**MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES**

**Theses of doctoral dissertation**

# GLOBAL OPTIMIZATION-BASED DATA PROCESSING METHODS FOR ADVANCED WELL LOGGING APPLICATIONS

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## I. SCIENTIFIC BACKGROUND AND AIMS

Inversion methods are widely used in applied geophysics (Oldenburg and Li 2005). The increase of accuracy and reliability of inversion estimation is in focus of scientific researches, which has a great practical impact on geophysical data processing, especially in well logging applications. In wireline logging, electrical and elastic rock properties are measured along with nuclear and dimensional measurements (i.e., caliper log) in the wellbore. Then the recorded well logs can be used to derive the geometry (e.g., structural dip, layer thickness) and the petrophysical properties of the rock formations (e.g., porosity, shale volume, water saturation and matrix volumes), which can enable the quantitative assessment of hydrocarbon and mineral resources. There are several options for the quantitative processing of well logging data. The conventional approach is the deterministic modeling (Asquith and Krygowski 2004), that usually rely only on one type of log to derive a given petrophysical parameter by using an empirical relationship.

A more sophisticated approach of well log interpretation is inverse modeling. By means of inversion, the petrophysical parameters can be derived by the simultaneous processing of the available well logs (Mayer and Sibbit 1980). Several possible solutions are available in the literature for the wireline logging inverse problem (Alberty and Hashmy 1984, Ball et al. 1987). Conventionally, inversion of wireline logging data is done in a local manner, meaning that data measured at a given depth point is jointly inverted to estimate the petrophysical parameters at that same depth point. This usually leads to a marginally overdetermined inverse problem, since we have just slightly more logging tools than unknowns (i.e., petrophysical parameters). Although this can be done very quickly and delivers adequate results, the low data-to-unknowns ratio sets a limit on the estimation accuracy of parameters. A possible solution, interval inversion was developed for increasing the data-to-unknowns ratio of the well logging inverse problem at the Department of Geophysics (Dobróka 1995). In this procedure, petrophysical parameters are assumed to be the functions of depth, therefore depth-dependent probe response functions are introduced to relate the measured data to the unknown physical properties of geological formations of longer intervals. In his PhD thesis, Szabó (2004) showed that the depth-dependent model parameters can be effectively discretized by series expansion using unit step functions as basis functions for describing layerwise homogeneous layers. For solving the interval inversion problem, he suggested a reliable and stable procedure based on conventional least-squares and least absolute deviations methods as well as a hybrid method combining the genetic algorithm with a linearized method, which reduced the starting model dependence of the inverse problem, and allowed to increase the estimation accuracy of model parameters.

Beside deterministic and inverse modeling, multivariate statistical methods can also be used to process well logging datasets. As such a method, factor analysis can be used to reduce the number of measured variables into a smaller number of uncorrelated parameters, while keeping most of the information contained in the original variables to help the data interpretation and to possibly reveal hidden information (Lawley and Maxwell 1962). Therefore, in well log applications it can be effectively applied because the acquired datasets are usually fairly large due to the numerous types of applied logging tools. In wireline logging applications, these new variables are called factor logs, which can be related to petrophysical parameters of the investigated geological formations through regression analysis (Szabó 2011). An inversion based solution of factor analysis was also suggested by Szabó (2016) with the use of genetic algorithm.

Geophysical inverse problems are conventionally solved by linearized (known as gradient-based) methods (Menke 1984). These methods have several drawbacks, e.g., the result of the inversion procedure is greatly sensitive to the starting model. During the search in the parameter space, the inversion algorithm often gets stuck in a local minimum of the objective function near the starting model. To overcome such problems of the linearized inversion methods, optimization techniques utilizing random search have been developed in the past decades, which was made possible by the great advancement of computer performance. Some of the most commonly used global optimization methods in geophysics are simulated annealing (SA), genetic algorithm (GA) and particle swarm optimization (PSO) which are outlined by Sen and Stoffa (2013), Holland (1975) and Pace et al. (2019). These soft computing methods are capable to search through a greater extent of the possible solutions than the linearized inversion methods without trapping in a local minimum. Therefore, they are able to find an optimal solution even when the starting model is of great distance from the globally optimal solution. Nowadays this is increasingly important when the optimization tasks we face have very complex objective functions with several equivalent solutions (local minima). This feature of the global optimization methods is made possible by the stochastic nature of these algorithms and the fact that during the search they use more comprehensive information about the parameter space. However, this makes such algorithms computationally intensive, but the availability of relatively inexpensive workstations had already made the use of these methods practical.

Inversion method development has been in the focus at the Department of Geophysics, University of Miskolc for decades. My aim in this thesis is to introduce new global optimization based methods for the advanced interpretation of well logs that rely on the previous developments detailed above. I intend to solve the problem of factor analysis by simulated annealing and by the efficient population-based particle swarm optimization and thus offer faster alternatives. Furthermore, I investigate the applicability of factor analysis to estimate the permeability of hydrocarbon bearing formations. As for interval inversion, I suggest a newly developed metaheuristics based solution. Instead of Heaviside step functions, I use Legendre polynomials to describe faster vertical variation of model parameters, and their series expansion coefficients are estimated by meta-heuristic optimization algorithms. Using the same well logging dataset, I aim to demonstrate that the results of factor analysis (i.e., shale volume log) can be effectively incorporated into interval inversion to further increase its overdetermination ratio. By introducing these new data processing methods, I try to offer new possibilities for the advanced analysis of wireline logging data.

## II. ACCOMPLISHED INVESTIGATION

In this thesis, I aimed to developed data processing methods that can be applied on actual well logging datasets. For testing purposes, I gathered datasets ranging from groundwater formations to hydrocarbon bearing formations. I have carried out all method developments introduced in the thesis in MATLAB environment.

As a first step in my PhD thesis, I attempted to improve the mathematical treatment of factor analysis. Instead of the conventionally used maximum likelihood approach for the calculation of factor scores, I suggested methods, where the values of factor scores are estimated in a globally optimized procedure by either simulated annealing (FA-SA) or particle swarm optimization (FA-PSO) by decreasing the misfit between the measured and calculated data. I tested the feasibility of the newly developed methods on well logging data measured in aquifers and in hydrocarbon bearing formations as well.

With the application of the developed globally optimized factor analysis (FA-PSO), I determined the correlation relationship between the first factor log extracted from well logging datasets and the decimal logarithm of intrinsic permeability of hydrocarbon-bearing formations. I tested the applicability of the suggested regression model on well logs measured in Hungarian hydrocarbon exploratory wells and also validated the model by core data.

To eliminate the starting model dependence of the interval inversion method originally developed at the Department of Geophysics, I solved the inverse problem by a newly developed metaheuristic approach. Furthermore, for increasing the reliability and accuracy of the estimated model parameters, I derived the shale volume by the newly developed globally optimized factor analysis (FA-PSO) from the same dataset and then incorporated it into the interval inversion procedure to increase its overdetermination ratio and the accuracy of inversion estimation. By a comparative analysis on well logs measured in a Hungarian hydrocarbon exploratory well, I demonstrated the positive effect of the increased overdetermination ratio on the interval inversion method.

PSO as a metaheuristic approach, its output is highly effected by the control parameters that worth to be set as optimal as possible at the start of the searching mechanism. Therefore, I further developed the suggested globally optimized method of factor analysis (FA-PSO) by the automated selection of some of its control parameters by simulated annealing in an outer iteration loop (FA-PSO-CC). In this way, I tried to generalize the improved method of factor analysis in regard of some if its control parameters, so there is no need to set them empirically in the initialization phase based on suggestions from literature. This way they can be selected automatically for the given optimization task.

For further optimizing the results of the developed factor analysis (FA-PSO), I suggested an improvement in which not just the factor scores are optimized by particle swarm optimization but the factor loadings as well in the same procedure (FA-PSO-FL). This simultaneous optimization can reach a better fit between the measured and calculated well logs and thus offer a better solution overall. To thoroughly test the feasibility of the newly developed methods, all developments and improvements presented in this thesis are tested on measured well logging data and validated by core derived petrophysical parameters where available.

## III. NEW SCIENTIFIC RESULTS

**Thesis 1**

I have developed global optimization based solutions of factor analysis that are capable to estimate the factor scores by means of simulated annealing and particle swarm optimization, separately. Factor analysis is solved as an inverse problem, the optimal values of factor scores are estimated by finding the best fit between the measured and calculated data. By the above manner, I have developed the FA-SA and FA-PSO algorithms. The two developed methods are both capable to derive the factor scores from wireline logging datasets in a reliable way, while factor loadings are fixed during the procedure. By processing in situ datasets, I proved the feasibility of the suggested methods in different measurement sites, and estimated the shale volume directly from the global optimization-derived factor logs.

**Thesis 2**

I have established a regression model between the first factor log estimated by the particle swarm optimization based factor analysis (FA-PSO) and the permeability of hydrocarbon-bearing formations. This allows the estimation of permeability from an independent well-log-analysis method, which is based on the comprehensive interpretation of all available wireline logs. The developed method has been tested on Hungarian hydrocarbon bearing formations using in situ data. The factor analysis derived permeability is compared and successfully verified by deterministic modeling and laboratory based measurements.

**Thesis 3**

I have developed a particle swarm optimization based interval inversion method for estimating the petrophysical parameters of hydrocarbon formations from wireline logging data. The implementation of the metaheuristic approach highly reduces the starting model dependence of the inverse problem. I have increased the overdetermination ratio of the interval inversion method by incorporating the factor analysis derived shale volume log into the inversion procedure. Thus, by taking shale volume along the inverted interval as known (fixed) parameter, the number of unknown model parameters is decreased and the accuracy and reliability of the estimated petrophysical model is significantly improved. I performed detailed stability tests, and proved that the results of randomly initialized PSO-based interval inversion procedures are consistent.

**Thesis 4**

I have developed a hyperparameter estimation based data processing approach for the automated selection of control parameters $c_1$ and $c_2$ for the particle swarm optimization assisted factor analysis (FA-PSO). The factor scores are estimated in the inner loop of FA-PSO-CC, while the optimal values of control parameters $c_1$ and $c_2$ are automatically determined in an outer iteration loop by simulated annealing. By processing in-situ well logging data, I proved the feasibility of the suggested method in Hungarian groundwater formations, and estimated the shale volume directly from the global optimization-derived factor scores. The result was confirmed also by core measurements.

**Thesis 5**

I have further developed the particle swarm optimization-based factor analysis algorithm (FA-PSO) given in Thesis 1 by iteratively re-calculating the factor loadings. The factor scores and factor loadings are optimized simultaneously in a stable inversion procedure. The newly developed algorithm of factor analysis - named FA-PSO-FL - optimizes the factor loadings as well by PSO based on the misfit between the observed and calculated well logging data. By processing in situ data, I proved the feasibility of the suggested method in Hungarian groundwater formations, and estimated the shale volume directly from the global optimization-derived factor scores. The estimation result was also confirmed by core measurements.

**PRACTICAL APPLICATION OF THE RESULTS**

In the framework of my PhD thesis I carried out inversion based method developments in MATLAB environment for the advanced processing of wireline logging data. The developed methods are capable to effectively process wireline logging datasets and to estimate the petrophysical parameters of formations which are necessary for the quantitative assessment of hydrocarbon and mineral resources. The improved factor analysis based data processing methods (FA-SA, FA-PSO, FA-PSO-CC, FA-PSO-FL) can provide a reliable and independent estimate to shale volume and permeability of sedimentary formations through regression analysis. Once the regression relationships are found between the first factor extracted from a well logging dataset and the petrophysical parameters (i.e., shale volume, permeability) of a given formation in a specific area, the relationships might be used in neighboring wells as well as an independent estimate to these parameters. This can reduce the operating costs, such as the need for taking more core samples to determine the before mentioned petrophysical parameters. The suggested globally optimized interval inversion method aided by factor analysis can estimate the petrophysical parameters from well logging data in a highly overdetermined procedure, which results in more accurate estimations of the desired petrophysical parameters. Since these parameters are the basis for calculating movable hydrocarbons their most reliable estimation is of crucial importance. The increased overdetermination ratio also gives the possibility to automatically estimate the value of some zone parameters within inversion, while still maintaining a good level of resolution of the estimated model parameters. In the future I intend to use this procedure for unconventional reservoirs where multi-mineral models need to be built and therefore the number of unknowns is considerably higher than in case of conventional reservoirs. Currently I am working on a paper with my supervisor in which we summarize the applicability of factor analysis for permeability estimation in hydrocarbon formations and intend to publish it in an international (Q1) journal.

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## IV. LIST OF RELATED PUBLICATIONS AND PRESENTATIONS

### JOURNAL ARTICLES

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2. Abordán A., Szabó N.P.: Particle swarm optimization assisted factor analysis for shale volume estimation in groundwater formations. Geosciences and Engineering 6(9):85–95 (2018)

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2. Abordán A., Szabó N.P.: Particle swarm optimization based interval inversion of direct push logging data, MultiScience - XXXIII. microCAD International Multidisciplinary Scientific Conference University of Miskolc, 23-24 May (2019)

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