UPSCALING PERMEABILITY

by
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ABSTRACT

In reservoir simulation, the engineer needs a set of permeability values estimated on grid block which are as representative as possible of the true value. However, the sample data is limited to small scale measurement relative to the scale of reservoir simulation. Therefore, we need to upscale the permeability data measurement by averaging permeability on volumes. Prior to obtain the appropriate averaging method, an upscaling experiment was performed. The averaging method at the plug scale can be specified from the probe data and the Hassler cube data, by comparison.

I. INTRODUCTION

Reservoir simulation is widely used in the oil industry for planning and monitoring the development of oil and gas fields. The main purpose of reservoir simulation is to predict the production rate which will correspond to different methods of operation. A mathematical model is run on a grid of block values. It is important to provide the simulation model a set of grids which are as representative as possible of the true values of the petro- physical parameter. It is meaningless to run a very sophisticated numerical model on grid models which are not representative of the true values.

However, the sample information is limited to a small scale measurement relative to the scale of reservoir simulation. Therefore, we need to scale-up the petrophysical measurement. Statistical and geological techniques are used to extrapolate the limited data set over the remaining reservoir value. The effectiveness of averaging and extrapolation techniques depends on the sample support. The sample support, or the data employed in upscaling, should be of an appropriate volume to provide local homogeneity and local stationarity to satisfy the geostatistical criteria. These conditions are also important for use in a finite difference simulator. Averaging or upscaling should be performed over representative data. Permeability is an important factor in rock properties, since it is related to flow and an intensive variable. Because of this character, permeability is a more difficult property to find representative for upscaling and only a few guidelines are available.

Dependant on the scale of the simulator grid blocks, it is very likely (in real rocks) that heterogeneities occur at a scale significantly smaller than grid blocks (e.g., in laminated sediments over 1 cm or less). Therefore, average or effective properties are required. In this case the geologist must describe the scale lengths and magnitude of the variability (depositionally and/or diagenetically, as required for the analogue) with sufficient samples of an appropriate size and spacing. Understanding the relationship of variability to permeability structure (e.g., laminated or nodular) will indicate the appropriate averaging procedure. This can be achieved by the use of statistics if flow of a single fluid phase is required. Numerical simulation is required to derive the two-or more-phase average properties. In this paper, we demonstrate the method in quantifying the upscaling process and to obtain the appropriate averaging method. The averaging method at the plug scale can be specified from the probe data and the Hassler cube data, by comparison.

II. SAMPLE SUPPORT PROBLEM

In engineering and geology, the microstructure (lamination) might be important and therefore needs to be captured. The complex microstructure in sedimentary rock might cause significant variability in measurement. In the terminology of geostatistics, this is a classic problem of insufficient sample support, producing artificially heightened variance over small spatial scales as a result of a sampling volume that is too small. Therefore, the measurement should be taken at a scale large enough to encompass a representative elementary volume (REV).

Then the high variability will be reduced that means homogeneity and stationarity condition can be achieved, and the sample support problem can be handled.

The support and stationarity conditions are also important in a finite difference simulator where, to avoid numerical problems, adjacent grid block values should not have major contrasts. Averaging or upscaling should also be performed from data at representative volumes. The Representative Elementary Volume (REV) is the fundamental support volume for measurement, simulation, and averaging.

A. *Representative Elementary Volume*

The Representative Elementary Volume should be smaller than the entire flow domain, but it should be larger than the size of single pores, since volumes much larger than unit cell are required for the volume to have representative physical properties (Bear,1972). The volume of REV is not a necessary constant within or between reservoir rock. The volume will vary from place to place, because of the variability of grain size, progression of bedforms, and discontinuities in reservoir rock.

When a porous medium is heterogeneous with, for example, permeability varying in space, the upper limit of the length dimension of the REV should be a characteristic length that indicates the rate at which change in permeability take place. The lower limit is related to the size of the pores or the grains.

Bear (1968) defined the REV based on a continuum approach. The REV can be illustrated in Figure 1. Let P be a mathematical point inside the domain occupied by the porous medium. Consider a volume DUi (having the shape of a sphere) much larger than a single pore or grain, for which P is the centroid. Below a certain value of DUi, depending on the distance of P from boundaries of heterogeneity, these changes or fluctuation tend to decay.

III. THE UPSCALING EXPERIMENT

The upscaling experiment was performed to investigate the method of upscaling permeability. In this experiment, the results from probe permeameter experiments are compared with results from Hassler-sleeve cube experiments to check internal consistency within the permeability data at different scales. The method of permeability measurement is discussed in Appendix A.

Different samples from those described above were used for a set of upscaling experiments. The samples were different because of practical issues associated with the sample preparation –size and competency of the samples. The samples were first cut into rectangular blocks, then the probe permeameter experiment was carried out on each side of the block (using two tips – the small and the large). The blocks were cut orthogonal to bedding, where bedding could be detected. After the probe experiment, the sample blocks were cut into cubes with 1.9 x 1.9 x 1.9 cm dimensions (see Figure 2). The permeability of cubes (horizontal and vertical) was measured by the Hassler-sleeve steady state permea-meter.

The following samples were used for the upscaling experiments:

- Sample A: an outcrop sample, the sample can be described as gray, tight, wackestone or packestone with small vugs. Allochems include ooids and bioclasts.

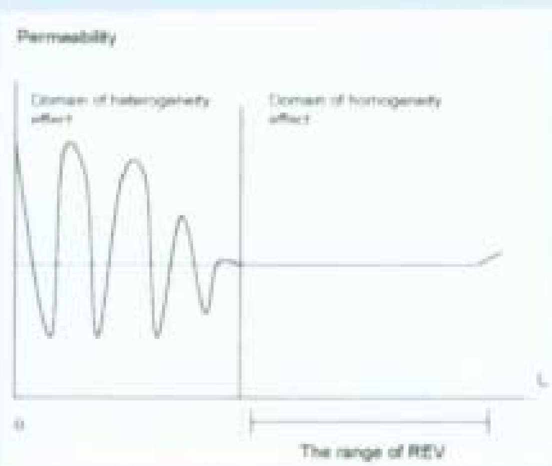

Figure 1
The representative elementary volume concept

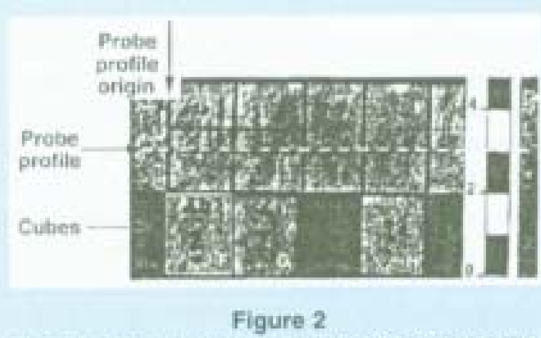

Figure 2
The location of cubes and probe permeability profiles for the upscaling experiments.

Dolomite replaced the micrite matrix, then dissolution of bioclasts yielded moldic porosity. Further dissolution of moldic porosity in both wackestone and packestone created the isolated vuggy pores.

- Sample B: generally, the sample is described as massive, light coloured, fine and rounded grainstone, with small vugs and fractures. Thin section analyses indicate intergranular and intraparticle porosity within foraminifera.
- Sample C: the sample is described as fine-medium grainstone, brown colour, dolomitised, stratified with small vugs.
- Sample D: the sample can be described as a very fine grained, well sorted, rounded,
  homogeneous and isotropic sandstone.

IV. THE EXPERIMENT RESULTS

The results of the upscaling experiment for all the samples are displayed in Figures 3 - 6. Where the probe experiment indicates appropriate sample support (i.e., where the different support volumes give the same permeability), the Hassler-sleeve cube is generally consistent with averaged probe data.

In homogeneous and isotropic rock such as sample D with a coefficient of variation (Cv) of less than 0.5, it is not difficult to obtain good sample support. Figure 3 shows that the probe data overlay and the single cube data matches. Measurement with different sample support gives very similar values. These permeability data can be for various modelling applications.

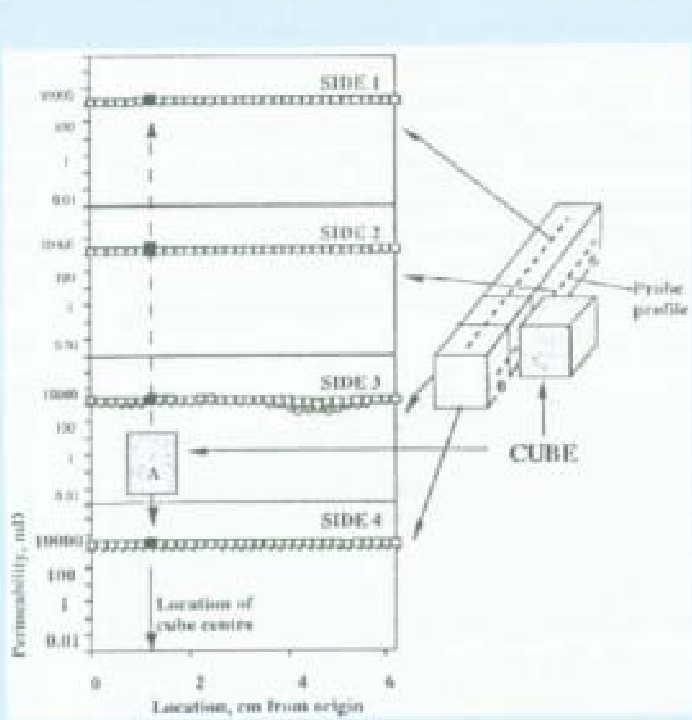

Figure 3

The upscaling experiment for sample D. The permeability display shows the profiles from the trimmed rectangle of sample prior to the cutting of a cube (refer to Figure 4). The cube data are superimposed at the location of the centre of the cube. The probe data for each of the four sides (diamonds-small tip; open squares-large tip) and plug data (solid squares-plotted at the location centre of the cube, A) are comparable. This rather characterless result for the homogeneous sample should be compared with that seen in the more heterogeneous experiments (refer to Figures 4-6)

In heterogeneous rock (Cv about 1.0) one cannot rely on a single measurement value. In such rocks a multiple volume support was applied to check the consistency of permeability data. Sample B and sample C indicate appropriate sample support, so these data can also be used (Figure 4 and Figure 5). In the very heterogeneous rock (Cv > 1.5), such as sample A (see Figure 6), the probe permeability data cannot be used to estimate the upscaled (cube measurement) with any degree of confidence.

The arithmetic, harmonic, and geometric average discussed in Appendix B were calculated from the probe data for the cubes and then compared with the Hassler sleeve cube data (Figure7). In very homogeneous rock (e.g., sample D), all of the averaging methods yield similar results to the cube permeability. In a completely homogeneous field, the various averages should be exactly the same. In sample B, the best averaging method was obtained from the harmonic average. It seems that the best averaging method for a discontinuous system of pores is the harmonic average, because in this system, the permeability will be dominated by the low matrix permeability.

Sample C indicates stratification, and the Hassler sleeve cube measurement shows anisotropy. In the stratification system, where flow is parallel to layers, the best averaging method might be closed to the arithmetic average. The horizontal cube permeability is close to the

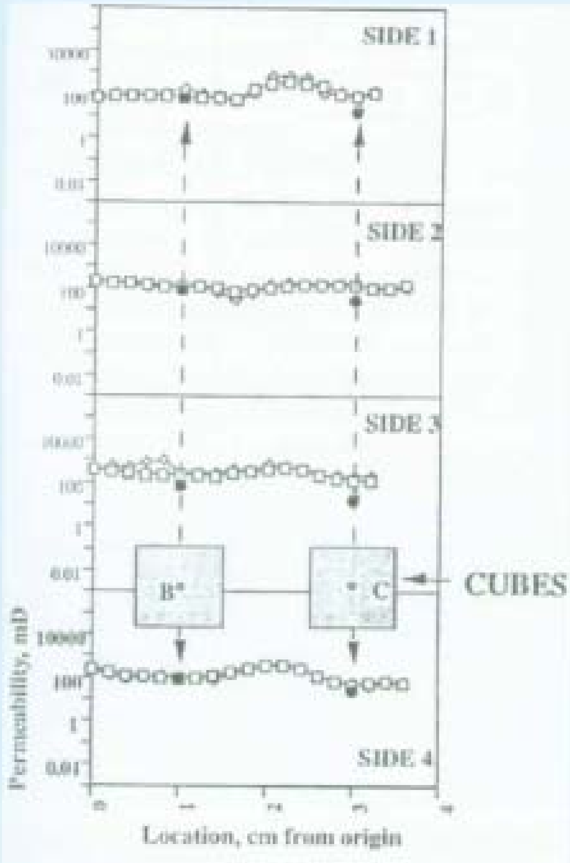

Figure 4
The upscaling experiment result for sample B. The probe data for each of the four sides (diamonds-small tip, open squares-large tip) and plug data (horizontal solid circles, vertical triangles-plotted at the location centre of the cubes, B and C) are very similar for sample B. For cube C the permeability is less than measured by the probe data- possibly due to local heterogeneity. The profiles on each of the sides are similar. Note that the cubes are isotropic and that the values are different for the two plugs

arithmetic average, and, whilst the vertical cube permeability is not matched by any average, the harmonic average is the closest. This result is consistent with averaging in a layered system.

V. CONCLUSIONS

There are some points that should be considered in upscaling:

- Data employed in upscaling should be of an appropriate volume to provide local homogeneity and local stationarity to satisfy the geostatistical criteria. In the permeability assessment, these conditions occur when two or more mutually adjacent, locally homogeneous volumes yield similar value of permeability or vary systematically.

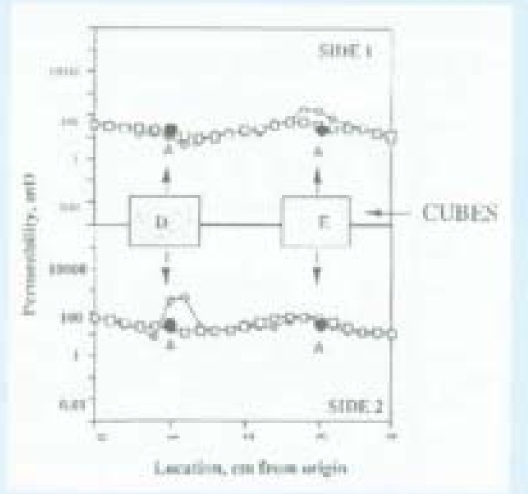

Figure 5
The upscaling experiment result for sample C. The probe data for each of the four sides (diamonds-small tip; open squares-large tip) and plug data (horizontal solid circles, vertical triangles-plotted at the location centre of the cubes, D and E) show differences. The profiles on each of the sides are similar suggesting layering. Note that the cubes are anisotropic and the values similar for the two plugs. The cubes match the arithmetic average of the large probe data - the vertical permeability measured in the cubes is less than detected by probe, suggesting the presence of thin low-permeability layers not detected by the probes

- Based on REV theory, the permeability must be measured at a scale large enough to encompass a representative elementary volume (REV) which is related with the pore type and fabric. At some scale, each adjacent sample that attains an REV will display similar values of permeability as we can see in intergranular pore type.
- The best average for unconnected vuggy carbonate with random system is closer to the harmonic average than the geometric average, whilst the best averaging method for laterally extensively layering system is the arithmetic average.

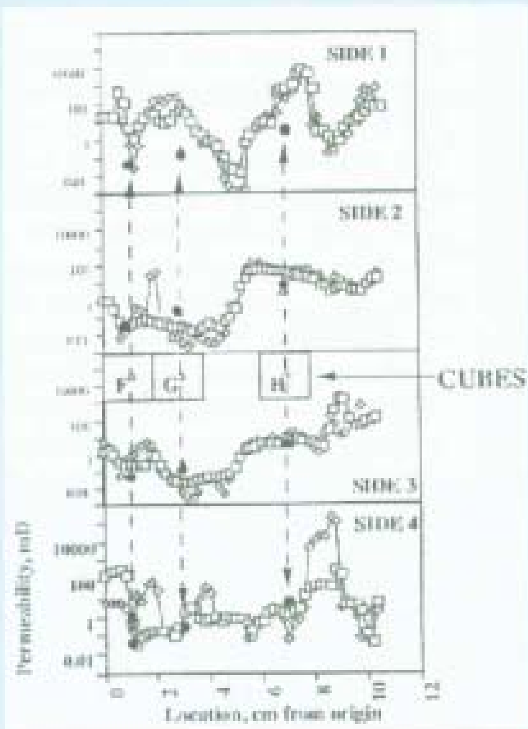

Figure 6
The upscaling experiment result for sample A. The probe data for each of the four sides (diamonds – small tip; open squares – large tip) and plug data (horizontal solid circles, vertical triangles – plotted at the location centre of the cubes, F, G, and H) are all very different. In addition, the profiles on each of the sides are different. Note that the values are different for the three cubes

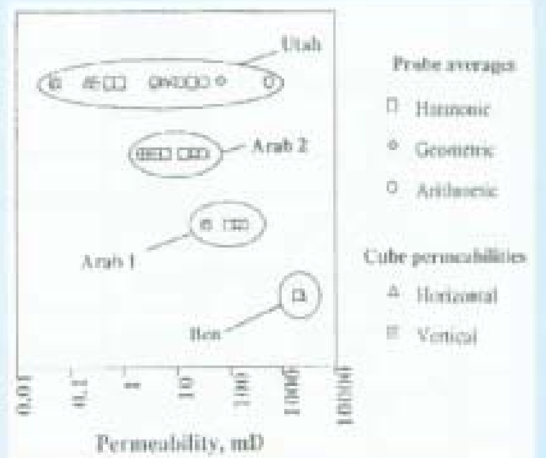

Figure 7
Comparison between the various averaging methods of the probe data with the cube permeability data. The increasing spread from the homogeneous (sample D) to the very heterogeneous (sample A) reflects the increasing heterogeneity and therefore increased in the effective permeability

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APPENDIX A
PERMEABILITY MEASUREMENT METHOD

The two most widely encountered method for small scale permeability measurement in oil industry are: the

Hassler cell type measurement and the probe permeameter. The former has a long established history and documented procedure. The later, has only recently become accepted as a method for permeability measurement.

Hassler Cell Permeameter

The samples were cut into cube form for core analysis and then cleaned. During the measurement, the samples are encased in a compliant sleeve within a steel cylinder which is called core holder. Pressure on the sleeve ensures that the sample is sealed on faces parallel to the flow direction. Nitrogen is injected into the upstream end of the sample, flows quasi-linearly through the plug, and vents to the atmosphere. The permeability is determined by Darcy's law from the measurement of stable flow rate (Q), presuure drop (P), area (A) and length (L) of the sample.

The relatioship between permeability and flow rate is generally linear, as described by Darcy's Law. In region of high flow rate or low permeability, however, non-linear effects are apparent. At high flow rates, non-linear flow results from inertia and, at very high rates, turbulence. These effects can be corrected (Forcheimer, 1901), but, where possible (i.e., unless the permeability is very high) these flow regimes should be avoided by maintaining as low a pressure drop as practical on the sample.

In low permeability media, a second non-linear phenomena occurs. Gas slippage is the term given to the increased flow of gas relative to that expected from a liquid. The sample has an effective higher permeability to gas because: a) gas molecules are loosely bonded and can travel easily before encountering neighbours and b) there is no zero-velocity boundary layer (as found with liquids), increasing the effective diameter of the pores. The effect of slippage can be corrected (Klinkenberg,1941), and the equivalent liquid permeability can be determined.

Probe Permeameter

The Probe permeameter is becoming increasingly important in reservoir characterisation, because it has advantages in petrophysical analysis which are a non-destructive, cheap, fast measurement and a capability to assess high density data measurement. Therefore, the probe has ability to characterize the permeability variation and distribution, and particularly to closely relate to the variation in geology.

The probe permeameter used in this experiment was an unsteady state probe or pressure decay device (PDPK-200). The instrument measures the time rate of pressure decay as nitrogen flow to sample through the tip's probe. Based on the Darcy's Law, permeability is calculated as the ratio of gas flow rate to the pressure function and the geometric factor.

$$Kg = \frac{29392 \mu P1 Qi}{Gori(P1^2 - Pa^2)}$$

where,

Go : Goggin geometric factor
Pa : Ambient atmospheric pressure, psi
P1 : Pressure in the probe, psi
Qi : the volumetric gas flow rate at this pressure, cm^3/sec.
ri : internal tip seal radius, cm
μ : gas viscosity, cp

In the operating condition, the injection pressure should not be too high in order to avoid the turbulence effect which influenced the measurement result of permeability. Moreover, the injection pressure should be outside the region of slippage and the gas permeability will be close to liquid permeabilities.

APPENDIX B
AVERAGING PERMEABILITY

Statistical analysis has been used to estimate the effective permeability, however, permeability is related to flow and that means an intensive variable. The flow transmitted by any given region depends upon the permeabilities of surrounding regions. For example, consider a highly permeable region of a reservoir encased in shale (e.g., lenticular bedding). No matter how permeable is the centre, the outer shell of low permeability material prevents flow. The total permeability of a region usually depends upon the precise flow geometry. Unlike permeability, porosity is an additive property, for example, the pore volume of fluids in a lens contributes to the total amount of fluid in a region without regard to whether the fluid can move or not.

In the case of linear flow parallel to a stratified medium, typical of a shallow marine sheet sands, of I layers, the aggregate permeability (kt) of the region is the expected value of the layer permeabilities. In this case, permeability is additive.

$$kt = \frac{\sum_{i=1}^{I} kihi}{\sum_{i=1}^{I} hi} = E(k)$$

When linear flow is orthogonal to the layers, permeability is no longer additive. Its inverse, however, is additive. The aggregate resistance to flow, kt^{-1}, is given by the expected value of the layer resistances to flow (Figure B-2).

$$\frac{1}{kt} = \frac{\sum_{i=1}^{I} hi / ki}{\sum_{i=1}^{I} hi} = E(k-1)$$

The aggregate permeability for linear flow parallel to layer (=E(k)) is often called the arithmetic average and the aggregate permeability for linear flow normal to layer ($E(k^{-1})$) is the harmonic average of the permeability random variable, k, when the layers are of equal thickness.

In geological systems, while containing some degree of ordered permeability variation, they don't meet the layered situations described above. Matheron (1967) proposed the aggregate permeability for those system. When ln(K)~N(m, s^2), s is small, and the flow is 2-D, ln(kt)=E(ln(k)), the geometric average is appropriate. Various simulation studies (e.g. Warren and Price, 1961) have extended this result to less restrictive situations with some success. This result does not require that the system be totally disordered. As long as the scale of the ordered or structured element is small compared to the region for which kt is sought, the geometric average will apply, given that k is log normally distributed and exhibits only moderate variation □