Proceedings of Global 2009
Paris, France, September 6-11, 2009
Paper 9225

Assessing the Spatial Continuity of Low Permeability Media for Deep Waste Disposal: the Boom Clay Case

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Abstract – *The Boom Clay is currently investigated as potential host formation for the deep disposal of high-level and/or long-lived radioactive waste in Belgium. As such, the formation is expected to play a role of natural barrier, to slow the migration of radionuclides towards the biosphere for a sufficiently long time when the man-made barriers are no longer effective. In this context, the Boom Clay aquitard requires to be precisely characterized in terms of hydrogeological parameters, to confirm its role of geological barrier between its surrounding aquifers. Therefore, hydraulic conductivity and migration parameters have been intensively measured in a few boreholes in Belgium, mainly located in the Mol-Dessel area, assuming a good lateral continuity of the geology. Combining these measurements with more densely acquired geophysical information allows quantifying their spatial variability and consolidating the continuity assumption. From a methodological point of view, the modeling of hydrogeological parameters requires to solve several issues. First, it is required to find a consistent geo-reference system allowing to laterally correlate thin observations derived from boreholes separated by several tens of kilometers. Then, in order to provide a reliable 3D model, it is compulsory to integrate the correlation between the scarcely sampled target parameters (core measurements) and numerous geophysical logs (gamma ray, resistivity). Geostatistics provides a suitable framework to analyze and solve these issues.*

I. INTRODUCTION

The general safety objective of disposal as the final step of radioactive waste management is to protect Man and environment, now and in the future. The safety objective and the strategy for disposal are implemented through different safety functions, i.e. functions that the disposal system should fulfill to achieve its general safety objective of providing long-term safety through concentration and confinement strategy. One of the safety functions considered by ONDRAF/NIRAS is to delay and attenuate the releases, itself subdivided into several sub-functions: limitation of contaminant releases from the waste forms, limitation of the water flow through the disposal system and retardation of contaminant migration.

A number of engineered and natural barriers, fulfilling different safety functions, are placed between the contaminants and the accessible environment. The set of components and barriers contributing to the confinement strategy constitute the “disposal system”. This system thus relies on the multiple barrier principle: the “super-container” containing the vitrified waste, the repository itself and the host formation in which the disposal could be constructed. The latter is the most important as it is the one that has to slow the migration of radionuclides towards the biosphere for a sufficiently long time when the man-made barriers are no longer effective.

The Boom Clay is currently investigated as the reference host formation for such disposal in Belgium [10]. It is required to precisely characterize this aquitard in terms of hydrogeological parameters, to confirm its role of geological barrier between its surrounding aquifers. Hydraulic conductivity and migration parameters (diffusion coefficient and diffusion accessible porosity) have been intensively measured in few boreholes in Belgium, mainly located in the Mol-Dessel area, assuming a good lateral continuity of the geology. Combining these measurements with more densely acquired geophysical information allows quantifying their spatial variability and consolidating the continuity assumption.

Despite an interest in vertical / horizontal hydraulic conductivities and also migration parameters, only the vertical hydraulic conductivity (Kv) modeling is presented in this paper.

Geostatistics aims at providing quantitative descriptions of natural variables distributed in space and time [2]. Initially developed to address ore reserve evaluation issues in mining [9], it has been applied since the seventies in hydrogeology [3] and with similar approaches in geological modeling and reservoir characterization [5]. In the present case, geostatistics allows (i) to describe the spatial variability of hydraulic conductivity, (ii) to properly integrate correlated variables such as grain-size or geophysical data, (iii) to quantify the uncertainty attached to the hydraulic conductivity estimates.

The paper first describes the geological context and the available data: core analysis and geophysical logs. Then, the methodology is detailed, including a brief reminder of geostatistics. Finally, results are presented with a particular highlight on Mol-1 key borehole.

II. MATERIAL

II.A. Geological Context

The Boom Clay is a marine Oligocene clay of approximately 100m thick deposited in the North Sea basin (Fig. 1). It is known in Germany, The Netherlands and Belgium as a continuous layer gently dipping (~1°) towards the north-north-east but also gaining thickness in this direction. The reason for the latter is dual: firstly the sedimentation rate was larger more towards the center of the basin (north) and secondly the southern part experienced significant erosion at the end of the Oligocene.

One of the most remarkable characteristics of the Boom Clay is its structure of bands that are several tens of centimeters thick, reflecting mainly cyclical variations in grain size (silt and clay content). Also, the Boom Clay has always been assumed to be extremely laterally continuous [10]. This explains why considerable effort has been done to investigate its behavior mainly in the Mol-Dessel nuclear area, where an underground laboratory (HADES-URF) has been set up in the early eighties.

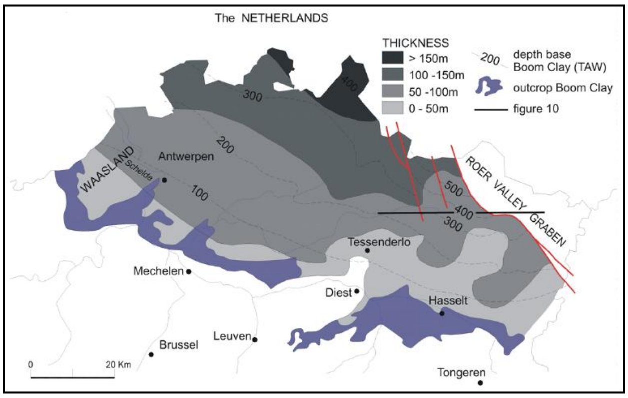

Fig. 1. Outcrop and subcrop of the Boom Clay also showing depth to base relative to sea level and thickness (from [10]).

II.B. Core data: hydraulic conductivity and grain-size

Focusing exclusively on the Boom Clay formation, one set of vertical hydraulic conductivity (Kv) has been determined on 134 samples coming from 5 boreholes: Mol-1, Weelde, Doel-2b, Zoersel and Essen. Kv data are derived from two different approaches: permeameter cells (83 measurements) and migration experiments (51 measurements).

The consistency between the hydraulic conductivities measured with permeameter cells or migration experiments has been evaluated on seven cores of Mol-1 borehole where both techniques have been applied. These measurements are performed on different plugs, as it is not possible to use the same sample (plug) for both experiments. The average difference in depth between the plugs is 15 cm, which is significant compared to possible variations of hydraulic conductivities between the clayey and silty beds. Despite this, the differences between the two Kv logarithms are lesser than 0.2. Consequently, the final vertical hydraulic conductivity database is obtained by merging permeameter cells measurements with migration experiments results.

Regarding grain-size, 410 analyses have been acquired for the Boom Clay formation on four boreholes: Mol-1, Weelde, Zoersel and Essen. Consistently with previous work [7], we exclusively consider the variable d40 as a potential explanatory variable for hydraulic conductivity modelling. This variable, defined as the size such that 40% of the particles are finer than this diameter (in µm), is the one that maximizes the correlation with hydraulic conductivities.

II.C. Geophysical logs

Hydraulic conductivities have to be measured in laboratory from core samples, resulting in expensive acquisition and analytical costs. On the other hand, almost all boreholes are logged. Geophysical logs can therefore constitute the main source of information for transferring knowledge about target parameters outside from a few cored and analysed boreholes. As a consequence, numerous research projects had been focused for decades on the evaluation of hydraulic conductivity from geophysical logs, mainly for Oil & Gas applications [1].

The geophysical database is mainly constituted by ONDRAF/NIRAS, SCK●CEN and some deep logs from the Geological Survey of Belgium (GSB). Only gamma ray and resistivity logs are analysed in this paper, because of their expected correlation with hydraulic conductivity data. Fig. 2 presents such logs obtained on Mol-1 borehole.

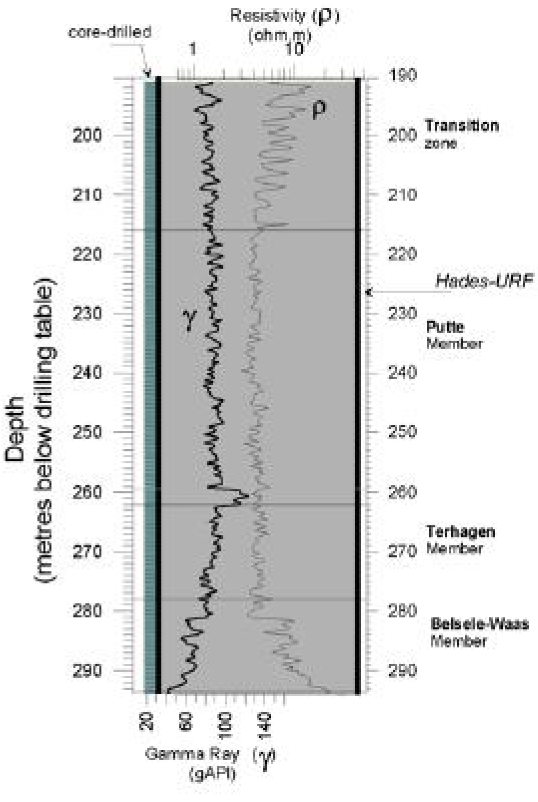

Fig. 2. Stratigraphic log of the Mol-1 borehole: gamma ray and resistivity curves, location of main litho-stratigraphic units and of the underground laboratory Hades-URF (from [10]).

Before evaluating the correlation with hydraulic conductivity, a preliminary quality control of the logs allowed to select relevant curves and put aside useless logs. Two preliminary empirical tests allowed to discard logs with insufficient resolution, by looking at:

- the general shape and the noisy aspect of the log,
- the possibility to clearly identify clear markers using Gamma Ray / Resistivity logs.

III. METHODOLOGY

III.A. Geostatistical framework

Geostatistics is classically applied to study the spatial variability of a target parameter (hydraulic conductivity) in order to predict it at unsampled locations. Its use commonly relies on a two-step procedure. Firstly, variogram modeling consists in (i) describing the spatial continuity of the target parameter from input data and (ii) fitting analytical models defined by a few parameters (range, sill, nugget effect) to this experimental variogram. Then, spatial prediction at unsampled locations is obtained using kriging-like techniques.

Secondary information is usually available in addition to the target parameter. In the present case, grain-size data are more densely sampled on cored boreholes and geophysical logs are also available on both cored and other boreholes. Correlation analysis and regression is widely used as a statistical method to search for relationships between core permeability, grain-size data and well log parameters [1]. Then, cokriging techniques aim at integrating this secondary information and therefore reducing the uncertainty about the variable of interest at unsampled locations.

See [2] for a complete overview of geostatistics or [4] for a presentation focused on radiological data.

III.B. Choice of a geo-reference system

Analysing the lateral variability of hydrogeological parameters within the Boom Clay implies to work in a geo-reference system which is consistent with the formation; this will be required to laterally correlate thin observations derived from boreholes separated by several tens of kilometers.

Due to the global dipping and the thickness increase of the Boom Formation towards the North-East, an « horizontalization » step (unfolding) is compulsory. Therefore, we used the Double Band (DB) level as a vertical « zero » reference. This Double Band corresponds to two silty beds located towards the base of the Putte member. Using gamma ray and resistivity logs, it can be clearly defined by two resistivity peaks located just above a high positive Gamma Ray peak

Working with the DB as vertical reference also avoids having to manage topographic uncertainties and errors in topographic references that sometimes occur on logs and available tables. Apart from the vertical reference, it is also compulsory to compensate varying thickness of the Boom formation and rescale to an homogeneous thickness reference. Finally, the Boom Clay thickness at Mol-1 is taken as a reference and all other boreholes are rescaled to this thickness, in order to be globally consistent.

Using available data about the top and base of the Boom formation, these surfaces have been interpolated using universal kriging [2] with a quadratic trend, together with the double-band surface (see Fig. 3). Considering the Mol-1 borehole as a reference, a rescale coefficient has been derived from the top and base surfaces of the Boom clay. This coefficient has been applied to other boreholes, to correct both the dipping and the thickness increase.

In the following, the obtained geo-reference system is referred to as the "DB-Mol" system.

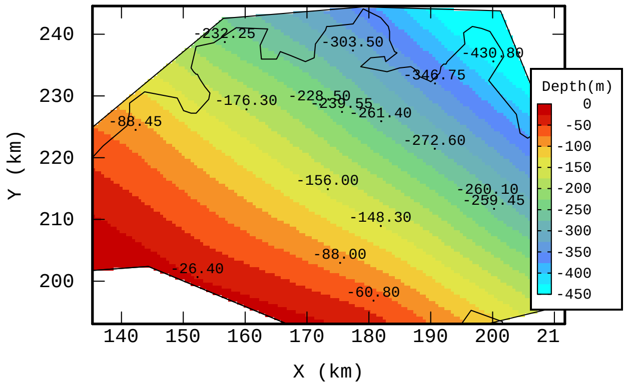

Fig. 3. Kriging of the Double Band (DB) depth over the area of interest. Contour of the northern Belgian border and measured DB values on boreholes are indicated.

Lefranc [8] presents an elegant approach for rescaling such logged boreholes. It is based on the variographic analysis of high resolution geophysical FMI logs, on which several nested structures linked to different cycles can be identified. Factorial kriging analysis [5] allowed her to extract one spatial component of interest, then to locate precisely the layers of interest and to derive a transformation from the original georeference system to a geochronological reference system. In this system it is then possible to accurately characterize the spatial structure. Though promising, this solution has not been retained because of the difficulty to empirically identify and mark the approx. 121 thin layers that constitute the Boom clay.

III.C. Hydraulic conductivity modeling

The amount of available information is critically varying from well recognized boreholes, such as Mol-1, to scarcely covered areas where boreholes have not been cored and only present a couple of gamma-ray and resistivity logs. In order to integrate the best available information in the modeling, a 1D modeling of hydraulic conductivity is first performed independently on each cored borehole with Kv measurements.

Several modeling algorithms are compared, from kriging of Kv alone to cokriging with grain-size, gamma ray and resistivity data. The algorithm choice is obtained from a quality control of the results and a standard cross-validation procedure. The latter consists in removing one Kv data at a time and estimating its value by kriging or cokriging using all the other Kv values; the procedure is iterated for each Kv data, allowing to compute statistics describing the quality of the estimation procedure: average error (bias), variance of errors standardized by the kriging standard deviation (named "variance of standardized error" in the following), correlation coefficient between true and estimated values [6].

Due to the huge variability between resistivity logs among available boreholes, 3D modeling of Kv over the area of interest only integrates grain-size data and GR logs. A correction of the latter is first performed, to account for calibration issues and improve the correlation with Kv data (see below).

IV. RESULTS AND DISCUSSION

IV.A. Consistency of geophysical logs

As the Boom Clay is expected to be a laterally homogeneous geological formation, it is important to assess whether the observed GR variations could be explained by geological trends or are due to calibration or technical logging issues (impact of mud salinity).

This is analysed in detail within the Mol-Dessel area. Fig. 4 presents several GR curves measured on Mol-1 and Dessel boreholes for the Boom Clay depth interval. It is reminded that both boreholes have been logged by the same company, Dessel in 1993 and Mol-1 in 1997.

Though both GR curves from Dessel borehole are consistent, clear discrepancies are noticeable on Mol-1 GR runs: GR curves derived from ROCKCLASS and ELAN are consistent but differ from the resistivity run (ait4). In this case, differences obviously cannot be due to the borehole geometry. Such discrepancies can therefore be attributed to calibration issues or external factors such as the drilling mud composition.

This analysis can be extended to other boreholes. For instance, Fig. 5 presents averaged GR values on boreholes located throughout the area of interest. The GR values are averaged on the Putte member only, expected to present the smoothest GR behaviour within the Boom Clay. The highest values are obtained for Essen and Herenthout boreholes, even if one should be cautious about the latter as the focus was on deeper horizons and not on the logging of the Boom Clay horizon. One can notice that there is almost as much variability between Mol-1 and Dessel than between any pair of boreholes from the area. Notice that, the GR average difference for the Putte member on Mol-1 borehole between a certain run (ait4 used in Fig. 5) and the GR contained in the ELAN compilation is equal to 8 API-units.

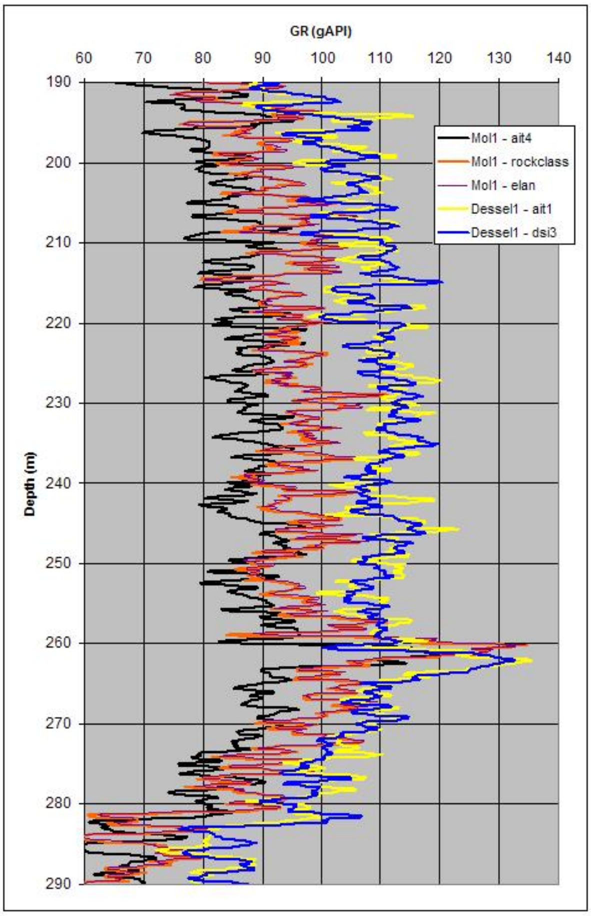

Fig. 4. GR curves obtained on Mol-1 and Dessel boreholes (gAPI). Depth is in mBDT.

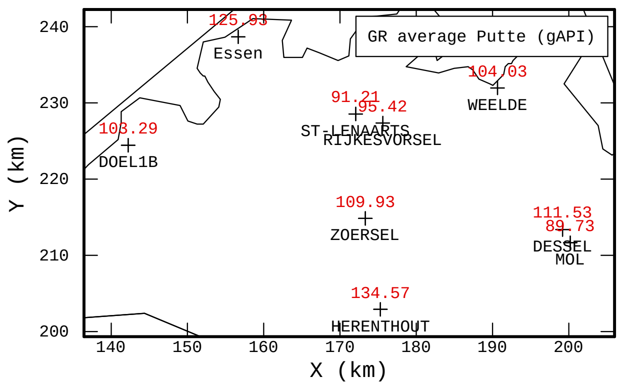

Fig. 5. Average GR values on Putte member for several NIRAS boreholes.

To conclude, the important lateral variability of gamma ray curves throughout the area of interest is at least partly attributable to technical issues. Having in mind this calibration issue, putting into evidence regional trends on gamma ray runs is quite impossible.

IV.B. Statistical analysis of Kv data

Basic statistics about Kv values are presented in TABLE 1 for the whole Boom Clay, together with the depth profiles Kv samples (see Fig. 6).

The sampling of Essen and Doel is sparser than for the other boreholes. The Herenthout Kv value is just presented for information, as this borehole is much more focused on deeper horizons; furthermore, the measured value for this borehole comes from the bottom of the Belsele-Waas member, which explains the higher Kv value.

TABLE 1

Basic Kv statistics within the Boom Clay (in logarithm).

Borehole	**N**	**min**	**max**	**mean**	**st. dev.**
Mol-1	41	-11.91	-10.01	-11.58	0.40
Weelde	28	-11.69	-9.92	-11.11	0.51
Zoersel	34	-11.51	-7.68	-11.05	0.79
Doel-2b	10	-11.40	-10.35	-10.96	0.30
Essen	10	-11.47	-10.00	-11.06	0.47
Herenthout	1	-8.87	-8.87	-8.87	-
TOTAL	124	-11.91	-7.68	-11.21	0.64

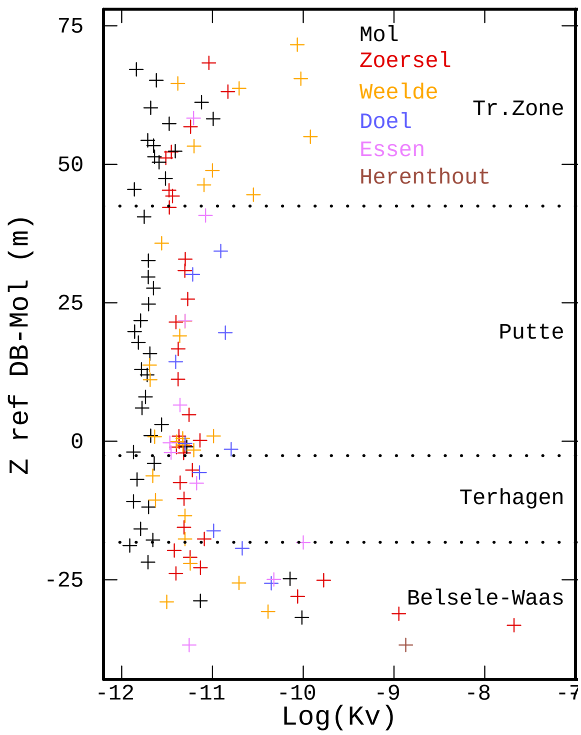

Fig. 6. Log(Kv) available profiles, in the DB-Mol reference system. Indication of main litho-stratigraphic units.

Apart from this borehole, minimum Kv values are similar for the different boreholes. There is much more variability for the maximum values, that range from -7.68 for Zoersel to –10.35 for Doel. For the latter, the low maximum value most probably comes from the fact that the to part of the Boom Clay is missing in Doel. In average, Mol-1 apparently presents the smallest Kv values, being about half an order of K magnitude below the other boreholes. Average Log(Kv) value over the Boom Clay is equal to –11.21, i.e. average hydraulic conductivity is equal to 6.17 10^{-12} $m.s^{-1}$.

Analysing Kv variations for each stratigraphic unit extends this global analysis (see TABLE 2). First, the top and bottom Boom Clay units (Transition Zone and Belsele-Waas member) clearly appear as more permeable, due to the increased presence of silt to sand layers. The similarity between Putte and Terhagen members is also noticeable. The variability also differs from one unit to another, with again the top and bottom units being more variable; this is also visible from the vertical profiles of Fig. 6.

TABLE 2

Basic Kv statistics within the Boom Clay (in logarithm), per litho-stratigraphic unit.

Unit	Nb	min	max	mean	st. dev.
Trans. Zone	30	-11.86	-9.92	-11.20	0.51
Putte	53	-11.87	-10.79	-11.45	0.25
Terhagen	24	-11.91	-10.00	-11.38	0.39
Bel.-Waas	16	-11.71	-7.68	-10.28	1.04

Correlation analysis of Kv with potential auxiliary variables is performed independently for each cored borehole.

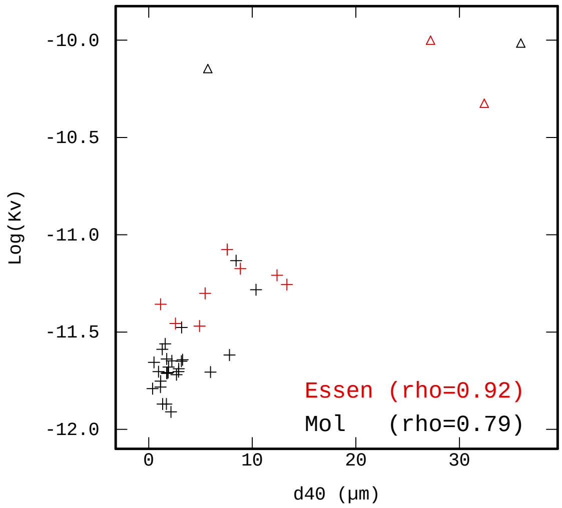

Fig. 7. Scatter-diagram of Log(Kv) (ordinate) versus grain-size variable d40 (abscissa), for Mol-1 (black) and Essen (red) boreholes. Indication of correlation coefficient (rho). Triangles correspond to samples obtained on the Belsele-Waas member.

As expected, the correlation between Log(Kv) and grain-size d40 variable is large, as illustrated on Fig. 7 for Mol-1 and Essen boreholes; indeed, linear correlation coefficients are equal to 0.79 and 0.92 for these boreholes. It appears that a few samples play a large role in this correlation (larger Log(Kv) and d40 values). However, the removal of these samples, that come from the more permeable Belsele-Waas member (bottom unit), leads to a limited decrease of the correlation coefficients, that become equal to 0.8 for Mol-1 and 0.6 for Essen (with only 8 samples remaining for the latter). Therefore, it seems meaningful to consider this global correlation between Log(Kv) and d40 for further analysis.

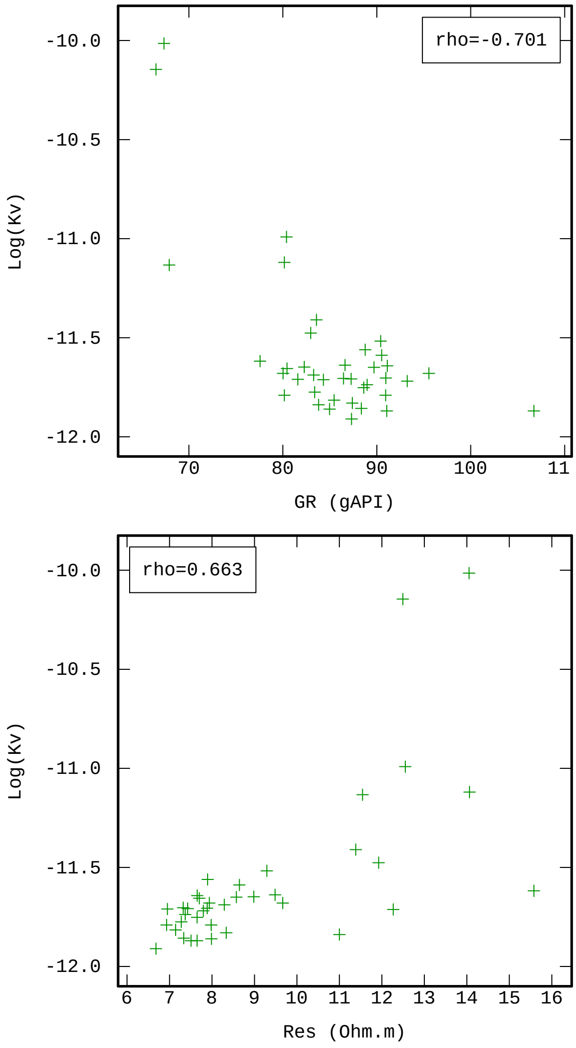

Fig. 8. Scatter-diagram of Log(Kv) (ordinate) versus GR (top, abscissa) and Res (bottom, abscissa). Indication of correlation coefficient (rho).

Correlations with gamma ray and resistivity logs are slightly weaker, with still a large role played by the more permeable units (see Fig. 8). Note that the geophysical logs have been vertically smoothed using a moving radius of 1m. Indeed, because of the cyclical variations between thin silty /clayey beds and the vertical uncertainty on logs, the correlation between core data and geophysical data is increased by this regularization. A multi-linear regression of Log(Kv) with GR and Res variables leads to a final correlation coefficient equal to 0.76 between the regressed variable and Log(Kv).

To conclude, two auxiliary variables are kept for the vertical modeling of Log(Kv), namely d40 and the result of the linear regression of Log(Kv) with GR and Res, denoted reg(GR,Res).

IV.C. 1D Vertical modeling

Fig. 9 presents the vertical variogram modeling of Log(Kv) on Mol-1 borehole, which shows two distinct spatial components: a small nugget effect (discontinuity at the origin) attributable to measurement errors and micro-scale variability, then a structured component which models the rapid increase of the Log(Kv) vertical variability. Similar structures have been used to model the multivariate variogram model constituted of Log(Kv), d40 and reg(GR,Res). This multivariate variogram model is fitted in the framework of the linear model of coregionalization, meaning that all simple and cross-variograms are fitted using linear combinations of the same basic structures [2].

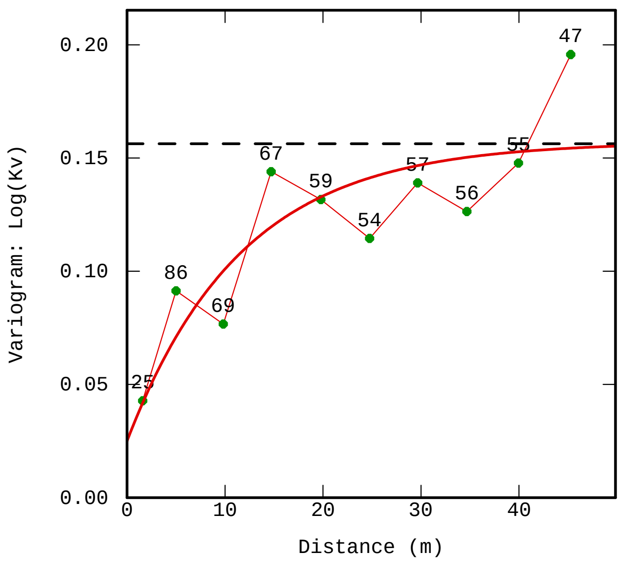

Fig. 9. Experimental variogram (thin line) and fitted model (bold line) for Log(Kv) on Mol-1. Number of pairs for each experimental point and statistical variance (dashed line) indicated.

The efficiency of kriging and cokriging of Log(Kv) with d40 and reg(GR,Res) are then compared using cross-validation. Statistical results together with a scatter-diagram of true vs. predicted Log(Kv) values clearly demonstrate that cokriging outperforms kriging (see TABLE 3, Fig. 10).

TABLE 3

Cross-validation results for Kv modeling in Mol-1 using kriging and cokriging (with d40, GR and Res): correlation coefficient, average error and variance of standardized error.

Estimation method	**Kriging**	**Cokriging**
Correlation coeff.	0.44	0.80
Avg. Error	$-1.1\ 10^{-2}$	$1.6\ 10^{-3}$
Var. Stand. Error	1.95	1.56

This confirmed what was expected, because of the integration of well correlated auxiliary variables in the cokriging procedure. Despite that, one can notice that prediction errors in K can reach one order of magnitude, in particular for more permeable data which are observed in top and bottom units, which show increased variability.

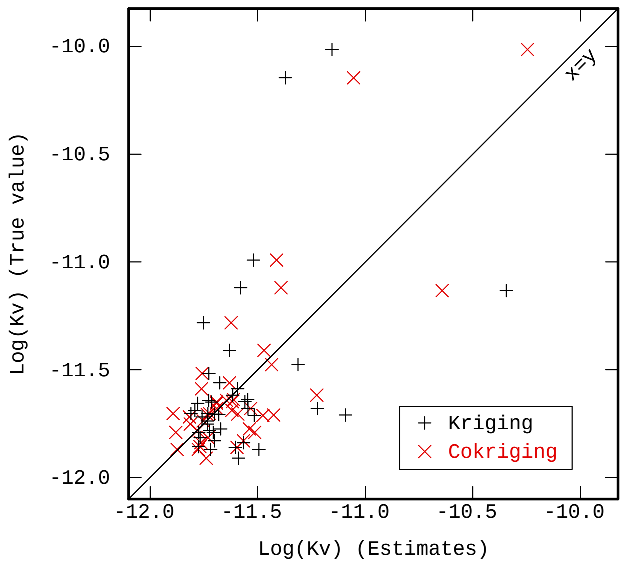

Fig. 10. Cross-validation results for Kv modeling in Mol-1 using kriging and cokriging (with d40, GR and Res): estimates (abscissa) versus true values (ordinate). Indication of the 1st bisector (x=y).

Vertical Log(Kv) profiles obtained on Mol-1 using both kriging and cokriging procedures are displayed on Fig. 11. Consistently with the resolution of the regularized geophysical logs, the vertical resolution of the 1D model is equal to 1m.

First, it can be observed that the kriged profile is by construction relatively smooth, this smoothing being reinforced by the presence of a nugget effect in the Log(Kv) variogram model. Cokriging reduces this smoothness due to the weight given to both grain-size and geophysical data. One has to keep in mind that the amount of information integrated in the cokriging procedure is muc larger than for the kriging, as it includes numerous grain-size data and exhaustive knowledge of the geophysical logs at each target location (collocated variable). The most appealing impact of these auxiliary variables on the estimated profile is at the bottom of the Transition Zone (Depth approx. equal to 43m in the DB-Mol system), where a peak is clearly visible on the cokriged profile. This peak is due to the resistivity log, as it can be seen on Fig. 2.

Differences between the two profiles are globally lesser than 0.5 (one half of an order of K magnitude), except for local peaks such as the one previously discussed. These differences are on average more important in the Transition Zone and also in the Terhagen unit.

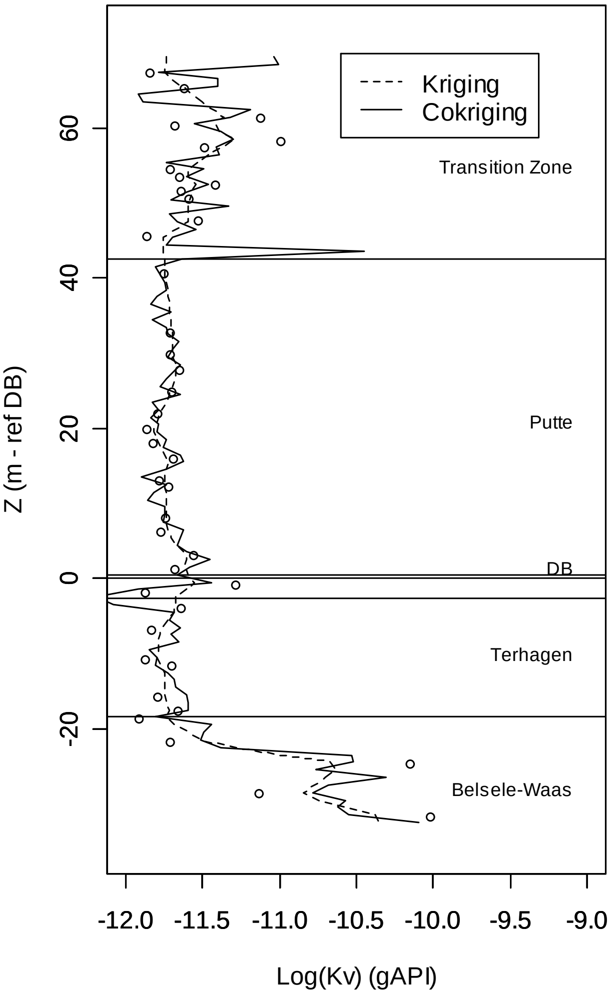

Fig. 11. Vertical profiles of Kv predictions in Mol-1, using kriging and cokriging. Actual data values represented by circles. Indication of main litho-stratigraphic units.

One major advantage of kriging-like techniques is the ability to estimate the uncertainty associated to the Log(Kv) (co)kriged profile. Fig. 12 illustrates this by displaying the (co)kriging standard deviation profiles associated to the preceding estimates. The average kriging standard deviation is equal to 0.22. Local increases of this standard deviation can be observed on depth intervals under-sampled in terms of Log(Kv), for instance around 35-40m depth (DB-Mol reference system).

Compared to kriging, the cokriging approach leads to an average reduction of the standard deviation equal to 13.3%. This reduction locally reaches 25% in under-sampled depth intervals that are scarcely sampled with Log(Kv). In such depth intervals, the reduction of uncertainty in the Log(Kv) prediction is explained by the presence of well correlated grain-size data. Such important observation leads to sampling optimization possibilities, grain-size being cheaper to analyze compared to hydraulic conductivities.

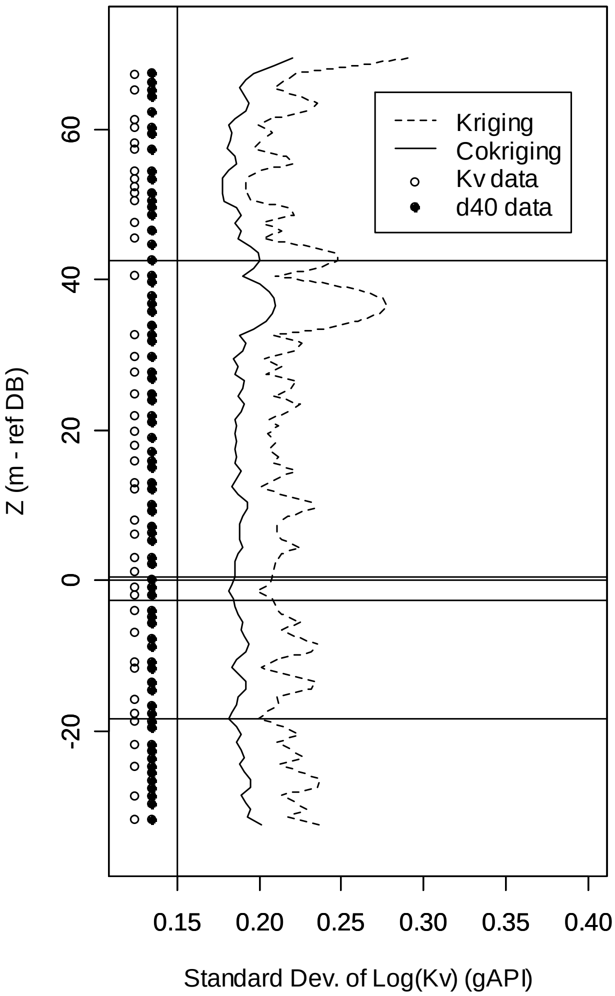

Fig. 12. Vertical profiles of Kv standard deviation of predictions in Mol-1, using kriging and cokriging. Depth location of actual data values represented by circles: Kv (white) and grain-size d40 (black). Indication of the limit of main litho-stratigraphic units.

IV.D. 3D modeling

A final expectation of this project concerns the possibility to provide a 3D regional model of hydraulic conductivities, using all available boreholes. Due to the presence of various types of resistivity runs, it is not possible to build a global correlation model between hydraulic conductivities and this variable. Despite calibration issues, gamma ray logs are less subject to such inconsistencies. Therefore, a 3D model of hydraulic conductivities has been set up by integrating the correlation of Kv with available grain-size (cored boreholes) and gamma ray logs (all boreholes). Regarding the latter, a preliminary additive correction has been applied on each borehole in order to have similar average GR values for the three boreholes. This correction may be interpreted as an indirect way to reduce the impact of GR calibration issues on K modeling. As illustrated on Fig. 13, the resulting correlation between Log(Kv) and GR is much improved, the correlation coefficient increasing from 0.30 to 0.66. Note that the outlier data from the bottom diagram of Fig. 13 comes from the Top of the Transition Zone, subject to increased variability of both GR and Log(Kv).

Again, this modeling required to fit a multivariate variogram model between the variables, similarly to what has been presented in section III.C. A cross-section derived from this 3D cokriging model is illustrated on Fig. 14. This section is globally orientated West-East (slightly dipping towards the South, see Fig. 5) and passes through 3 key boreholes: Doel at the West, Zoersel in the center part and Mol-1 at the East. Note that, because of erosion, the top of the Boom Clay formation disappears when going towards the West.

The cross-section illustrates important trends of vertical hydraulic conductivities. First, vertically one can notice the expected more permeable behavior of the Boom Clay Bottom unit (Belsele-Waas member) and, though less pronounced, of the Top one. Also, the slightly more permeable DB-level (Depth ~0m in the DB system) is visible. Laterally, a global decrease of Log(Kv) is remarkable from West to East. This can be explained by the compaction increase as the Boom Clay goes deeper (in the original structural system) towards the East (see Fig. 3).

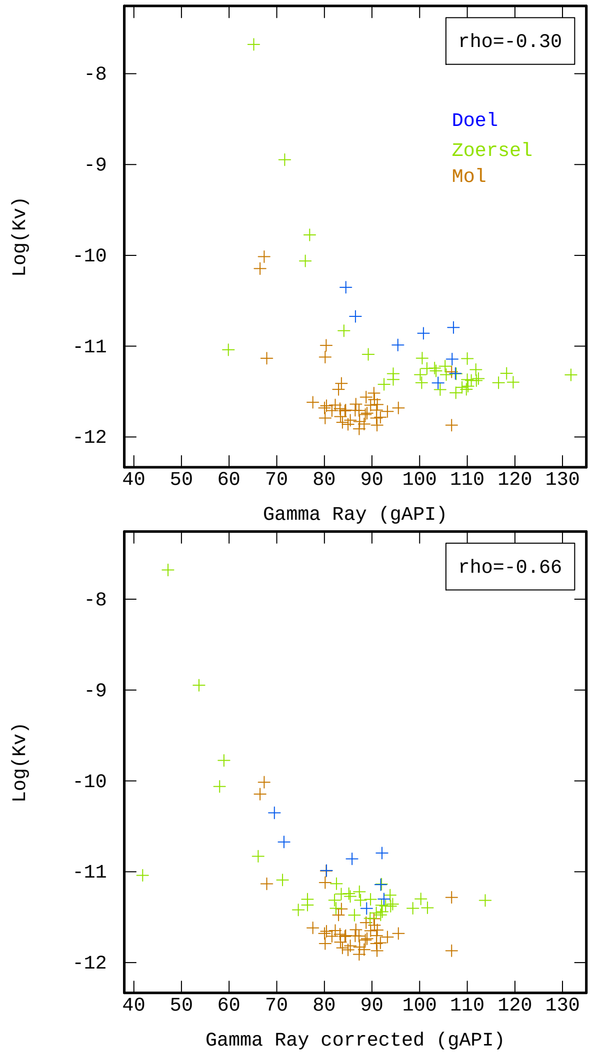

Fig. 13. Scatter-diagrams of Log(Kv) (abscissa) versus raw GR (top, ordinate) and corrected GR (bottom, ordinate), for three boreholes. Indication of correlation coefficient (rho).

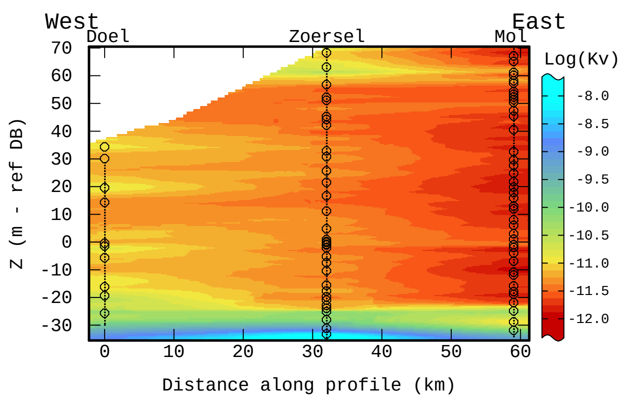

Fig. 14. 3D modeling of Log(Kv) – Cross-section along the profile Doel-Zoersel-Mol (see Fig. 5). Location of boreholes with actual Kv data (o).

V. CONCLUSIONS

Being currently investigated as potential host formation for deep disposal of high-level and/or long-lived radioactive waste in Belgium, the Boom Clay formation needs to be precisely characterized in terms of hydrogeological parameters. Focusing on vertical hydraulic conductivity, the paper illustrated the ability of geostatistics to provide a suitable framework for such a characterization.

In-depth analysis of the database consistency is a key aspect of this methodology, as the database presents an important heterogeneity level (various types of both core measurements and geophysical logs) and covers only scarcely the large area of interest density of information spatially variable). Then, the approach provided meaningful vertical estimation of target parameters, together with an estimate of the associated uncertainty, finally 3D modeling to capture regional vertical and lateral trends over the area of interest.

Further work includes the elaboration of recommendations for optimized sampling schemes, together with the quantification of local uncertainty with stochastic simulations.

ACKNOWLEDGMENTS

All geostatistical calculations and graphics have been obtained using the ISATIS software [Geovariances, 2008].

The authors thank ONDRAF/NIRAS (Belgium agency for radioactive waste and enriched fissile materials) for their financial support and SCK●CEN (Belgian Nuclear Research Centre) for providing data for this study.

NOMENCLATURE

Kv	Vertical hydraulic conductivity
GR	Gamma Ray (gAPI)
Res	Resistivity (Ohm.m)
d40	Size such that 40% of the particles are finer than this diameter (µm)
reg(GR,Res)	Regression of Log(Kv) with GR and Res variables

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