UNIVERSITY OF MISKOLC
FACULTY OF EARTH SCIENCE AND ENGINEERING
ISNTITUTE OF GEOPHYSICS AND GEOINFORMATION SCIENCE

Thesis of the doctoral dissertation (PhD)

INTERVAL INVERSION APPROACH FOR INTERPRETATION OF MULTI-WELL LOGGING DATASETS

Author:

Mahmoud Ali Gaballah Abdellatif

Scientific Adviser:

Prof. Dr. Norbert Péter Szabó

MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES

Head of the Doctoral School: Prof. Dr. Péter Szűcs

Miskolc-Hungary

2022.

I. SCIENTIFIC BACKGROUND AND AIMS

In the last decades, significant success has been shown by Geophysics in oil and mineral ores exploration. Several geophysical techniques have been developed for the detection or/and mapping of hidden deposits and structures related to hydrocarbon accumulation. Of course, borehole geophysics is one of the most widely used of all geophysical tools. It used to obtain further in-depth (in-situ) information that is crucial in better understanding of subsurface conditions via measuring, investigating, and analyzing the physical properties of the surrounding rocks by means of the drilled borehole. The most frequent and useful applied borehole geophysical methods are based on self-potential, electrical resistivity, sonic or acoustic velocity, temperature, natural and induced radioactivity. It is possible to figure out the drilled wells by examining core samples but the gained information via this way would be incomplete even useless to define the nature of the drilled rocks and clarify or distinguish between the types of fluids presented in the rock formations if not complemented by certain new borehole logging techniques which represent a tremendous source of information (Serra 1984). Substantially, the measured data through these techniques are typically effective in characterizing geologic, fluid flow, fracture patterns, and structural properties especially with the continual refinement that have been launched to the equipment and the automated interpretation systems used for this purpose (Aguilera 1980; Bonter et al. 2019; Akbar 2021).

Well-logging is a relatively new science where the initial work on the field goes back to less than 130 years. In 1896 lord kelvin in Britain measured the temperature with depth through shallow holes. Most of us think that the interior of the earth was as cold as caves, but the coldness does not exceed only a few meters. In general, the subsurface temperature increases at a rate of one or two degrees per 100 feet, and such changes show much of what is present around the drilled well which is not indicated by any other measurements. The idea of well- logging, especially the electric logs is taken from the method of measuring resistance at the surface which was firstly used by Schlumberger brothers in France for prospecting the metal ore mining industry but gradually extended its activities to involve exploration of possible oil-bearing structures. To better understand the surface measurements, the Schlumberger brothers needed to incorporate resistivity information from deeper formations and the first attempt was made in 1927. This first log marked a turning point in the history of hydrocarbon exploration despite being a little more than a simple hand-plotted graph. By 1929 the international demand for this process grew and subsurface logging was conducted in different countries around the world. Consecutively, new tools have been designed to complement electrical logging methods and provide measuring new parameters such as diameter, temperature, and inclination of the borehole. A significant contribution has been made through studying the relationship between resistivity, porosity, and water saturation in oil bearing formations (Archie 1942) and it known as Archie´s law which has become the basis of petrophysical interpretation yet.During the 1950s and 1960s, various electric logs were introduced, including the laterolog tool for measuring formation resistivity beyond the invaded zone using widely spaced electrodes, the microlaterlog tool for measuring the resistivity of the flushed zone with minimal influence from the mudcake or the undisturbed zone, and the microlog tool for detecting permeable zones across which a mudcake has formed. In addition to that sonic measurements are conducted for better depth control and placing equipment's of well completion, the slowing down time technique is used to measure formation hydrogen concentration by detecting energy reduction of source neutrons and finally the first density log enables realization of bulk density measurement using gamma ray attenuation. Furthermore, the latter three logs sonic, neutron and density have been independently used to estimate the apparent porosity. As a result of growing computer power and engineering development in the 1970s the SARABAND and CORIBAND programs have been introduced as the first computerized reservoir analysis. The SARABAND program was designed to analyze shaly sand rocks via measuring volume of clay minerals and calculating fluid saturations while CORIBAND deals with multimineral lithology (Schlumberger 2017) .

The year 1980 marked the beginning of a qualitative leap in the interpretation and processing of wireline logging data collected from deep borehole. Several computer-based inversion methods equipped with quality checking tools have been launched by petroleum companies for evaluating hydrocarbon formations such as Global system by Schlumberger (Mayer and Sibbit 1980), Ultra system by Gearhart (Alberty and Hashmy 1984), and Optima system by Baker Atlas (Ball et al. 1987).These computer-processed log interpretation systems provide more accurate and reliable estimation of petrophysical proprieties such as porosity, water saturation and matrix volumes compared to the conventional (quick look or deterministic) methods. Through the inversion methods, all the available data sets are combined in a joint inversion procedure to accurately derive the petrophysical parameters, while they are derived by using the conventional ones separately from each other by the analysis of a specific (single) well log.

Inversion of well-logging data using computer-based inversion systems is conducted in a local way which means processing data acquired in a particular depth-point and providing an estimate for the petrophysical parameter only to that point in a set of separate inversion runs (Drahos 2005; Mayer and Sibbit 1980). Such local inverse problem can be solved by using linear optimization techniques with obtaining fast and satisfactory results in typical cases. Since the number of probe measurements to some extent exceeds that of the petrophysical parameter unknowns (e.g., porosity, clay content, water saturation in invaded and uninvaded zones) to be determined in each depth-point, the problem represents a marginal overdetermined inverse one along the borehole. It is a known fact that in the case of inversion of a small number of measurement data, (and poor a priori information), the result is strongly affected by the measurement error (noise), thus we not always obtain a satisfactory result in terms of the accuracy and reliability of the local parameter estimation (Dobróka et al. 2016). It is possible to overcome this problem and obtain more accurate results by increasing the measured information from several well-logs, but it also has known technological limitations and additional costs. Given that the precise calculation of hydrocarbon reserves demands the most reliable estimations of the petrophysical parameters by reducing the harmful effect of data noise, a new method namely interval inversion has been introduced for the analysis of open-hole logging data (Dobróka 1995; Dobróka and Szabó 2001).

By means of this new method, all data of a longer depth interval are processed in one joint inversion procedure. Through the interval inversion procedures, the petrophysical properties of the geologic formations (unknowns) are related to the measured data by setting depth - dependent response functions. The series expansion-based approach (Dobróka 1995) is suitable for discretizing the model parameters by expanding them into a series and approximating them not only in one point but also in the entire processed depth-interval. By this formulation, the relative number of measured data compared to the series expansion coefficients which represent the unknowns of the inverse problem can be effectively increased. Hence, a high data to unknown parameters ratio can be achieved which enhances the quality of the interpretation results. The great advantageous property of the interval inversion method is its capability to treat an increasing number of unknowns without significant decrease of overdetermination ratio.

Solving the geophysical inverse problems can be performed by seeking the minimum of the objective function which is expressed as the misfit between the measured data and the calculated one. There are several optimization approaches that can be used to find the extremum of such an objective function. The most considerable ones are depending on the solution of sets of linear equations and termed as linear or gradient-based techniques (Marquardt 1963; Menke 1984;

Tarantola 1987). The linear methods are more favorable in practice due to their speed and efficiency, especially when having a proper initial model. Nevertheless, these methods assign the solution to a local optimum of the objective functions and cause truncation errors; hence they are not absolute minimum searching techniques. It is possible to avoid the local optimum solution of linear inversion methods and effectively find the absolute global optimum of the objective function by means of using global optimization methods. These meta-heuristic methods are characterized by high performance and efficiency such as Simulated Annealing (Metropolis et al. 1953), Genetic Algorithm (Holland 1975; Goldberg 1989) and Particle Swarm Optimization (Kennedy and Eberhart 1995)**.** As a result, several studies have been conducted based on these methods in the analysis of borehole data (Zhou et al. 1992; Dobróka and Szabó 2001& 2012, Goswami et al. 2004; Szabó 2004).

The interval inversion method has been introduced (Dobróka 1995; Dobróka and Szabó 2001) and further developed by the research work of the inversion and tomography research team of the Department of Geophysics, University of Miskolc and still of interest so far. The main objectives of my PhD studies are to further develop the interval inversion method for 1D petrophysical parameter distributions and its extension 2D cases. At first, I develop the Chebyshev polynomials-based interval inversion approach to characterize the reservoir rock in Komombo basin, Upper Egypt. I use a new alternative basis function (Chebyshev polynomials) for discretizing the model parameters. Thereafter, I further improve the 1D interval inversion method to evaluate the 2D petrophysical models. The 2D developments represent new innovative inversion approaches which integrate datasets of several neighboring deep wells to estimate lateral change of layer boundary coordinates together with the lateral and vertical variation of the petrophysical parameters. To accomplish this, I apply Legendre polynomials as an orthogonal set of basis functions instead of (non-orthogonal) power functions used in earlier applications. Thus, 2D petrophysical models can be obtained in a more accurate and reliable manner and geometry of the layer boundary of the geologic structures can be figured if the specified wells are in the same range.

II. ACCOMPLISHED INVESTIGATION

The main purposes of my PhD thesis were to develop the interval inversion methods for reliable estimation of one-and two-dimensional petrophysical parameters distributions. The majority of the developments are associated with processing of multi-borehole logging data. All method developments described in the thesis were performed by utilizing MATLAB programming language.

For the 1D case, I have developed the Chebyshev polynomials-based interval inversion approach to characterize the reservoir rock in Komombo basin, Upper Egypt. I used a new alternative basis function (Chebyshev polynomials) for discretizing the model parameters. The modified method shows a consistent estimation of the petrophysical parameters such as porosity, water saturation in invaded and uninvaded zones and volume of shale of Abu ballas reservoir. I checked the reliability of the results by using a variety of quality techniques that include measuring misfit between the field data and the calculated one, calculating error estimation and correlation coefficients. In addition, I derived the hydrocarbon saturation in the form of irreducible and movable of the investigated reservoir.

The 2D case involves a suit of improved algorithms that help in evaluating the two- dimensional petrophysical models. Initially and considering the estimation of lateral changes of layer boundary coordinates I developed a Legendre polynomials-based interval inversion approach. I solved the inverse problem by applying linear optimization-based Marquardt technique (DLSQ). I utilized simulated measurements of multi-layer structures related to hydrocarbon bearing formations to test the method. The thicknesses are obtained as quadratic values over the interval [-1, 1]. For ensuring the reliability of results, the errors of the estimated expansion coefficients are computed. I proved the feasibility of the suggested method and successfully estimated the lateral variation of layer boundaries of Egyptian hydrocarbon field data acquired along four wells with the help of series expansion-based polynomial coefficients.

After that I was able to improve the 2D inversion method in order to determine vertical and lateral variation of the petrophysical parameters along a 2D cross-section of several boreholes. I used the Metropolis algorithm-based simulated annealing (VFSA) to estimate the series expansion coefficients which are used to derive the petrophysical parameters. I evaluated the proposed method by using noisy simulated measurements of petrophysical models made of two-layer structures related to groundwater and hydrocarbon bearing formations. The data and model misfits are assessed to ensure the inversion procedures' stability and convergence. A large amount of input data relative to the number of unknowns results in a high overdetermined ratio, therefore more precise estimates are obtained in stable and convergent procedure than in the conventional local (1D) inversion schemes. The method's feasibility is demonstrated by analyzing in-situ well logging data from four wells in an Egyptian hydrocarbon field.

Successful estimation of both laterally varying petrophysical parameters and formation boundaries separately enabled me to further develop the method for determining both of them in a joint inversion procedure. In this case, the model vector comprises the series expansion coefficients of the petrophysical parameters besides the layer thicknesses which are estimated by using simulated annealing algorithm (VFSA). The feasibility of the modified method was verified on simulated and Egyptian field data related to hydrocarbon bearing formations. Accordingly, two-dimensional models were created, the geometry of the geological structures and the morphology of hydrocarbon reservoirs were well defined as well. After reaching the near vicinity of the optimum via the VFSA algorithm and for quality assurance on inversion results I switched the program to the DLSQ in order to perform linear optimization. I implemented the Menke's 1984 discrete inverse theory for calculating estimation errors of parameters and correlation coefficients. With the minimal estimated errors and correlation coefficients in case of the simulated and Egyptian hydrocarbon structure, I effectively proved the efficiency of the hybrid algorithm (VFSA+DLSQ) in processing several neighbouring deep wells.

III. NEW SCIENTIFIC RESULTS

1. Chebyshev polynomials-based interval inversion method for the analysis of well logging data

I have developed an improved interval inversion method using a new discretization scheme for analyzing well logs measured in hydrocarbon formations. I used Chebyshev polynomials as new alternative basis functions to assure small correlation between the estimated model parameters and great overdetermination ratio. The modified interval inversion algorithm-based using orthogonal Chebyshev basis functions showed a significant success to accurately estimate the model parameters of the Komombo basin, Upper Egypt reservoir rock in steady inversion procedure.

2. Legendre polynomials-based interval inversion method for estimating lateral changes of layer boundary thicknesses

I have developed an orthogonal Legendre polynomials-based 2D interval inversion approach that can determine the lateral changes of layer boundary coordinates. The thicknesses are obtained as cubic functions over the interval [-1, 1]. The inversion method was tested on two models built-up of homogeneous multilayer structures related to hydrocarbon bearing reservoirs. Linear optimization algorithm has been used to solve the inverse problem and characterize the accuracy of the expansion coefficients. By processing multi-borehole in-situ logging data, I proved the feasibility of the suggested method and successfully estimated the lateral variation of layer boundaries of Egyptian hydrocarbon field.

3. Legendre polynomials-based interval inversion method for estimating lateral variation of petrophysical parameters

I developed a 2D Legendre polynomials-based interval inversion approach for determining lateral varying of petrophysical parameters. I assessed the method by using noisy simulated measurements on petrophysical models made of two-layer structures related to groundwater and hydrocarbon bearing formations. The numerical experiments aided to investigate the stability and convergence of the 2D interval inversion procedure. To ensure the accuracy and reliability of the inversion results, the misfit of data and model distance are tested. A large amount of input data relative to the number of unknown results in a high overdetermination ratio, consequently more reliable estimates are obtained in stable and convergent procedure than in conventional local (1D) inversion schemes. I applied global optimization technique to get the best fit between the measured and calculated data. The feasibility of the 2D interval inversion method is shown by analysing in-situ well logging data acquired in four wells situated in Egyptian hydrocarbon field.

4. Interval inversion of multi-borehole logging data for estimating simultaneously laterally varying petrophysical parameters and formation boundaries

I further developed the 2D Legendre polynomials-based interval inversion algorithm which allows the determination of lateral changes of the layer-boundary coordinates together with the vertical and lateral variations of petrophysical parameters along a 2D cross-section of several boreholes. The method is assessed using noisy simulated measurements on petrophysical models made of two-layer structures related to groundwater and hydrocarbon bearing formations. The numerical experiments aided to confirm the stability and convergence of the inversion procedure. To test the accuracy and reliability of the inversion results, the misfit of data and model distance are tested. The feasibility of the 2D interval inversion method is shown by analysing in-situ well logging data acquired in four wells situated in Egyptian hydrocarbon field.

5. Characterizing the quality of the estimated parameters

To measure the accuracy of the inversion results, I further developed the global inversion method. I suggested a hybrid 2D inversion technique VFSA+DLSQ for minimization the inverse problem. At the end of linear inversion phase, I could characterize the estimation error and reliability of estimation by the elements of the model covariance matrix and correlation coefficients, separately. I tested the hybrid inversion method on simulated datasets of the utilized two models in my study. Furthermore, the feasibility of the method is shown by evaluating Egyptian field data.

IV. PRACTICAL APPLICATION OF RESULTS

In the framework of my PhD thesis, I demonstrated a new perspective interval inversion-based methods relating to single and multi-well data processing applications by using the MATLAB environment. The developed methods could accurately evaluate one- and two- dimensional petrophysical models. It was concluded from the results of the simulated examples and the evaluation of well-logging measurements that the global inversion methods (e.g., simulated annealing) based on the estimation of lateral variation of petrophysical parameters and formation boundaries is significantly effective and powerful that can be proper to apply in industrial practice simultaneously besides the deterministic methods of long standing. The only criterion to maintain the methods more effective and powerful is to keep the high overdetermined ratio. The application of the developed methods can be extended to include the processing of groundwater and non-conventional reservoirs on both 2D and/or 3D features.

V. LIST OF RELATED PUBLICATIONS AND PRESENTATIONS

JOURNAL ARTICLES

1- Abdellatif. M, P.N. Szabó., 2020. Chebyshev polynomials-based interval inversion approach for the analysis of borehole geophysical data: a case study from Egypt. Geosciences and Engineering, Vol. 8, No. 13 (2020), pp. 83–95.

2- Abdellatif. M, P.N. Szabó., 2022. Interval inversion of multiwall Logging data for estimating laterally varying petrophysical parameters and formation boundaries. Actageodetica et Geophysica. Accepted 13 May 2022.

CONFERENCE PAPERS AND ABSTRACTS

1- Abdellatif. M., Petrophysical studies of Abu Ballas Reservoir, Komombo basin, Egypt by using local inversion technique. DOKTORANDUSZOK FORUMA, MISKOLC, 2019. November 21.

2- Abdellatif. M, P.N. Szabó., 2020. Interval inversion approach for estimating petrophysical parameters of Abu Ballas reservoir, Komombo basin, Egypt. XII international youth scientific and practical congress “ Oil and Gas Horizons” Gubkin University, Russian 18-21 November 2020.

3- Abdellatif. M, 2021. 2D Interval inversion method for estimating lateral changes of layer boundaries. The XVI International Forum-Competition of Students and Young Scientists. St. Petersburg Mining University. June 2021.

INTERNATIONAL CONFERENCE PRESENTATIONS

1- Interval inversion approach for estimating petrophysical parameters of Abu Ballas reservoir, Komombo basin, Egypt. XII international youth scientific and practical congress " Oil and Gas Horizons" Gubkin University, Russian 18-21 November 2020.

2- 2D Interval inversion method for estimating lateral changes of layer boundaries. The XVI International Forum-Competition of Students and Young Scientists. St. Petersburg Mining University. June 2021.

DOMESTIC CONFERENCE PRESENTATIONS

1- Petrophysical studies of Abu Ballas Reservoir, Komombo basin, Egypt by using local inversion technique. DOKTORANDUSZOK FORUMA, MISKOLC, 2019. November 21.

2- 2D interval inversion method for the analysis of multi-well logging data. Inverziós Ank**ét**, University of Miskolc, November 2-3-2020.

3- Chebyshev polynomials-based interval inversion for interpreting well logging data. Youth Performers Day, Miskolc University 25 May 2021.