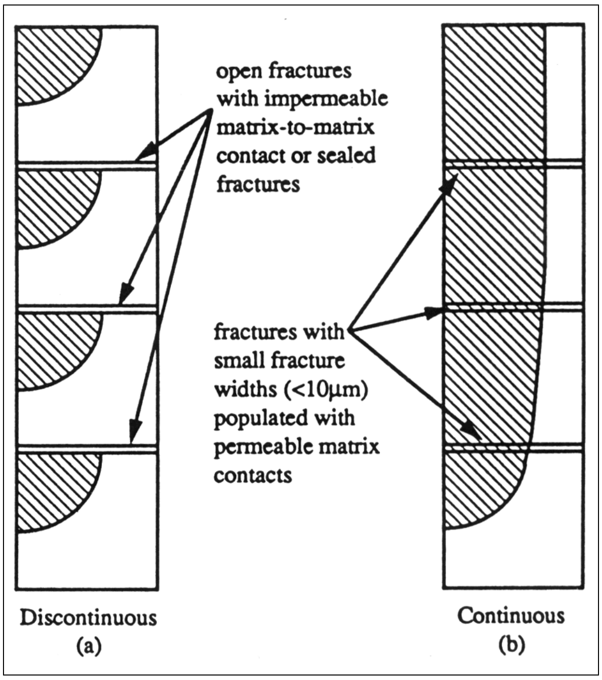
$$\frac{\partial}{\partial x}\left(\frac{k}{\mu B}\frac{\partial P}{\partial x}\right)_m - q'_{mf} = \frac{\partial}{\partial t}\left(\frac{\phi}{B}\right)_m$$

Here, a flow term is included on the left side of the matrix block equation, allowing direct transport within the matrix block system itself.

With the basic concepts and equations stated above, we will not discuss equations in detail. However, in order to understand the physics of fractured reservoir flow, we will discuss some of the key mechanisms that are particularly important in fractured reservoirs.

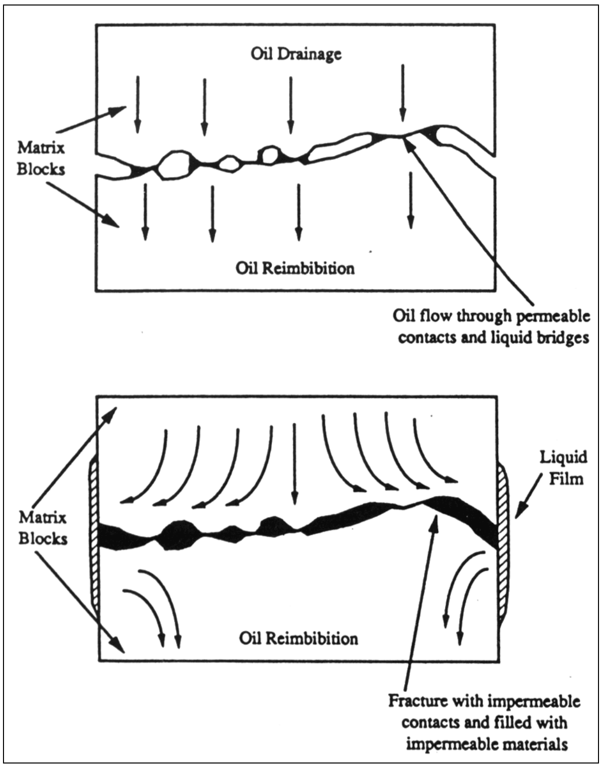
The concept of ***capillary continuity*** between matrix blocks in fractured reservoirs is now widely accepted. A schematic comparison of capillary-gravity dominated saturation distributions for a discontinuous system and a system with capillary contact between matrix blocks is shown below. However, the discontinuous concept is still being used in most commercial dual-porosity models to handle block to block interactions.

Several authors have presented simulation results where the fracture system allowed for various degrees of matrix to matrix contact. Their results show dramatically higher recoveries for capillary continuous systems compared to discontinuous ones.



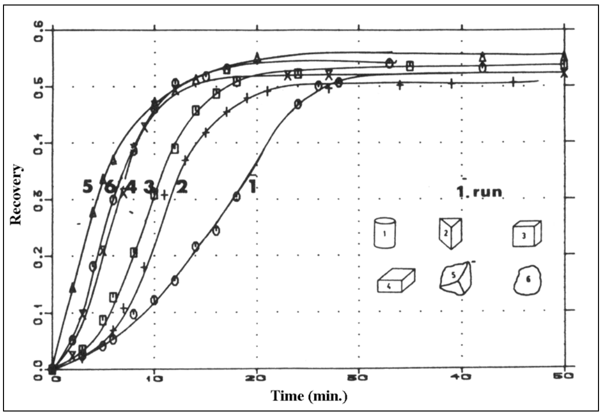
An important aspect in gas-oil gravity drainage of fractured reservoirs is the process of ***re-infiltration***. When drained oil from an upper matrix block enters into a matrix block underneath, the process is called reinfiltration.

The flow from one block to another (reinfiltration) is either achieved by 1) film flow across contact points or 2) by liquid bridges. This liquid transmissibility across the fracture is therefore an important parameter for calculating the rate of drainage of a stack of matrix blocks. The figure below illustrates the contact points and the liquid bridges:



Oil may be recovered by ***diffusion*** during gravity drainage in fractured reservoirs. Methods for estimating the amount and rate of this recovery in such reservoir processes are in early stages of development and poorly tested. It is very limited published data against which theories and prediction methods can be tested adequately. The effects of diffusion on overall recovery can for most systems be neglected for practical purposes. However, for small matrix blocks, diffusion may be the key mechanism for oil recovery.

The ***shape and size of matrix blocks*** will strongly affect the matrix-fracture fluid exchange process. Torsæter and Silseth conducted water imbibition experiments on chalk and sandstone cores of different shapes and sizes, and typical results are presented in the figure below. Obviously, within a gridblock of a dual-porosity simulation model, matrix blocks of varying shape and size will exist.



Several authors have reported simulation studies for the purpose of matching results of laboratory experiments. Such matching of experimental results is not trivial, the outcome of the simulations is very sensitive to the shape and magnitude of the capillary pressure curve.

A major cause of the difficulties reproducing experimental results is probably that the capillary pressure and relative permeability curves used in the simulations were measured at flow conditions different from those of the experiments. An important issue to be addressed in fractured reservoir simulations is the one of ***co-current vs. counter-current flow***.

The above discussion of physics of fluid flow in fractured reservoirs is included in order to stress the uncertainties involved in fractured reservoir simulation. Current models are not very representative of the processes taking place.