Thoughts on Permeability Scaling

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Representing the heterogeneities at sub-meter scales in a full-field reservoir simulator is not a reasonable task because of computational limitations; small scale heterogenities must be represented with upscaled effective values. Properties such as porosity can be rescaled by simple averaging methods but permeability as a non-additive property should be rescaled on a realistic model where all geological features and heterogeneities are presented explicitly. Complexity of the geometry will affect the effective permeability measurement. A major concern is which sample volume will be the representative one. In fact by re-scaling, we are trying to replace a heterogeneous medium with a hypothetical homogenous medium at the chosen grid size. In this paper we are interested in different geological length scales. Five models have been generated randomly in 3D and 2D and upscaled considering various isotropic sample volumes. The goal of performing the following experiments is to see how permeability varies with sample support. Various summary measures are analysed. In summary: 1) effective values often converge to the geometric average (as expected for random media), 2) variance decreases when the size of the sample volumes increase, and 3) variability is seen at all scales.

Introduction

To optimize reservoir performance and forecast oil recovery, reservoir simulation is the key point, that is conducted on a simulation model including properties and reservoir geometry as input data. However, geomodel on a very fine scale is applied for reservoir characterization. There is scale difference between simulation model and geomodel. To build geomodel, different scales of data are used including core data (about 1 inch), well log data (about 0.5 ft), seismic data (about 10-100ft). Geomodel captures complex geological features effective on fluid flow with approximately 10^7 grid cells [48]. In reality, multiple simulations should be done and also to quantify uncertainty numerous geostatistical realizations are needed and these are all CPU demanding. So, for realistic applications geomodel is too expensive and it should be upscaled to have coarsened model applicable for fast simulation of different process. In subsurface flow modeling, the most important property to upscale is permeability which is a very active area of reserach. Comperehnesive reviews of current methods are given in [51, 52, 53].

Using coarsened model is of importance for fast simulation of different process specially thermal recovery process. Both permeability and transmissibility could be upscaled. Transmissibility upscaling has been shown to provide more accurate coarse-scale models than permeability upscaling for highly heterogeneous systems [48].

The main issue is to which volume size, the properties should be rescaled where heterogeneity is captured reasonably. Statistical representative elementary volume [44] is a volume within which the statistics of quantity of interest varies insignificantly and property is homogenous and statsitically stationary.

In that representative elementary volume, the property should be homogenous and statistically stationary and based on Bear's theory [6], it should be large enough to capture representative amount of heterogeneity. Statistical REV is a volume within which the statistics of the quantity of interest varies insignificantly. By considering different sample volumes, various length scales are evaluated.

It is important to take advantage of detailed geological information as much as we can. In this report, we try to show how permeability varies with different isotropic sample volumes and look for finding possible geological length scale for 2D and 3D cases. Histograms, REV plots, variance reduction plots and horizontal and vertical variograms are provided for analysis.

Upscaling, REV and Length scale concept

Only porosity and the absolute permeability are upscaled for single phase flow problems and resulted upscaled properties can be applied to multiphase flow problems with good accuracy as well [48]. In these models, relative K is the same as coarse-scale relative permeabilities at the fine scale. This method is referred to as single-phase upscaling [52]. In two-phase upscaling, the two-phase flow parameters, such as relative permeability, are also upscaled [54]. Single phase flow upscaling is frequently used because of less computational cost.

Flowsim Program
All the upscaling calculations have been performed by applying the modified version of flowsim program including SIP and Gband algorithms (please see CCG paper number 405) that 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 per-meability in each direction is also calculated by solving the steady-state single-phase flow equations with no flow boundary conditions" [55].

Representative Elementary Volume / Length Scale
By definition, statistical representative elementary volume is a volume within which the statistics of quantity of interest varies insignificantly and property is homogenous and statistically stationary [44]. Different items influence on the determination of the length scale (REV) of a process, including geological features (heterogeneity), transport phenomena and fluid flow, chemistry and process design where each of them has its own length scale [56]. To understand the physics of process, we need to model the process accurately at correct length scales considering all factors affecting on the determination of REV. In fact looking for dimensions of grid blocks that can represent reservoir heterogeneities besides the physics of the process is the main issue [56]. In that representative elementary volume, the property should be homogenous and statistically stationary and based on Bear's theory [6], it should be large enough to capture representative amount of heterogeneity. Statistical REV is a volume within which the statistics of the quantity of interest varies insignificantly.

Length Scale of Steam Assisted Recovery Process [56]
Gates shows that for SAGD and any steam based process, different length scales are evaluated based on reservoir geology, physics of flow and transport phenomena, chemistry and wellbore and field process operation.
Ian discusses that transfer processes in heterogeneous porous media should be described by smaller grid blocks and presents how length scales of SAGD process are associated with well sizes and designs and how length scales are affected by thermal process. Wells lengths, diameters, wells perforation lengths, spacing between wells, position of the tubing strings and etc are all effective factors in determination of the length scale. In recovery process, the length scale of heterogeneity span nearly ten orders of magnitude from microns to kilometers whereas wells and process designs and the degree of control span from meters to kilometers. Usually length scales of thermal recovery in reservoirs are 1 meter in the cross-well plane and about 100 meters in the down-well direction. For detailed information, please see Gates paper.

Pervious Works (Literature Review on REV)
Reservoir performance evaluation is done by applying a numerical model and static and dynamic analysis of the model. The spatial distribution of the lithological properties and heterogeneities have to be presented in the best way in the numerical model to have the greatest assessment [1]. One side is generating numerical model, other side is applying upscaling technique and in between the important decision is to choose the scale that the properties should be re-scaled to. Sub-meter scale lithological properties and heterogeneities should be rescaled to ideally representative values seeing that computational limitations don't let us to use them in a full-field reservoir simulator before rescaling. Some issues when rescaling heterogeneities can be seen in the following papers; [2, 3, 4, 5, 47]. Four conceptual scales associated with averaging properties in porous rock media have been proposed by Haldorsen & Lake [42]. Representative Elementary Volume (REV) has been introduced by Bear [6] at which the parameter of interest is both statistically stationary and homogeneous. REV concept will guarantee consistent upscaling in flow simulation studies.
REV represents a large enough volume of the property field capable to capture a representative heterogeneity. Representative elementary volume concept has been discussed vastly by researchers in relation to the calculation of effective petrophysical properties [15, 16, 17, 18, 30]. Porosity (additive property) is just upscaled by simple averaging schemes while permeability (non-additive property) upscaling should generally be performed on practical models where sedimentological heterogeneities are considered clearly. Variograms could be of great help to characterize the permeability [14]. Percolation theory [7] and effective media theory [8, 9] are common methods to estimate effective properties. Deterministic modeling of sedimentary structures is presented in detail in [10, 11, 12].

Jackson characterized the effective permeability of facies using 3D models. He shows that the key controlling point is the connectivity and continuity between low and high permeable layers and it's not easy to capture these key factors in different length scales [12]. He also discussed that averaged effective permeability is a function of sample volumes while flow direction and facies types are major points in selecting the suiTable averaging scheme to reduce the introduced error resulted by upscaling technique [13]. McKinley characterized permeability by variogram analysis [14].

In the following papers, flow barriers are modeled stochastically and also by using different correlation lengths in the vertical and horizontal directions, anisotropy is presented. The effect of the block-size corresponding to the scale of heterogeneity have been discussed as well [19, 20, 21]. Ozdemir and Ozguc determined REV for porosity with this assumption that porosity varies exponentially at wall regions of the porous medium [22]. Leung and Srinivasan assessed uncertainty introduced by scale up in reservoir models when REV scale is larger than volume support size [23, 31]. The relation between statistical moments (mean, variance and integral scale) of the upscaled permeability to the permeability of homogenous porous media is discussed when the flow is steady [24].
Lake and Srinivasan used variance of the mean of a random variable to study REV and changes in horizontal and vertical permeability and also to get robust estimation of uncertainty in assigning scaled up values [25]. The effect of geological heterogeneity on flow has been investigated for continuous and discrete domains considering geostatsitical approaches by Eaton. REV is used to reinterpret hydrofacies as scale-dependant hydrogeologic units [26].

One could find useful information about correlation length and the effect of scale on flow in [27], [28], [29], [32]. Sorek investigated that how REV scale could affect phase balance equation when dealing with different types of fluids in a heat transfer phenomena [33].Yong presented a new method for 3D conductivity up scaling in heterogeneous porous media. He shows that his method is more successful than traditional up scaling techniques and also porosity upscaling is critical when dealing with contaminant transport. Upscaled porosity in such cases is beyond the traditional porosity obtained on the REV scale. The similarities and differences between conductivity and porosity upscaling are also discussed [34]. Vogel and Brown quantify REV and a scale disparity factor to find a sample size. The sample size is used to determine a meaningful semivariogram when correlation lengths are specified. Directional semivariograms and a scale disparity factor are used to get vertical and horizontal correlation lengths in small and large scales considering this point that REV analysis is scalar in nature and semivariograms are based on vector analysis [35].

Three volume averaging methods as REV tests are presented by Brown, Hsieh and Lucero including prismatic volume averaging, stacked slice averaging and a qualitative test. They tried to evaluate proper core sample size at laboratory and found all core sizes suiTable for the experiments comparing their respective REV size and also they show that one single core is not enough for the experiments [36]. The authors applied their proposed method to determine REV based on porosity and phase volume fraction in two-phase systems [37]. Rooij focused on upscaling from REV-scale to a larger scale beyond REV considering water flow through porous media with different degrees of heterogeneity. He investigated the validity of Darcy's law under superposition principle [38]. Data quality implications of an REV have been examined by Robinson and Estabrook for porosity and water saturation in an unsaturated porous media [39]. Gray and Miller proposed thermodynamically constrained averaging theory (TCAT) approach to deal with inconsistencies and ill-defined variables in porous media modeling [40]. Nachabe and Morel discuss how to scale aquifer flow equation. They demonstrate that small-scale macroscopic variability of aquifer transmissivity effects the megascopic behavior of the flow in the aquifer in both space and time [41]. The flow of two fluids has been studied theoretically by Quintard [43] at pore level with stokes equations and also local volume averaging has been applied for derivation of Darcy-scale equations over a large region compared to the length scale of heterogeneities. The numerical results have been compared statistically with the experimental data as well. Zhang systematically studied the scale dependency of the permeability and porosity and assess the concept of statistical REV on a reservoir model based on lattice Boltzmann simulations. A single statistical REV is defined while deterministic REV isn't defined as there are still changes at the scale of the whole domain [44].

One could find a good reviews on current limitations of implementation of multiscale modelling in [45]. The authors discussed how many scales should be modeled and upscaled and on which scales, one should focus on. Nordahl and Ringrose evaluate the representative elementary volume for permeability at the lithofacies scale with a new insight. They show that REV varies with changing in lithofacies types and also depends on the measured property (vertical and horizontal permeability) [46].

3D Case Studies: 100 realizations of 1000 grid cell models

The goal of performing the following experiments is to see how permeability varies with sample support. To quantify the variability, variance is calculated for 100 realizations. Theoretically, stationarity and homogeneity should be obtained to get the feasible REV

Generating the models and get effective values

100 realizations of two random 3D permeability fields have been generated. The first K-field is a bimodal case generated by ellipsim (Gslib) program and the second one is a lognormal case generated by sgsim (Gslib) program. The idea of having 100 realizations is to provide a large number of results for sTable statistics/ histograms. The first model size is counting 10 by 10 by 10 grid cells. The second one is a 8 by 8 by 8 model in which the size of the ellipsoids are considered less than the grid size.

In the next step, flowsim, that is a program for single-phase flow upscaling, has been used to get the effective permeability values of different isotropic sample volumes that fit the model. SIP algorithm has been applied to solve pressure equations necessary to calculate effective permeabilities. A 2 by 2 by 2 sample volume is isotropic and a 2 by 2 by 3 is an example for a non-isotropic sample volume. The considered isotropic sample volumes are 1, 2, 5 and 10 grid blocks in x, y and z directions. The results to be analysed are including the histograms of upscaled K-fields, REV plots in X, Y and Z directions and also plots of reduction of variances with sample support as scale increases, all for 100 realizations. CPU Time has been measured as well. We are interested in CPU time as SIP algorithm has been applied Table 1 lists the sample volume sizes, size of the output model and measured CPU time for 3D models.

Analyse the results

Variability of effective permeability values in different directions are shown by REV plots, see Figures 4 and 5. We can also clearly see a general trend in reduction of variance with sample volumes for 100 realizations.

Effective values are converging to the geometric average and also variance is decreasing while the size of the sample volumes are increasing. To investigate the mentioned goals, the subsequent workflow has been followed. Since plots in all directions are almost the same, the histograms, REV plots and variance reduction plots are just presented in X direction for the models. Looking at the histograms and REV plots in different directions, they confirm the randomness of the generated models since the plots of effective values are similar for all direction and Keffx ~= Keffy ~= Keffz, as it was expected.

Table 1

	Sample Volume (X axis of REV plots)	ISOTROPIC Sample Volumes (X axis)	Output Model Size	CPUtime (min)
lognormal 3D model	V1	1*1*1 (point data)	10*10*10	----
	V2	2*2*2	5*5*5	86.6
	V3	5*5*5	2*2*2	27.9
	V4	10*10*10	1*1*1	16.3
bimodal 3D model	V1	1*1*1 (point data)	8*8*8	----
	V2	2*2*2	4*4*4	212.8
	V3	4*4*4	2*2*2	52.5
	V4	8*8*8	1*1*1	29.0

Geometric average of the lognormal model has been calculated by simple averaging of the geometric averages of 100 realizations in the model and and geometric average of the bimodal model, that is a K field including 75 percent shale (k = 3 md) and 25 percent sand (k = 1000), has been calculated by the following formula.

$$\exp(0.75 * \log(3) + 0.25 * \log(1000)) = 12.82 \quad (1)$$

The geometric average values are 457.13 and 12.82 for the first and second cases respectively. Looking at Figures 4 and 5, it is clear that the effective values are going to be closer and closer to the geometric average for both cases. Figures 6 & 7 clearly show that the variance is reduced and variability becomes smaller when the scale of averaging is about 10 times of the scale variability. Based on REV plots (Figures 4 and 5), at smaller sample volumes, vertical and horizontal permabilities are varying significantly. histsmth (Gslib) program has been used to plot Figure for lognormal case. Variance and mean values are reported for all upscaled models as well (Figure 2) but histsmth is not applicable for the binary model, so the histograms are presented for the binary case (Figure 3).

2D Case Studies: 1 realization of 1000000 grid cell models

In this section, we are facing with three 2D bimodal cases and comparing the variation of permeability with scale. Models have same percentage of shale and sand but the length of the low permeable features are different.

Generating the models and get effective values

Work flow is as follows: 3, 2D Micro models have been generated by ellipsim program including 1000 * 1000 * 1 and 1 realization. All models have 10% shale and 90% Sand. In the models, shale thickness is constant (1 cm) and shale lengths are various; 0.2 m, 1 m and 5 m for first, second and third case respectively. Consistency is important in creating the models. The radius of the ellipsoids in the Y and Z directions should be equal to the y size and z size respectively (Figure 1). Radius [1] in ellipsim parameter file is replaced with 50 and 250 to build the second and third models respectively.

After creating the micro models, in the subsequent stage, the mini models are generated by applying flowsim program and upscaling the micro models (1000 * 1000 * 1) to 200 * 200 * 1 grid cell models. Geo-model is created in the next step from mini model directly by upscaling the Mini model (200 * 200 * 1) to 40 * 40 * 1. To have better analysis, the micro model has been upscaled to the following model sizes as well: 100 * 100 * 1, 10 * 10*1. To get REV plots, point data are upscaled to different sample volume size directly (Table 2) while for creating the geomodel, mini model is upscaled instead of point data model (micro model), see Tables 2 and 3. Finally all models are upscaled to one grid block, see Table 4. There is slight difference between effective permeability in x direction (horizontal k) for 3 models and they are closer to geometric average rather than other kind of averages while there is remarkable changes in vertical effective permeability between the models. Model with shortest length shale breaks (model 1) has higher effective vertical permeability. It's worthy to mention that SIP algorithm has been applied to get the effective value and sample volumes are isotropic. The results to be analysed are including the histograms of upscaled K-fields, REV plots in X, Y and Z directions and also vertical and horizontal variograms for all cases.

Table 2: To plot REV plots

Sample Volume	Input Model (Micro Model: Point data)	Output Model
5*5*1	1000 * 1000 * 1	200 * 200 * 1
10 * 10 * 1	1000 * 1000 * 1	100 * 100 * 1
100 * 100 * 1	1000 * 1000 * 1	10 * 10 * 1
1000 * 1000 * 1	1000 * 1000 * 1	1 * 1 * 1

Table 3: To generate Mini and Geo Models

Sample Volume	Input Model	Output Model
5*5*1	1000 * 1000 * 1 (point data: micro model)	200 * 200 * 1 (mini model)
5*5*1	200 * 200 * 1 (mini model)	40 * 40 * 1 (geo model)

Table 4: Upscaled to 1 * 1 * 1

	Shale Breaks Length (m)	Keff X	Keff Y	KA	KG	KH
Model 1	0.2	8804.906	469.445	8833.140	8816.516	8799.503
Model 2	1	8934.903	19.720	8966.566	8948.122	8928.971
Model 3	5	8955.226	11.566	8975.613	8956.536	8936.704

Analyse the results

Looking at the variograms (Figure 14), it seems that while all vertical variogarms are pure nugget effect and vertical continuity is fixed, horizontal continuity has a dominant influence on vertical permeability and it is similar for all models. Variograms of the second model are presented, see Figure 14. Also some small samples of all models have been analysed (code written by Matlab) including a full shale break, partially shale break and no shale break layer (Figure 9). Effective K for all samples are listed in Table 5. For example, M1S1 is sample of model 1 with full length shale break. M1S2 is the one with partially shale break and M1S3 is the sample with no shale. Comparing the similar samples, it is clear that if the scale of interest is less than the size of the features then the influence of the feature is seen in special continuity and not in the effective property at the scale of inertest. Figures 11, 12 and 13 present the histograms of the effective K with different sample volumes and in horizontal and vertical directions. They show similar trend in convergence to the geometric average.

Table 5: Getting Small Samples

Model	Keff X	Keff Y	Keff Z	Keff X	KA	KG	KH
M1S1	9230.856	12.977	9230.846	4621.917	9230.846	4923.883	12.984
M1S2	9677.337	9035.586	9800.020	9356.461	9800.020	8317.640	49.756
M1S3	10000.007	10000.007	10000.000	10000.007	10000.000	10000.000	10000.008
M2S1	9375.059	15.973	9375.062	4695.516	9375.062	5623.413	15.976
M2S2	9706.580	8669.440	9791.688	9188.010	9791.688	8254.043	47.776
M2S3	10000.008	10000.008	10000.000	10000.008	10000.000	10000.000	10000.014
M3S1	9375.062	15.973	9375.062	4695.518	9375.062	5623.413	15.976
M3S2	9496.348	6490.511	9583.375	7993.429	9583.375	6812.919	23.945
M3S3	9999.985	9999.985	10000.000	9999.985	10000.000	10000.000	10000.014

Variability of K values in different directions are shown by REV plots. Figures 15-17 show the REV plots for all 2D models in vertical and horizontal directions. Horizontal plots are pretty similar. Looking at vertical REV plots, the effective permeability values are converging to the lower value for the third case comparing to others.

Conclusion

In this paper, considering 2D and 3D models and isotropic sample volumes, effective permeability values are presented by REV plots. We tried to show how permeability varies with scale. Looking at 3D cases, effective values are converging to the geometric average in x, y and z directions. It has been shown that how variance decreases when the size of the sample volume is increasing. Looking at the results for 2D cases, in different directions, it is clear that the effective values are going to be closer and closer to the geometric average for all cases. At smaller sample volumes, vertical and horizontal permabilities vary significantly. Variance is reduced and variability becomes small and smaller when the scale of averaging is about 10 times of the scale variability. Considering the variograms, while vertical continuity is fixed (that is pure nugget effect) in 2D cases, it is clear that horizontal continuity has a dominant influence on vertical permeability. Also when the scale of interest is less than the size of the features then the influence of the feature is seen in spatial continuity and not in the effective property at the scale of inertest. There is variability at all scales and grid scaling should be done considering engineering constraints. In reality the scales of relevance are not entirely dictated by scale of geology and it could be dictated by data and flow process.

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ellipsimL1.out              -file for output realizations
1                           -number of realizations
1000   0.5  1               -nx,xmn,xsiz
1000   0.5  1               -ny,ymn,ysiz
1      0.5  1               -nz,zmn,zsiz
52079                       -random number seed
0.10                        -target proportion (in ellipsoids)     (shale proportion)
10 1 1   90 0 0.0  3        -radius[1,2,3],angle[1,2,3],weight
```
Figure 1: ellipsim parameter file

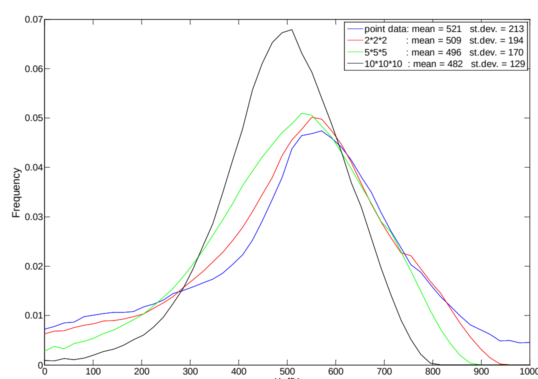


Figure 2: Histograms of Upscaled Models for 3D lognormal model

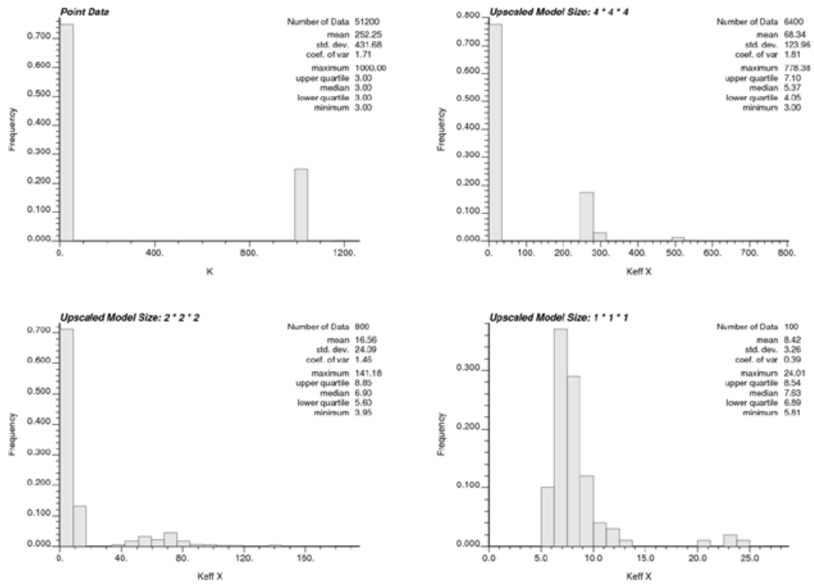


Figure 3: Histograms of Upscaled Kx for 3D bimodal case considering different sample volumes (similar to y and z directions)

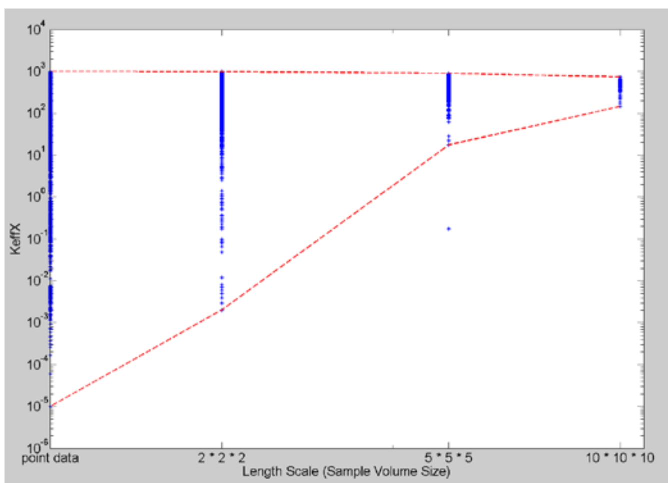


Figure 4: REV plot in x direction for lognormal 3D model (100 realizations)

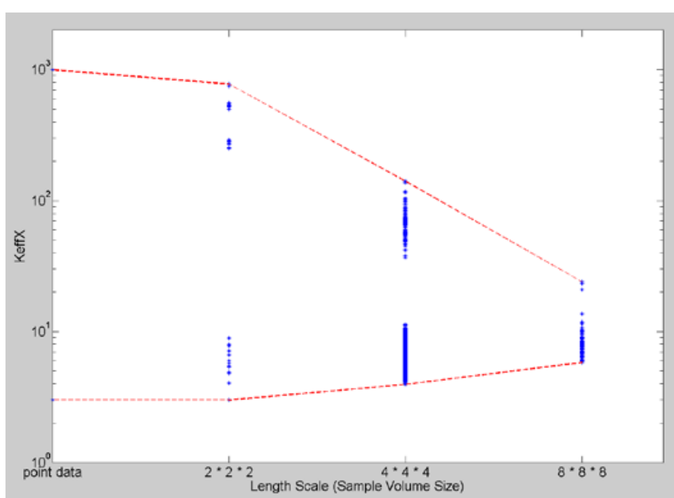


Figure 5: REV plot in x direction for bimodal 3D model (100 realizations)

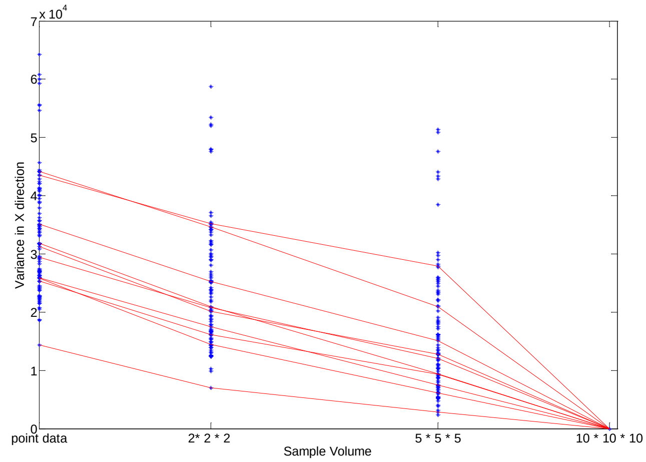


Figure 6: Variance reduction lognormal 3D model (100 realizations), 10 random realization selected to plot

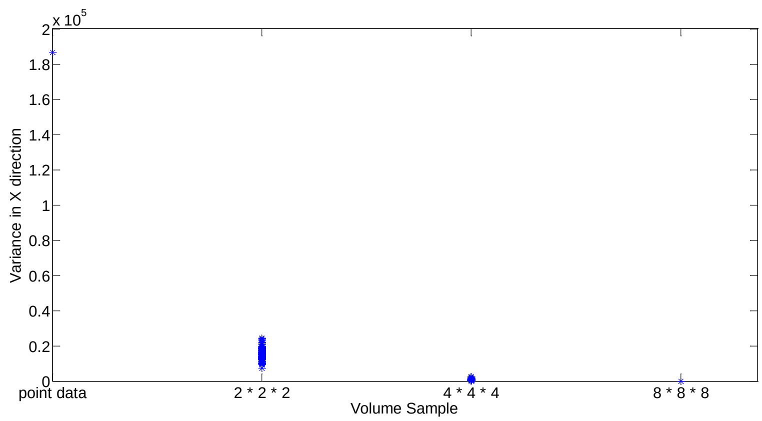


Figure 7: Variance reduction in X direction for the binary model, 100 realizations (Y and Z directions have similar plots)

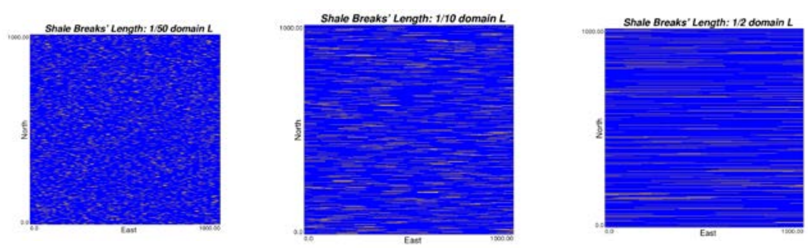


Figure 8: 2D binary models generated by ellipism: 10% shale and 90% sand with different shale breaks length

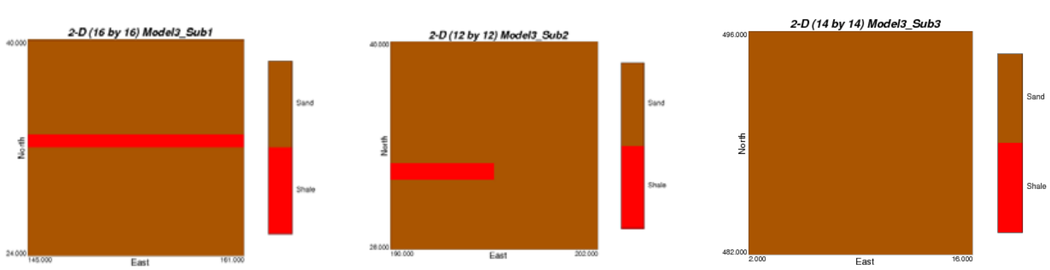


Figure 9: Small Samples a) with a complete shale break, b) partial shale break, c) no shale break

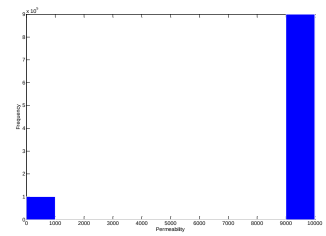


Figure 10: Point data for all 2D models

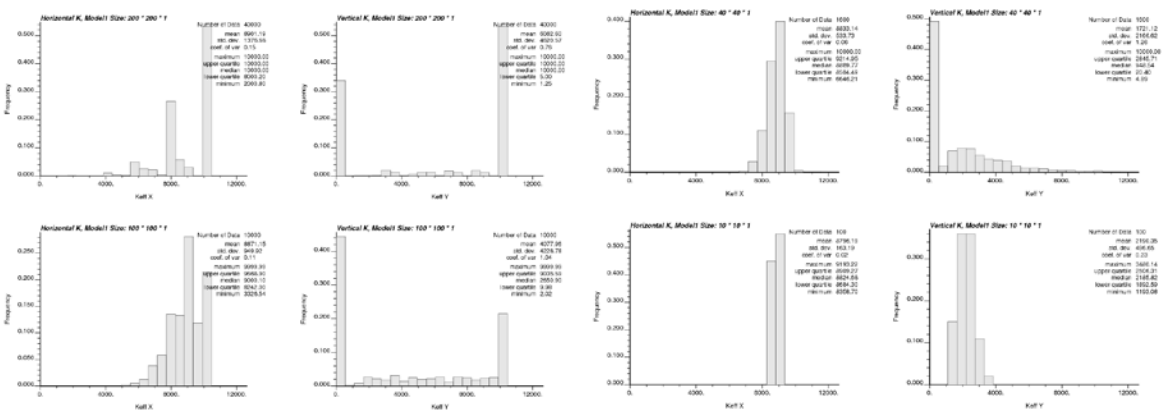


Figure11: Histograms of effective K (Model1): LHS plots: Horizontal K, RHS plots: Vertical K, SB length: 0.2 m

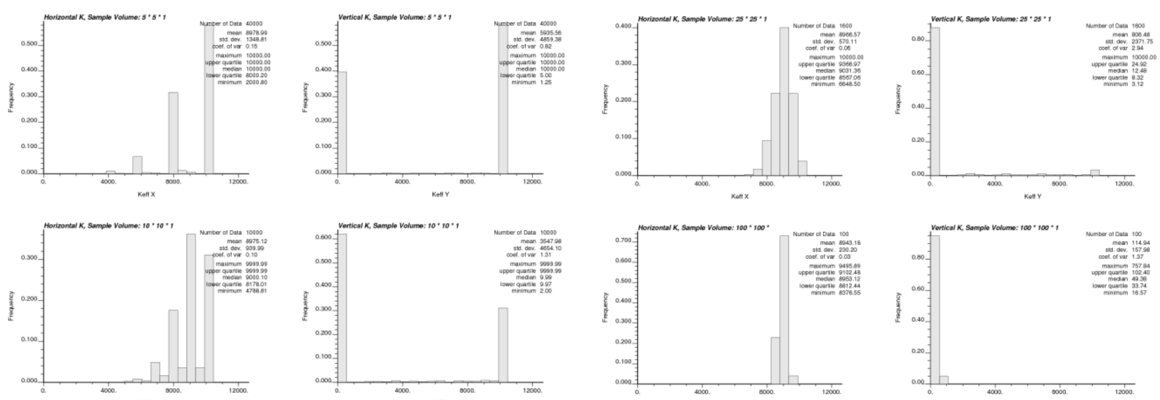


Figure12: Histograms of effective K (Model2): LHS plots: Horizontal K, RHS plots: Vertical K Comparing to Model1 histograms there are major differences. Shale Breaks' Length: 1m

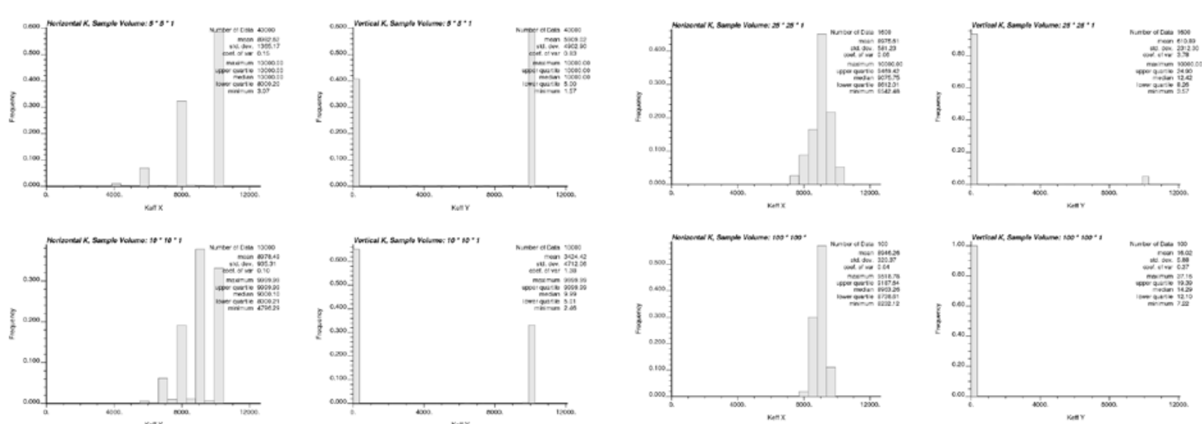


Figure13: Histograms of effective K (Model3): LHS plots: Horizontal K, RHS plots: Vertical K Shale Breaks's Length: 5m

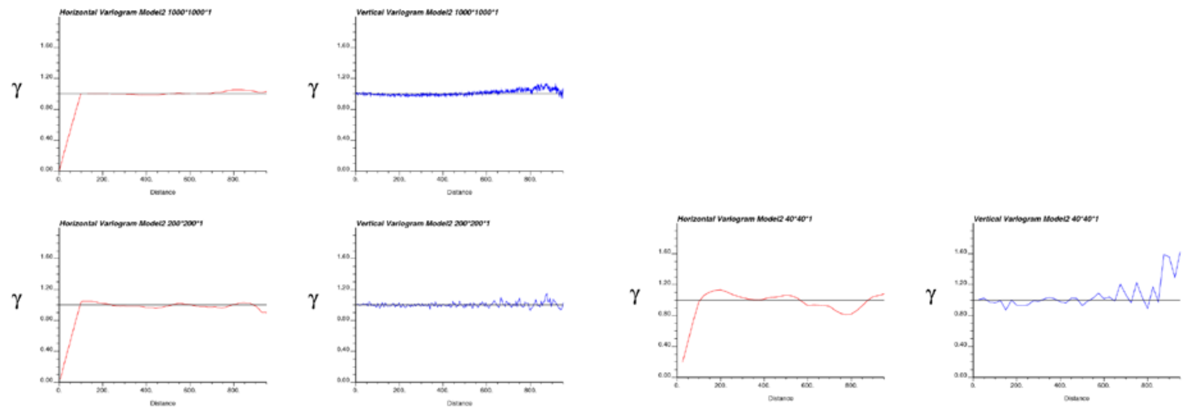
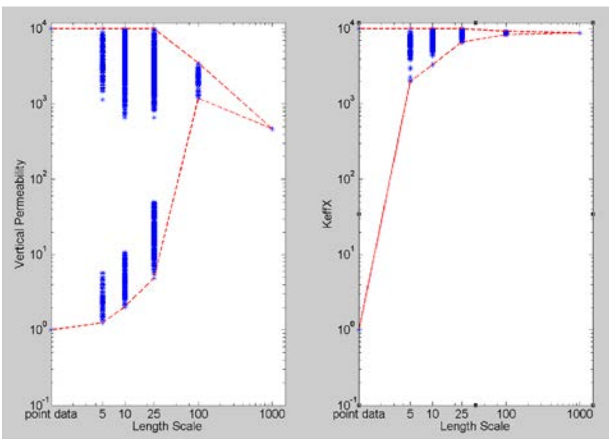


Figure 14: Vertical and Horizontal Variograms for Point data2 (micro model2), mini model2 and Geo model 2, almost similar behaviour have seen for 2 other models



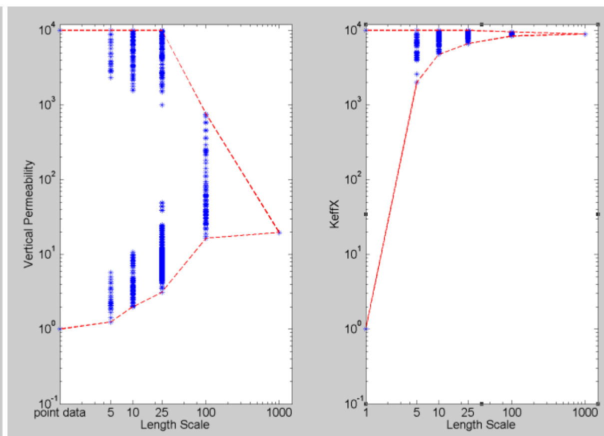


Figure 15 (left): REV plots for shale break length: 0.2 . Figure 16 (right): REV plots for shale break length: 1 m

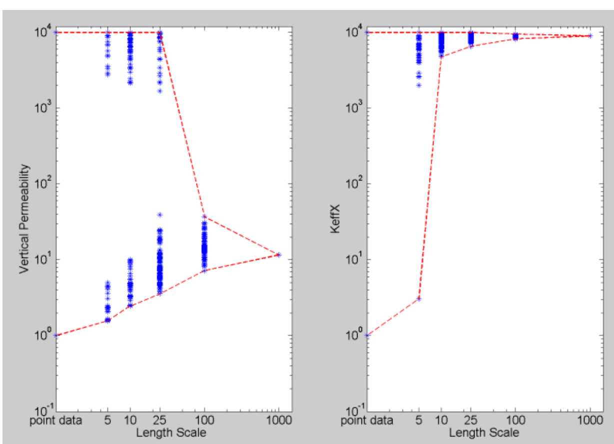


Figure 17: REV plots for 2D model 3 (shale break length: 5 m)

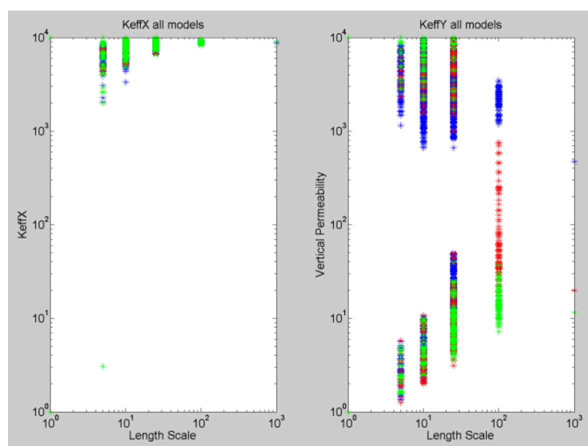


Figure 18: all in one