DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/45

Geomodels for fine-scale flow simulation of chalk reservoirs

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GEUS

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G E U S

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The present report describes part of the work performed at GEUS in connection with EFP-96 project 1313/96-0006: “Upscaling and stochastic modelling”.

Abstract

This report presents procedures for producing and analysing fine-scale geomodels. The geomodels are constructed in order to carry original measured data at the correct scale in the input stage. This is achieved by selecting cell size at the same scale as the core analysis data used for input.

This report presents an example of fine-scale porosity-permeability models of a reservoir sequence, and selected methods to generate these models. The purpose of investigating these models is to analyse effective properties as a consequence of the layering and contrasts in the model. These effects are largely ignored in most large-scale geostatistic reservoir models sofar.

Outcrop data has been used as analogue for the layered structure in the chalk geomodels, and the correlation structure is used to induce layering in the model, reflecting beds of approximately one meter thickness. The variability and range of porosity and permeability values are derived by comparison to actual well data. The contrasts in the sedimentary sequence are developed by a combination of sedimentary processes, compaction processes and effects from later diagnesis.

The detailed geomodel has been subjected to single-phase flow simulation, and the average anisotropy factor Kv/Kh can be derived for each type of model. The porosity/permeability relation for the effective properties reflects the upscaling that is carried out with this procedure.

Preliminary results from analysing the effective properties of the detailed geostatistical model of size 80x80x1 m. is illustrated. The detailed models have been subjected to single-phase flow simulation in order to get the effective permeabilities for the models. The procedure is applied in order to investigate the consequences of layering in the formation on the effective and directional permeabilities.

Introduction

For the geostatistic modelling of full field reservoir models fairly large simulation cells are traditionally used. For a study of the chalk reservoir in the Dan Field and the Valhall field have been used geostatistic model cells of size 80x80x1 meter (Frykman & Deutsch 1996, Dons 1996). Heterogeneities that exist at smaller scales than the cell size have therefore not been explicitly represented in the geostatistic model. This study will therefore focus on investigating the effect sof these small scale heterogeneities on the effective properties for the individual large-scale model cell.

Small scale heterogeneities are described from outcrop studies and from detailed analysis of well log data, where layering in the order of meter size causes variations in the porosity and permeability distribution.

In order to investigate the effects of this small-scale layering on the flow properties for a large volume, a detailed model of porosity and permeability distribution has been constructed for a 80x80x1 meter block. Its properties are based on the Dan Field data and the porosity/permeability relation in the uppermost Maastrichtian zone M12. The model therefore represents a typical uppermost Maastrichtian, fully oil-saturated reservoir type. The outcrop data has aided in the construction of the model by supplying the variogram structure with the short distance correlation lengths. The features of the model is described and its average

porosity and effective directional permeabilities have been calculated by single-phase flow-simulation.
By using the realistic input parameters for small scale structure and porosity/permeability relation, the results from the presented geomodel example show that permeability anisotropy Kv/Kh averages 0.96 for a 80x80x1 meter size volume. These results can be transferred to full field geostatistic modelling by simulation of two different permeability fields for the horizontal and vertical direction describing the permeability anisotropy for the large geostatistic cells of the full field model.
The strategy could be further applied including additional petrophysical properties as capillary pressure and relative permeability functions. The intention is to use a more advanced flow simulator to derive the effective multi-phase functions for the geomodel .

Previous studies of geostatistic modelling of chalk reservoirs have largely ignored the change-of-support effect on the simulated properties (Almeida & Frykman 1994). Other studies by Frykman & Deutsch (1996) and Dons (1996) have utilized simple averaging technique for deriiving conditioning data, and no anisotropy has been assigned to the model cells. The generated models from these studies have probably included too much variability in the descriptions by relying on core plug data as conditioning data. The aim here is to derive the effective properties of larger volumes by investigating the effects of small scale heterogeneities. At the same time the study serves to illustrate how to include information from small scale measurements (core-plugs, wire-line logs) and information from analysis of chalk outcrop data in the modelling process generating large geostatistical models. Principles for this type of upscaling have been discussed previously by Damsleth & Tjølsen (1994) and by Tran (1995a, 1995b) as a procedure to overcome scaling problems, and has been applied in a recent case study on a clastic reservoir sequence by Sweet et al. (1996).

The procedure used in this paper relies on that the conditioning hard data in the constructed model are assigned to volumes of a size that can be represented by measurements at the scale of core plug volumes. In this case cells of size 1x1x0.2 meters are used as support volume for core plug porosity and permeability values. Whether or not this volume of 0.2 cubic-meter can be represented by one plug measurement is open for discussion, but could be further evaluated by even more detailed investigations of core material.

The effective properties for the geomodel block of 80x80x1 meter are derived by single-phase flow simulation, and it gives the upscaled effective data for the representative histograms, the bivariate relation for porosity/permeability, and the anisotropy factor for vertical/horizontal permeabilities. The change in the variogram structure by the upscaling is only described by the reduced population variance for the effective properties. The change in the correlation ranges is unknown since the model is too small to quantify any range changes.

Data

Porosity/permeability data

The distribution of the porosity and permeability data available from 8 wells in the uppermost Maastrichtian zone M12 on the Dan Field is shown in Figs. 1 and 2, and the porosity/permeability relation is plotted on Fig. 3. The reservoir zonation and stratigraphy is presented in Fig. 4.

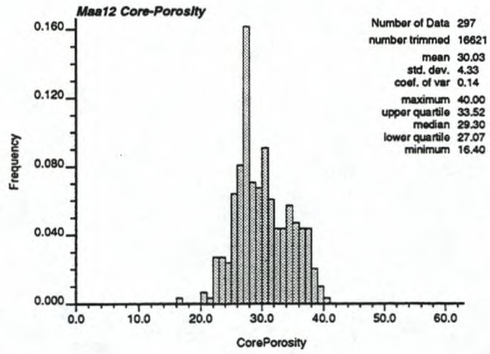


Figure 1
Histogram of core porosity from wells in the uppermost Maastrichtian Maa12 reservoir zone.

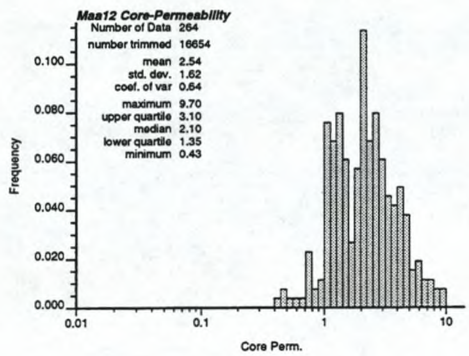


Figure 2
Histogram of core permeability from wells in the uppermost Maastrichtian Maa12 reservoir zone.

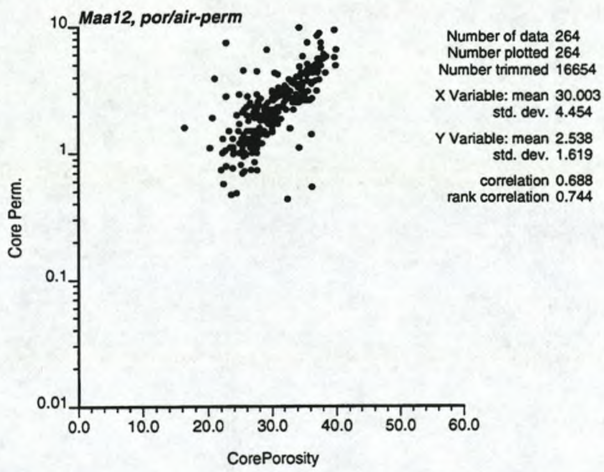
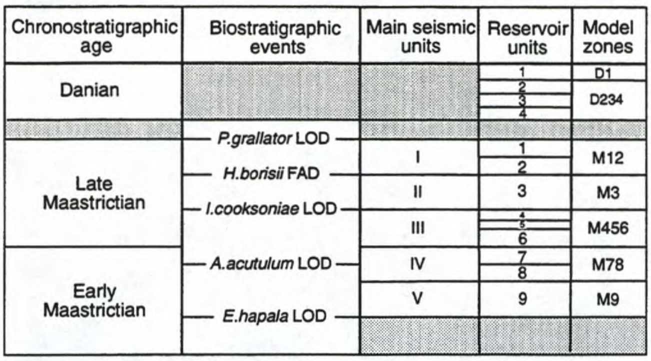


Figure 3
Crossplot of core porosity and permeability from wells in the uppermost Maastrichtian Maa12 reservoir zone.



Modified from Kristensen et al. (1995)

Figure 4
Stratigraphic scheme showing the unit-subdivision and the reservoir zones used on the Dan Field (Modified from Kristensen et al. 1995).

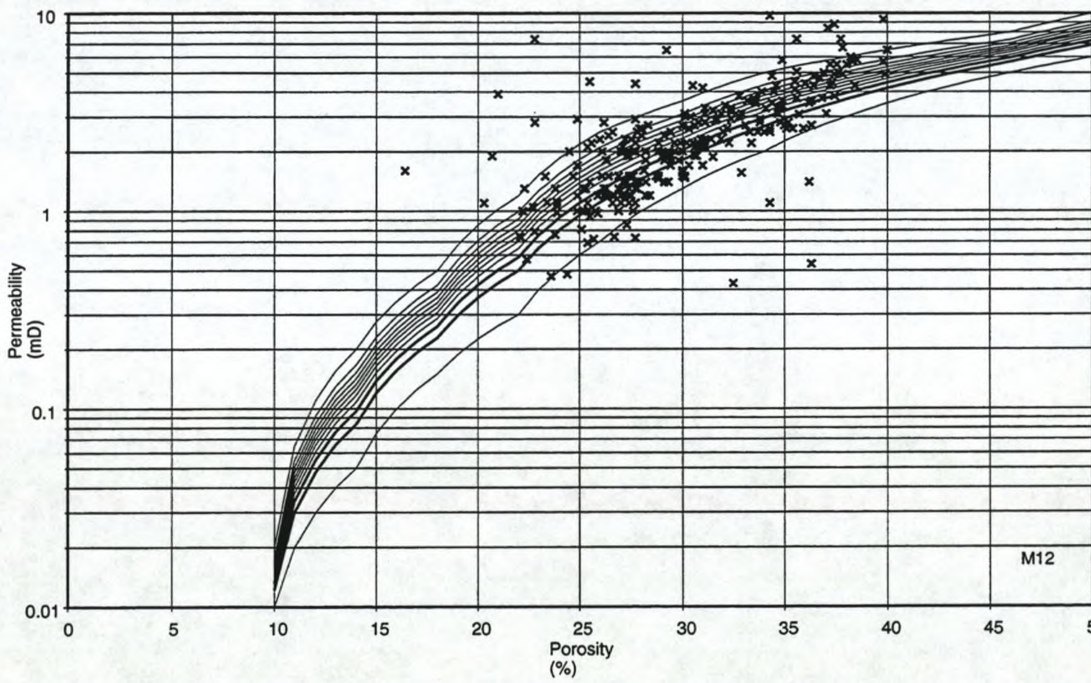


Figure 5
Crossplot of core porosity-permeability data and the constructed decile distribution (10% fractions) for the data population.

This relation is to be honoured during simulation of the permeability model using the already generated porosity model as secondary variable (soft data). The background for constructing the envelope is an evaluation of the quality of the plug measurements. From detailed evaluation of the outcrop plug samples Rügen, Germany, it is seen that fractures in the plugs might invalidate the measurements for a large part of the plug samples. It can be seen that the invalidated values mostly fall in the upper range of the permeabilities outside the main cloud formed by the measurements.

Using this experience on the core plug data, we choose to restrict the range for the porosity/permeability envelope similarly (Fig. 5).

Variography

The variography of the total data set from all Dan Field wells in the M12 zone has been analysed, and the vertical correlation ranges have been modelled (Fig. 6a,b). One single well from this zone, the M10x, has also been analysed in detail and shows clearly a vertical short correlation range of 1.5 meters (Fig. 6c).

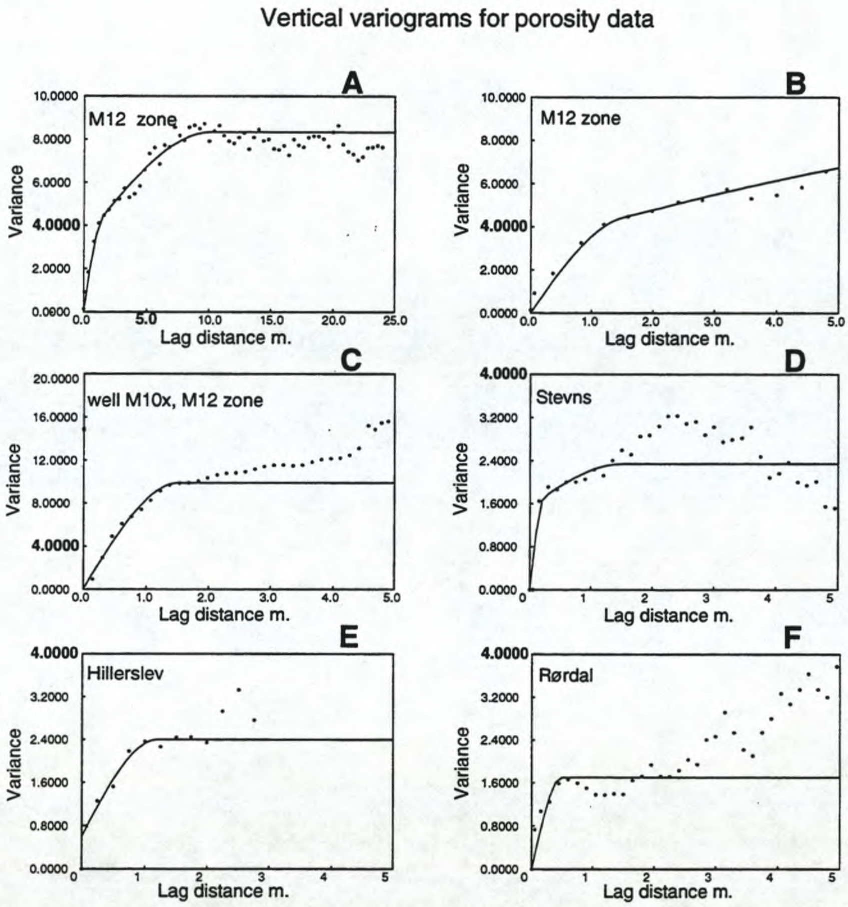


Figure 6
Variograms for different data.

The variography of porosity data from different outcrops (Fig. 6d,e,f) suggests that very short correlation ranges can be modelled (0.2-1.2 meter). These models do not contradict the models based on the well data, and supports the definition of the very short ranges for the detailed modelling. The outcrops occur at different stratigraphic positions in the Maastrichtian, and the layering may thus have slightly different depositional origins, which has to be investigated further.

For the horizontal variography, the long range structures of 400 and 900 meters derived from the porosity well data are used.

Modelling

The models are generated in GSLIB 3D grids (Deutsch & Journel 1992), The format is shown on Fig. 7 and it should be noted that this grid format deviates from e.g. Eclipse grid format, which is common to many commercial reservoir simulators.

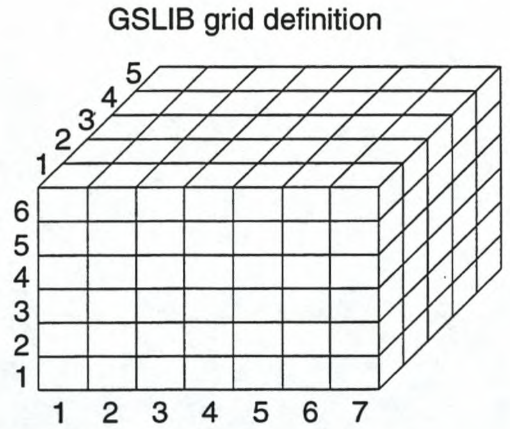


Figure 7
Grid format for the GSLIB grids for the models

For the generation of the detailed model, a cell size of 1 x 1 x 0.20 meters is used. For this study the data for porosity and permeability derived from the core-plug data, is found representative for this volume of 0.2 m^3. This could of course be questioned, and subjected to investigation at an even finer scale.

The geomodel example, Model-5, is simulated as an unconditional simulation with SGSIM v.2.0, using two spherical structures of 1 and 10 meter range for the vertical and 400 and 900 meters for the horizontal, each structure accounting for 38/62 % of the variance respectively. These long ranges used for the horizontal variogram will cause a reduced variance in the horizontal direction within the 80 meter block, and will impose a horizontal continuity in the model. This lower sill value in horizontal direction is termed zonal anisotropy. Combined with the vertical variations the result is seen as layering.

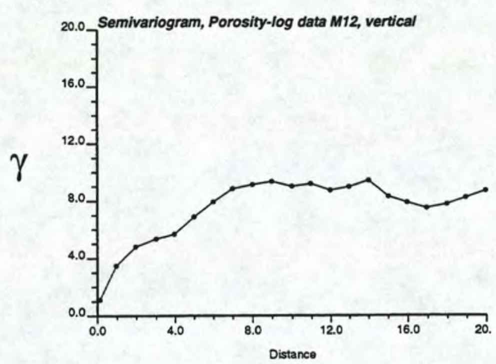


Figure 8
Variograms from the M12 data set.

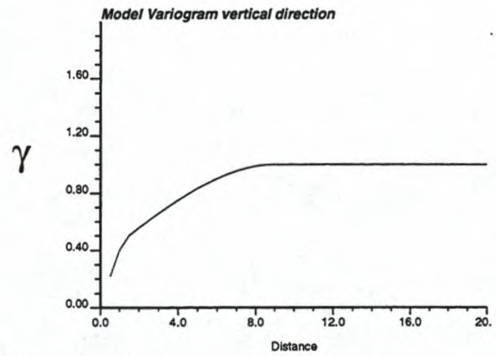


Figure 9
Model variogram for geomodel

For simulation of permeability, a method based on annealing with the program SASIM (Deutsch & Cockerham 1994) is used. The annealing scheme is used to honour the bivariate distribution and the variogram, and is using the prior porosity model as secondary data for the cosimulation of permeability with porosity.The description of the bivariate relation for porosity/permeability is carried out by specifying the envelope for minimum and maximum permeability, and constructing the decile distribution for permeabilities within the envelope (Fig. 4). This is then acting as a synthetic population used by SASIM to be honoured during the annealing scheme. The same variogram structure as for porosity is used for the permeability model, since no additional data on different permeability variograms are available.The total model simulated is 80x80x10 meters in order to illustrate the m-scale layering induced and to evaluate the variogram honouring by comparison to the model variogram used for input. For the evaluation of effective properties of larger blocks, the model is sliced into 10 individual blocks, each being 80x80x1 meter.

The model of permeability was then simulated using the previously simulated porosities as secondary data, honouring the relationship seen in Fig. 5 and the same variogram structure as given for the porosity. As porosity is used as soft data for the permeability simulation, the realisations show concurrent differences in permeability distribution. An example shows the layering in a vertical section (Figs 10 and 11).

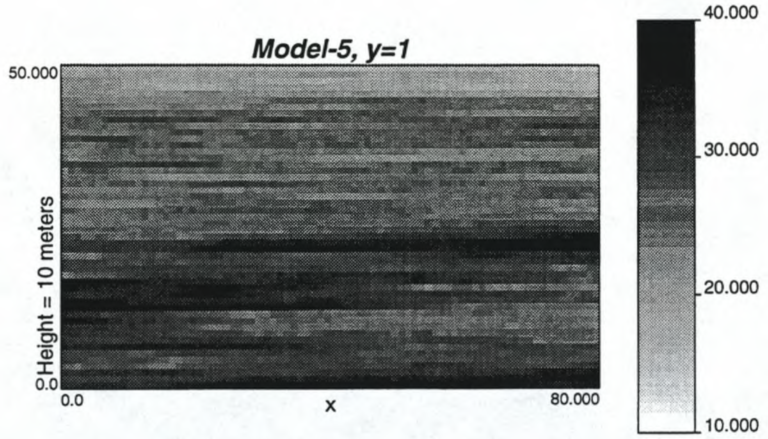


Figure 10
Vertical section at y=1 in model-5, porosity%.

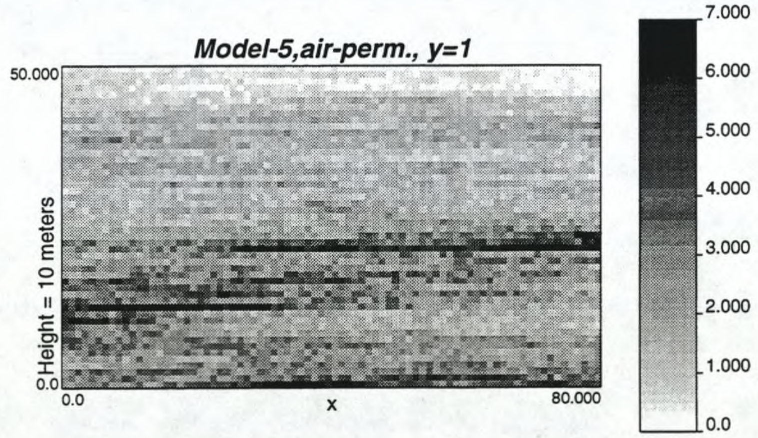


Figure 11
Vertical section at y=1 in model-5, air permeability mD.

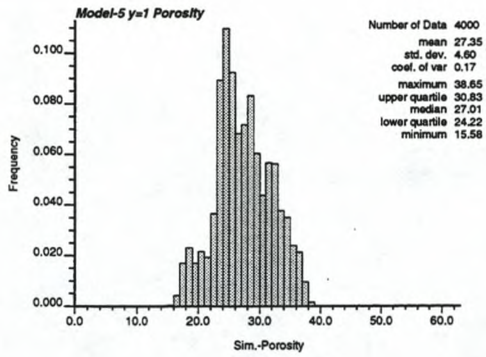


Figure 12
Histogram of simulated porosity for vertical section at y=1, Model-5

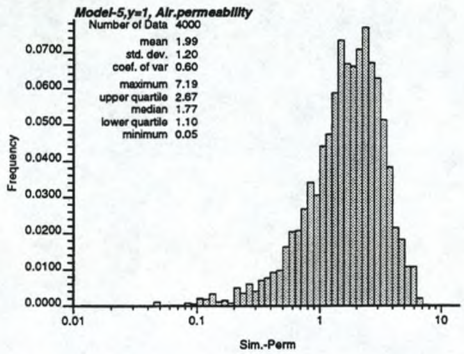


Figure 13
Histogram of air-permeability (log-scale) for vertical section at y=1, Model-5.

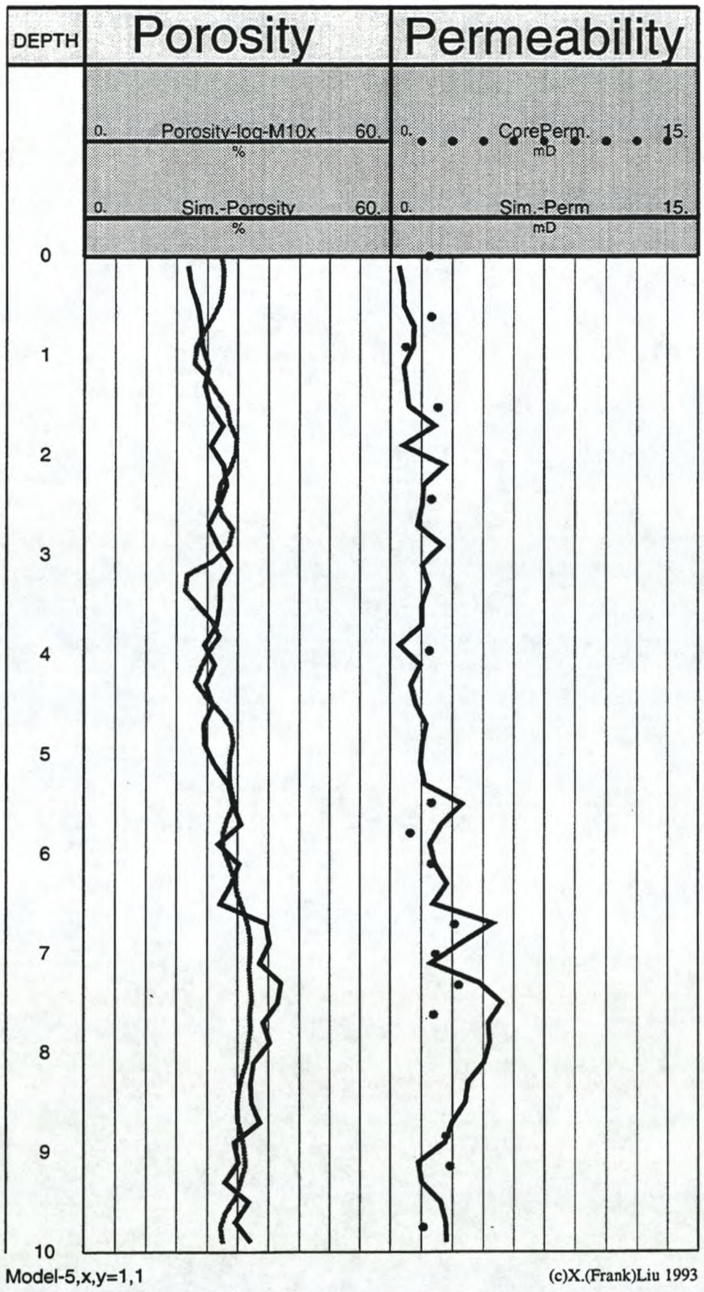


Figure 14
Plot of log data from the uppermost M12 in the M10x well, and simulated values for the vertical corner column of the model no.5.

The variogram for the simulated porosity model shows fair honouring of the input variogram model in the vertical direction (Figure 15), and the zonal anisotropy is reflected in the model as specified in the variogram model by the lower variance in the horizontal direction compared to the vertical direction (Fig. 16).

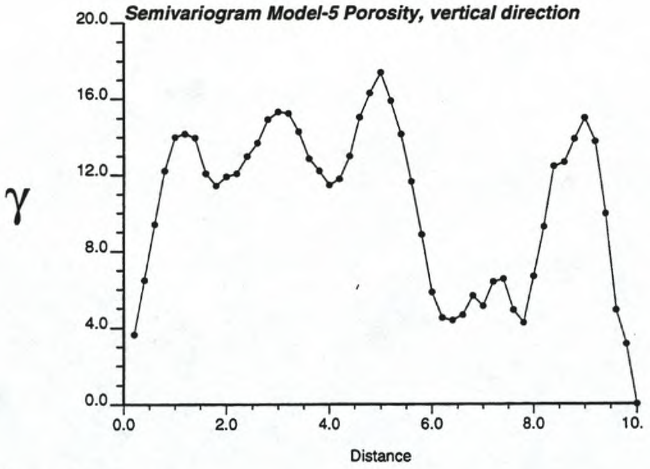


Figure 15
Vertical variogram for porosity Model-5

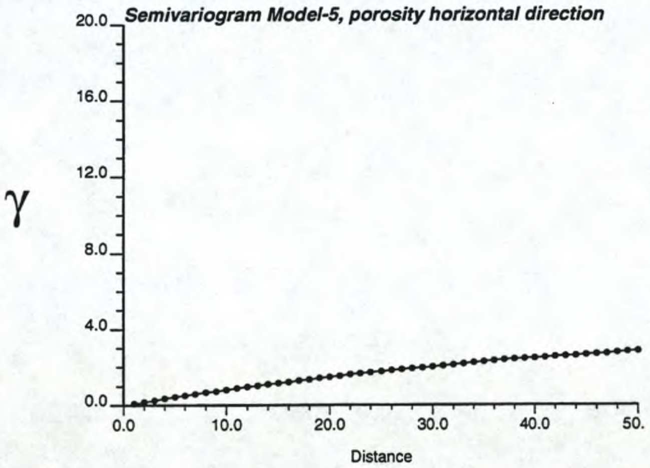


Figure 16
Horizontal variogram for porosity Model-5

Anisotropy analysis of model-5

The 10 meter thick realisation of the layered model is subdivided into 10 blocks, each being 80x80x1 meter, corresponding to a geostatistic modelling cell for a normal full field model. The effective permeabilities for the three directions for each of the 10 sub-models have been calculated with a flow simulator FLOWSIM (Tran 1995b), which computes effective permeability for the three main directions respectively using constant pressure gradients with no-flow boundaries.

The histograms for the porosity, permeability, anisotropy and the relation for the derived average porosity and effective permeability values for the 10 subcells are shown on Figs. 17-20.

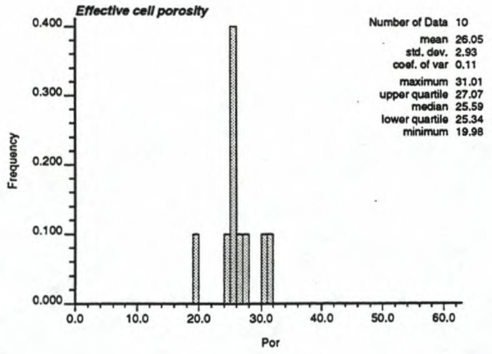


Figure 17
Effective cell porosity

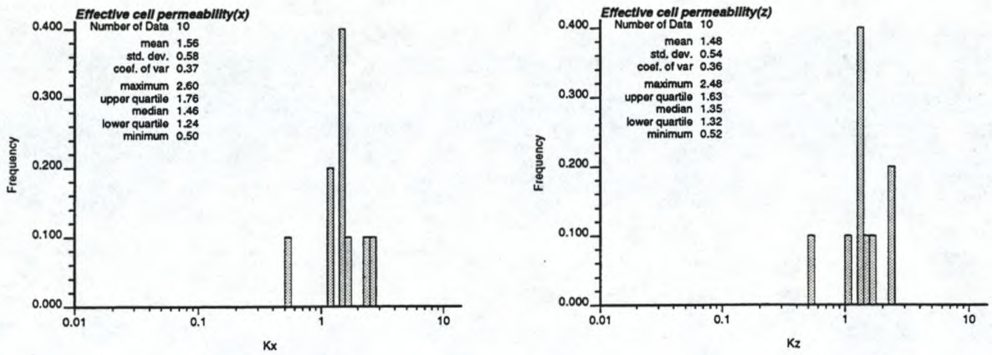


Figure 18
Effective permeability for x and z direction

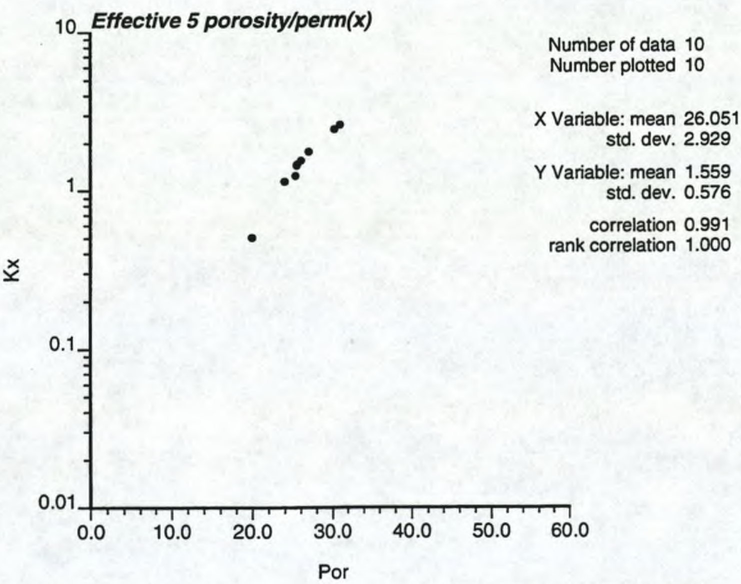


Figure 19
Relation for the effective cell properties.

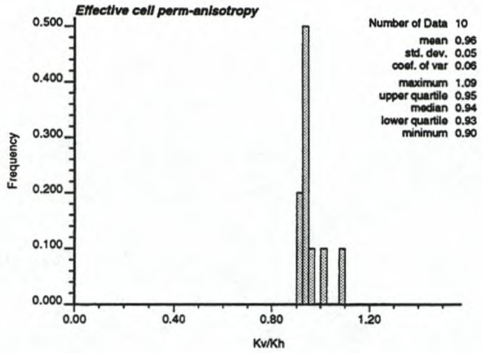


Figure 20
Ansisotropy factor for the effective cell permeabilities

The results show that the 80x80x1 meter blocks have a mean Kv/Kh of 0.96 (range 0.90 - 1.09) as shown on Fig. 20.

All the results for the 1 meter cells are shown on Fig. 19, and the results for the three directions (x,y,z) all fall close to the midline for the original data porosity-permeability relationship.
There seems to be a relation between the permeability level of the cell and the amount of anisotropy (Fig. 19). For the 1 meter cells there might be a correlation between the average permeability and the anisotropy factor, but this is based on very few and scattered data and must be supported by more studies.

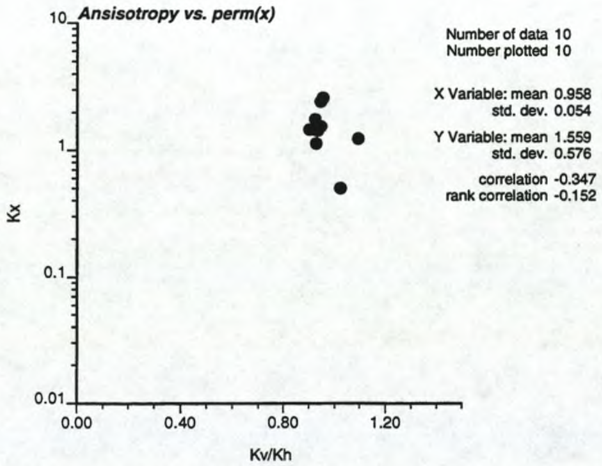


Figure 21
Anisotropy versus the effective permeability(x).

Fluid perm

For the purpose of flow simulation, the fluid permeability has been derived by conversion of the air permeability with an empiric relation assumed for Upper Maastrichtian samples.

$$K_{fl} = 0.52 \cdot K_{air}^{\ 1.083}$$

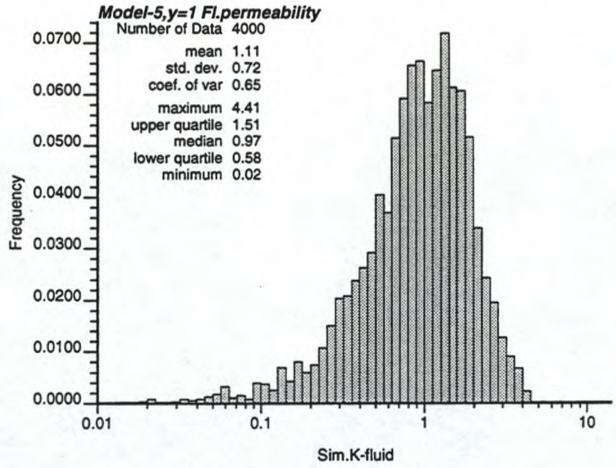


Figure 22
Histogram of fluid perm for y=1 in model

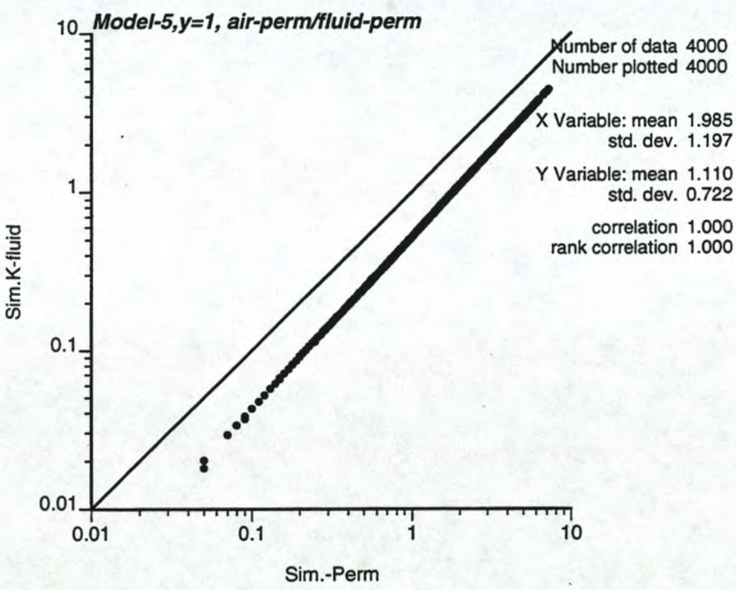


Figure 23
Crossplot of air- and fluid-perm for y=1

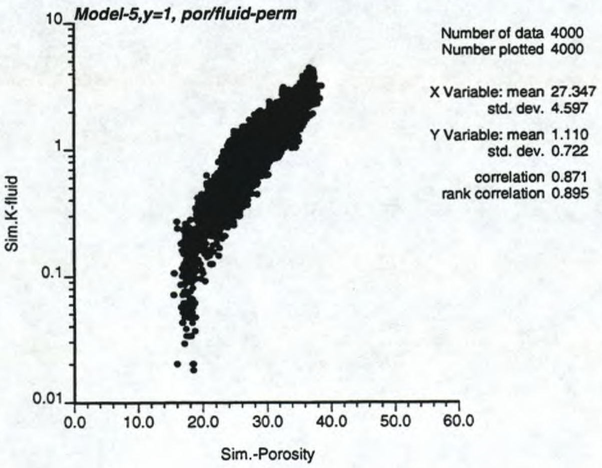


Figure 24
Crossplot of porosity and fluid perm for model-5 y=1.

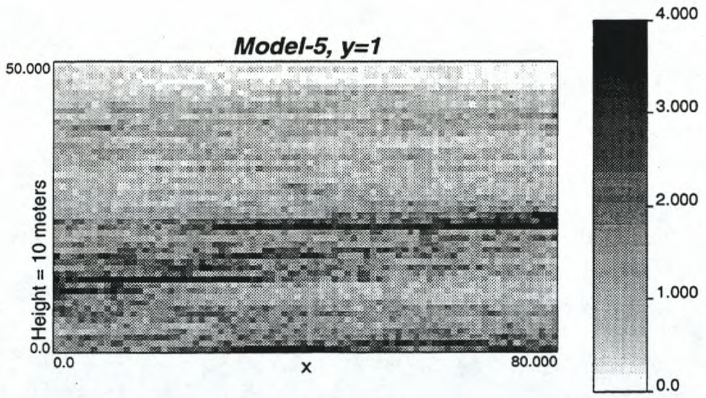


Figure 25
Section at y=1 model-5 showing fluid perm lin scale

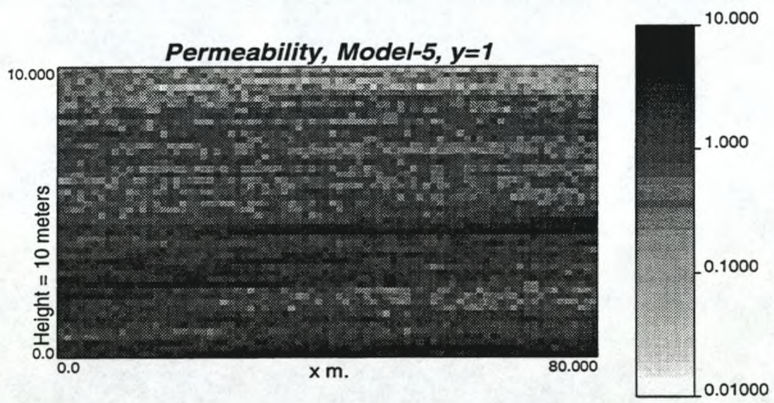


Figure 26
Section at y=1 model-5 showing fluid perm log scale

Discussion

For a model of 80x80x1 meter corresponding to a large geostatistic model block, and using a cell size of 1 x 1 x 0.20 meters, the mean permeability anisotropy factor is shown to be 0.96. This is a result of the internal layering in the package.

If anisotropy at very small scale (5-10 cm) is deduced by measuring both vertical and horizontal plugs from chalk core material, this has rarely any direct relevance for the larger scale anisotropy. This is because the features causing the small scale anisotropy (solution seams, clay laminae, stylolites) do not extend laterally very far, and the anisotropy will therefore be overestimated by the plug analysis. However, this effect must be further evaluated and can possibly be investigated by a similar model procedure at very small scale if the parameters for mm-size volumes can be supplied for input to the models.

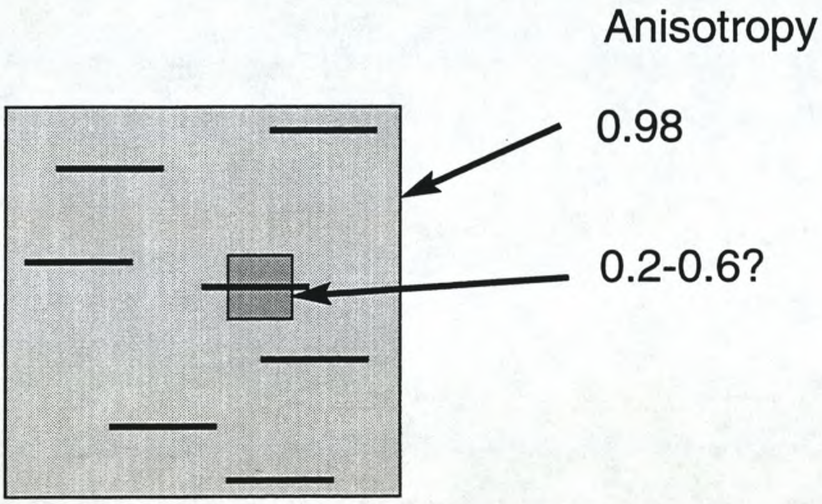


Figure 27
Illustration of the scale dependence of anisotropy measurements in a volume of chalk with small heterogeneities.

The derived porosity-permeability relation for the effective properties for the 80 x 80 x 1 meters geostatistic cells could be transferred and used for the full field modelling. However, some practical experience from work with clastic reservoirs indicates that the reduced variability as it is seen for the effective properties might not benefit adequately the history match of flow simulation. This reduced variability for the effective properties is partly due to the maximum entropy behaviour of the sequential gaussian method used for the geostatistic modelling (Journel & Deutsch 1993). To compensate for this effect, inclusion of higher variability, i.e. a distribution closer to "rock-properties", probably would give a better match of the response from the flow-simulation, or alternatively application of a modelling technique which can better reproduce high contrasts in the heterogeneity. Whether this pattern is also valid for chalk reservoirs remains to be tested by studies of fine scale reservoir flow simulations.

Conclusions

- Based on outcrop data, the well data and core plug data, geostatistic modelling is used to produce an finescale geomodel that includes heterogeneities at their relevant scale.

- From the detailed outcrop data it is seen that vertical correlation structure with short ranges exists, partly originating from a layered pattern in the porosity distribution.

- The layering has different origins depending on the depositional and diagenetic processes for the sequence analysed.

- The porosity-permeability trend for the reservoir data is probably specific for each field, for each reservoir zone, and depending on lithological and diagenetic differences.

- Using the porosity-permeability relation from the plug data and the short ranges from the outcrop investigations, a detailed geostatistic geomodel with distinct layering can be produced.

- Flowsimulation of the fine-scale model is used to investigate the effects of layering on the effective Kv/Kh ratio for a volume of 80 x 80 x 1 meters.

- The layering is causing an average anisotropy of 0.96 when using an 80x80x1 meter model, indicating that this cell size is a reasonable choice for the further large-scale geostatistical modelling with an isotropic modelling cell.

- If however, the average anisotropy in other cases is deemed critical, a large scale reservoir model with two permeability fields can be generated honouring this anisotropy. It can possibly also utilize the correlation between average permeability and anisotropy factor, where low permeability blocks are seen to have a higher anisotropy ratio than the high permeability blocks.

Acknowledgements:

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Appendix 1

Parameters for SGSIM

```
                    ********************
START OF PARAMETERS:
../average/meanfn.datw      \file with data
1 2 3 9 0 0             \ columns for X,Y,Z,vr,wt,sec.var.
-1.0     1.0e21          \ trimming limits
0                       \transform the data (0=no, 1=yes)
mpowtvd.trn                \ file for output trans table
0                       \ consider ref. dist (0=no, 1=yes)
histsmth.out             \ file with ref. distribution
1 2                      \ columns for vr and wt
10.0   48.0                \ zmin,zmax(tail extrapolation)
1      10.0               \ lower tail option, parameter
1      48.0               \ upper tail option, parameter
1                       \debugging level: 0,1,2,3
dbg.sgsimsu                  \file for debugging output
sgsim.5                  \file for simulation output
1                       \number of realizations to generate
80  .5  1.0              \nx,xmn,xsiz
 80 .5  1.0              \ny,ymn,ysiz
 50  0.1   0.20              \nz,zmn,zsiz
69065                     \random number seed
0   8                    \min and max original data for sim
32                           \number of simulated nodes to use (24 is
good)
1                       \assign data to nodes (0=no, 1=yes)
1    3                   \multiple grid search (0=no, 1=yes),num
0                       \maximum data per octant (0=not used)
500.0   500.0      10.0                 \maximum  search  radii
(hmax,hmin,vert)
  0.0    0.0   0.0        \angles for search ellipsoid
0                              0.58                            1.0
\ktype:(0=SK,1=OK,2=LVM,3=EXDR,4=COLC),corr.,red
../soft/tvdfnm12.gsl           \ file with LVM, EXDR, or COLC
variable
4                       \ column for secondary variable
2  0.00                    \nst, nugget effect
1  0.38 0.0  0.0  0.0 1.  \it,cc,ang1,ang2,ang3,power
    400.0  400.0  1.0     \a_hmax, a_hmin, a_vert
1  0.62 0.0  0.0  0.0 1.  \it,cc,ang1,ang2,ang3,power
    900.0   900.0  10.0    \a_hmax, a_hmin, a_vert
```

Parameters for SASIM simulation of permeabilities
Simulated Annealing Based Simulation

```
          ************************************
START OF PARAMETERS:
0 1 0 0 1                    \components: hist,varg,ivar,corr,bivh
1 2 1 1 1                    \weight:   hist,varg,ivar,corr,bivh
0                          \0=no transform, 1=log transform
1                          \number of realizations
80   0.5   1.0               \grid definition: nx,xmn,xsiz
80   0.5   1.0               \               ny,ymn,ysiz
50    0.1   0.2               \               nz,zmn,zsiz
69065                         \random number seed
2                          \debugging level
dbg.sasim                        \file for debugging output
sasimu.5                       \file for simulation output
1                          \schedule (0=automatic,1=set below)
1.0      0.1    70       8    3    0.00001           \      schedule:
t0,redfac,ka,k,num,Omin
100.0                         \  maximum number of perturbations
0.01                         \  reporting interval
0                          \conditioning data:(0=no, 1=yes)
../average/meanfn.dat             \  file with data
1  2  3  8                   \  columns: x,y,z,attribute
-990     1.0e21                  \  trimming limits
1                          \file with histogram:(0=no, 1=yes)
bomaa12.sub                  \  file with histogram
8  0                         \  column for value and weight
99                           \  number of quantiles for obj. func.
1                          \number of indicator variograms
2.78                          \  indicator thresholds
por.5                      \file with gridded secondary data
2                            \  column number
0                            \  vertical average (0=no, 1=yes)
0.75                          \correlation coefficient
bdpope.out                       \file with bivariate data
2   1   0                     \  columns for primary, secondary, wt
0.001   9.0                    \  minimum and maximum
12                            \  number of primary thresholds
12                            \  number of secondary thresholds
24                         \Variograms: number of lags
1                            \  standardize sill (0=no,1=yes)
2   0.0                      \  nst, nugget effect
1  0.38  0.0   0.0   0.0  1.   \it,cc,ang1,ang2,ang3,power
    400.0  400.0   1.0       \a_hmax, a_hmin, a_vert
1  0.62  0.0   0.0   0.0  1.   \it,cc,ang1,ang2,ang3,power
    900.0   900.0   10.0      \a_hmax, a_hmin, a_vert
```