Application of Adaptive Processing Technique for the Inversion of Open Hole Logs Recorded in Oil Fields of Indian Basins

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Summary

Adaptive Processing Technique for comprehensive well log evaluation solves the simultaneous system of logging tool response equations through statistical approach by using weighted least square minimization technique. It involves minimization of the incoherence function i.e. summation of square of errors between the measured and constructed logs by incorporating the total uncertainties on tools, parameters and response equations. It also simultaneously optimizes the unknowns and zones parameters in different way. It introduces the statistical theory that least square estimates are the mean estimates and only mean values are optimized while selecting minerals parameters for a particular zone. Process is adaptive in the sense that it uses the results of previous stage/level as the input to the next stage/level.

Adaptive Processing Technique has been successfully in use for comprehensive well log evaluation of all type of reservoirs of Indian Basins. Siliciclastics complex reservoirs of Upper Assam, Krishna Godavary and Kavery Basins, Western on Shore and offshore, fractured and non fractured carbonates reservoirs of Mumbai High have been processed with this package. Evolution of basic concept of inversion of open hole logs through weighted least square technique and how basic conditions, which ensures the mathematical feasible solutions for the log evaluation problem, are linked through parameter selection on cross plots are illustrated with actual field examples. Selection of parameters on cross plots which ensures feasibility of the mathematical solutions and minimum value of incoherence /error function are essential for the successful application of the package. The log analyst has to achieve the meaningful results by fine-tuning the parameters within the uncertainties defined on the log measurements. An improper parameter selection can produce a meaningless paralogs, which may not corroborate at all with the geological model/ reservoir characteristics of the field.

Introduction

During the Second World War, Norbert Weiner of MIT, USA, one of the foremost mathematicians of the century, was asked to develop a technique for extracting radar signals from noise. The method of least square optimization developed by him eventually proved to be useful in many other applications in information processing. This approach with different assumptions and limitations was also presented by Geophysical Analysis Group (GAG–MIT), under the leadership of E.A. Robinson, in sixties for enhancement of offshore seismic reflection data which is considered as digital revolution in seismic exploration. After a lapse of almost three decades,

Mayer and Sibbit (1980), used the least square optimization for formation evaluation (GLOBAL). This was followed by Alberty and Hashmy, 1984 (ULTRA).

This paper deals with application of - Adaptive Processing Technique for Comprehensive Well Log Evaluation (APTWEL) developed in 1984-88. APTWEL performs inversion of open hole logs by solving the simultaneous system of logging tool response equations through statistical approach by using weighted least square minimization technique. It involves minimization of the objective function i.e. summation of square of errors between the measured and constructed logs by incorporating the total uncertainties on tools, parameters and response equations. It also simultaneously optimizes the unknowns and zones parameters in different way. It introduces the statistical theory that least square estimates are the mean estimates and only mean values are optimized while selecting minerals parameters for a particular zone. Process is adaptive in the sense that it uses the results of previous stage/level as the input to the next stage/level.

Evolution of basic concept of inversion of open hole logs through weighted least square technique and how basic conditions, which ensures the mathematical feasible solutions for the log evaluation problem, are linked through parameter selection on cross plots are illustrated with actual field examples from Indian Basins. It ensures only feasibility of the mathematical solutions and minimum value of incoherence /error function. The log analyst has to achieve the meaningful results by fine-tuning the parameters within the uncertainties defined on the log measurements. An improper parameter selection can produce a meaningless paralogs, which may not corroborate at all with the geological model/ reservoir characteristics of the field. For the application of the package one must realize the importance of cross plot techniques for the identification/ selection of parameters, which depends mainly on perception of the interpretation model by the log analyst rather than the type of software package used.

Basic Concept of Inversion of Open Hole Logs

Description of petroleum reservoirs through well logs is an established procedure. Evaluation of well logs is a crucial link between the acquisition of well log data and final description of reservoir characteristics. Basic aim of well log measurements is to record the formation characteristics. Ideally, measuring tool should be placed directly in the formations, however for obvious reasons; it is done in a borehole, which is an environment quite different from the formations. This obliterates the informations recorded by the tools. Furthermore, many log responses are not direct measurements and are presented through calibration, adding to the uncertainty on the measurements. Well log analyst's aim is to extract informations pertaining to the formation seen from the composite signal recorded by logging tools. Formation responses are the composite response of the different minerals and fluids present in it; responses for which are not very accurately known under in-situ conditions. When the log analyst is exposed to such an uncertain environment and he has to extract informations, when input, output and transmission path properties are not known very accurately; statistical approach is the only approach left to him.

The problem of extracting formations characteristics from the log measurements seems similar to problem encountered in communication engineering, i.e. detection of desired signal from composite signal with noise. Case of reflection seismology is also similar. Overall advantage with them is the linear superposition of different components which allow easier extraction of the desired signal. Furthermore, signal at a time is supposed to be the outcome of the past signal i.e. auto-regressive or moving average or combination of both.

Log measurements are supposed to be a multi-channel simultaneous measurement independent of each other. Superposition of different components may or may not be linear. So it is an entirely different problem of extracting desired signal from logs. Inversion of open hole logs is performed by solving the simultaneous system of logging tool response equations through statistical approach by using weighted least square minimization technique. It involves minimization of the objective function i.e. summation of square of errors between the measured and constructed logs by incorporating the total uncertainties on tools, parameters and response equations.

Well Log Evaluation through the Inversion of Universal Logging Tool Response Equations

A log response L, mathematically, represents the volumetric average property of the constituents of the formation measured by particular logging tool:

$$\sum_{j=1,n} r_j * v_j = L \qquad \text{................} \qquad (1)$$

Where $\sum_{j=1,n} v_j = 1$, r_j = log response of j th constituent having volume v_j, n = total number of constituents in the formation

For number of log measurements equation (1) is represented by a matrix and vector notations:

$$\mathbf{R}_{ij} * \mathbf{V}_j = \mathbf{L}_i \qquad \text{.........................} \qquad (2)$$

Where $\mathbf{R}_{ij}$ = Response parameter of i th log measurement of j the constituent, $\mathbf{V}_j$ = Volume fraction of j th constituent, $\mathbf{L}_i$ = i th log measurement. Equation (2) is the simplest representation of the simultaneous linear tool response equations where fluid is being treated as a rock constituent. Computation of log responses (Li) by using equation (2), is known as ***forward modeling*** and solving the equation for volumetric (Vj) is known as ***inverse modeling*** or ***inversion of open hole logs.*** This equation is also used for computation of response parameters (**R**ij) by imposing known ranges from standard /known values from published literature, which makes the system of equations balanced. Response parameters are also referred as ***input*** or matrix parameters. Solution vectors Vj along with Phi, Sw and Sxo are referred as ***output*** or reservoir parameters and are generally, presented as ***paralog*** showing formation and fluid analysis of the rock system.

At first glance this linear system of equations appears to be very simple for solving unknown volume fraction of the constituent defined by specific response parameter on each log measurement. Any deterministic approach for solving these equations is difficult as:

- All the log measurements inherit statistical uncertainty / background with them.
- Formations in nature cannot be modeled with limited number of constituents and limited number of measurements.
- Response parameters are not perfectly defined for each constituent.
- Even existence of inverse of Response matrix R_{ij}, ensured before hand may not ensure positive values for the solutions, V_j.

These system of equations can be solved through statistical approach by minimizing summation of squares errors between measured and constructed logs by incorporating the uncertainties on measurements, generally known as weighted least square minimization technique.

Basic Concept of Weighted Least Square Minimization

If there are Li log measurements with σ_{oi} variances and correspondingly $\mathbf{R}_{ij} * \mathbf{V}_j$ theoretical or desired values with variances σ_{Ti}, error for ith log can be written as :

$$e_i = Li - \mathbf{R}_{ij} * \mathbf{V}_j$$

Where, e_i is presumed to be having zero mean random errors for i th log and finite second moment for the shake of applying least square optimization. Since log measurements are uncorrelated and independent measurements at a particular depth level, e_i are also uncorrelated and independent. Variance of left hand side of this equation is vector sum of right hand side i.e.

$$\sigma_i^2 = \sigma_{oi}^2 + \sigma_{Ti}^2$$ where is σ_i total uncertainty on e_i.

Now our problem is to find different weights for different logs, according to which squared errors ei^2 will be added. Let us start with only two log measurements errors e_1 and e_2. Summation of squared error (SSE) can be written as,

$$SSE = W e_1^2 + (1- W) e_2^2$$ where W is weight factor.

By the law of propagation of errors, variance on SSE can be written as

$$\sigma_{12}^2 = 2 \sigma_1^2 W^2 + 2 \sigma_2^2 (1-W)^2$$

To have σ_{12}^2 minimum, necessary condition is that partial derivative of it with respect to W must be zero. This operation on the above equation brings out

$$W = \sigma_2^2 / (\sigma_1^2 + \sigma_2^2) = (1/ \sigma_1^2) / (1/\sigma_1^2 + 1/\sigma_2^2)$$

Or, $$W_1 = (1/ \sigma_1^2) / (1/\sigma_1^2 + 1/\sigma_2^2)$$

$$W_2 = (1/ \sigma_2^2) / (1/\sigma_1^2 + 1/\sigma_2^2)$$

Through the law of induction, it can be proved that

$$W_i = 1/\sigma_i^2 / \Sigma 1/\sigma i^2$$

Since $\Sigma 1/\sigma i^2$ is a scalar quantity and constant for a particular level, it can be ignored for the computation of variable quantity SSE which can be written as,

$$SSE = Wi\, e_i^2 = \Sigma e_i^2/\sigma_i^2$$

Or, $$f = \sum_{i = 1, nom} (\mathbf{R}_{ij} * \mathbf{V}_j - \mathbf{L}_i)^2 / \sigma?_i^2 \quad .... \quad (\mathbf{3})$$

Where σi represents total uncertainty on ith tool, parameter and response equation, nom denotes total number of log measurements. As ***f*** represents SSE i.e. a measure of lack of coherence between measured and constructed logs, it is generally referred as ***incoherence function***. In expression of ***f***, there is no need of normalizing logs and variances, since we will be dividing numerator and denominator with the same quantity i.e. mean log value.

Dual fluid system i.e. presence of hydrocarbon in addition to water further complicates the situation and linear system of equation (2) becomes non-linear viz...

$$Phi \{r_{mf\ i} * Sxo + r_{h\ i} * (1 - Sxo)\} + \mathbf{R}_{ij} * \mathbf{V}_j = \mathbf{L}_i \qquad (\mathbf{4})$$

$$\{Vcl^{(1 - Vcl/2)} / \sqrt{Rcl} + Phi^{m/2} / \sqrt{aRw} \} * Sw^{n/2} = 1/ \sqrt{Rt} \qquad (\mathbf{5})$$

$$\{Vcl^{(1 - Vcl/2)} / \sqrt{Rcl} + Phi^{m/2} / \sqrt{aRw} \} * Sxo^{n/2} = 1/\sqrt{Rxo} \qquad (\mathbf{6})$$

Where fluid components are excluded from constituents Vj, r_{mf} and r_h represent the log responses of mud filtrate and hydrocarbon respectively. Vcl and phi denote clay volume and effective porosity respectively. All other parameters have usual meanings.

Minimization of objective function in least square sense is performed by solving first partial derivative matrix equations i.e. ***JACOBIAN*** with the condition that second derivative matrix i.e. ***HESSIAN*** is positive, using standard non linear programming technique. Global minimum for objective function is ensured only for a particular combination of input and output parameters. However, theoretically, same value of objective function can be achieved with infinite number of combinations of input / output parameters, even with uniquely determined system of equations i.e. equal number of unknowns and equations. While high incoherence function indicates that model does not fit the data, a low does not verify that the model is correct. For example, different models may fit the data equally well, but give different answers. Imposition of constraints from core measurements viz. porosity, mineral volumes and grain density and production testing results on input / output parameters, makes the formation evaluation more realistic and reliable in a particular geological setting.

Basic Conditions For the Inversion of Open-Hole Logs

A. Normalization of Logs and Calculation of uncertainties

Normalization of logs implies that:

- All the log measurements are brought to the standard environment i.e. uniform hole size namely bit size by applying all the environmental corrections.
- All the logs are averaged according to the minimum resolution log to have same vertical resolution for all the logs.
- For the moment, let us presume that the logs are normalized to their mean value in a particular zone. So all the logs represent the repeated measurements of same quantity with different uncertainties / variances. By uncertainty, we mean the precision with which a true value is known. Often it implies that there is 50 – 50 chance that any one of a true value will fall within a given range. It does not necessarily reflect anything about the accuracy of the measurement, which is a comparison with true value. If we assure uncertainties in terms of standard errors i.e. variances divided by mean value, many mathematical operations like law of propagation of errors becomes very simple.
- Total uncertainties are composed of two components namely; uncertainty on log measurement and uncertainty on theoretical response equation viz. σ_{oi} and σ_{Ti}. Uncertainty on measurement is to be calculated from positive and negative corrections (environmental) separately, in addition tool tolerances and finally standard deviation is to be calculated as σ_{oi}. The uncertainty on theoretical response equation σ_{Ti} is to be calculated from law of propagation of errors as :

1. $\sigma_{Ti}^2 = \sum_{j=1}^{n} Rij^2 \; \sigma Vj^2$, when there is uncertainty only on mineral volumes.
2. $\sigma_{Ti}^2 = \sum_{j=1}^{n} Vj^2 \; Rij^2$, when there is uncertainty only on mineral volumes.
3. $\sigma_{Ti}^2 = \sum_{j=1}^{n} (Rij^2 \, \sigma Vj^2 + Vj^2 \; \sigma Rij^2 \,.\, \sigma Vj^2)$, when there are uncertainties on mineral volumes as well as on mineral responses.

Where, σRij^2 = variance of mineral response for jth mineral and ith log, σVj^2 = variance of jth mineral volume,

Rij = mineral response of jth mineral for ith log,

Vj = mineral volume of jth mineral

B. Pre-Knowledge of Log Response Parameters

Standard log response parameters for almost all type and group of known minerals are generally well published. These parameters cannot be directly used for inversion of logs, as formations in nature cannot be modeled with limited number of pure mineral constituents. Actually, lumping of the group of minerals is done to keep the number of minerals less than or equal to the available number of logs in order to have mathematically feasible solutions. Furthermore, lumping of response parameters in a particular ratio do not ensure the validity of parameters, for example a thick formation where ratio it self may be varying with depth.

C. Existence of Inverse Matrix of Log Response Parameters

Simplest way to perform inversion/solution of simultaneous equation (2), through deterministic approach, is to invert response parameter matrix R_{ij} to get inverse matrix of it. Multiplication of inverse matrix with right hand log response column vector L_i provides the solution vector V_j. Basic condition for the existence of mathematically feasible solutions V_j is that response matrix R_{ij} should be invertible or inverse of response matrix of R_{ij} exists. To perform the inversion process, log analyst has to ensure the positive ness of the determinant of the response matrix before hand. This involves the unwanted computation of determinant of log response matrix.

Other method is the graphical procedure based on the mixture theory involving equation (1). If log responses of the different constituents are defined as vertices of a multidimensional polygon defined by the number of log measurements, it ensures the existence of the inverse of response matrix of Rij as well as the existence of mathematically feasible solutions Vj. Multidimensional polygon is visualized by generating cross plots for all possible subsets/planes viz. four log measurements will have six planes / cross plots. Vertices of the rock components are kept same on all the cross plots. This method also ensures the validity of response parameters as these are derived from actual log measurement (Yadav, *et al* 2002)

D. Convexity of Summation of Square of Errors

First, straight forward solution of the stated problem through statistical least square approach is to partially differentiate with a respect to the unknowns and solve the resulting simultaneous equations namely "Normal equations". Constraints can be taken into consideration through Lagrange multipliers technique. When the tool response equations are linear / non-linear, resulting normal equations will be linear / non-linear. To solve the non linear equations, some iterative scheme is the only solution to the problem. In such cases, mathematical programming technique is the best and efficient method. Before looking for mathematical programming techniques following conditions must be satisfied:

- Object function **f** should be convex as mathematical programming techniques are applicable to only convex functions.
- Hessian Matrix i.e. Matrix of second derivatives should be semidefinite and positive.
- Mathematical programming technique selected should ensure the convergence at a global minimum.
- If log responses of the different constituents are defined as vertices of a multidimensional polygon defined by the number of log measurements, it ensures the existence of the inverse of response matrix of Rij as well as the existence of mathematically feasible solutions Vj.

Adaptive Processing Technique of Well Log Evaluation

Adaptive processing technique allows very effective interaction of log analyst for deciding various parameters at various stages. Result of a particular pass is to be used as input for the next pass. When here are very little changes in results, convergence is supposed to be achieved. It composed of mainly three stages for processing a particular horizon.

Stage - 1:: Optimization of Matrix Response Parameters

Response parameters selected, either through cross plots or through log readings calibrated for matrix against the clean rock constituent, are to be treated as starting values. Further refinement of mineral parameters obtained through cross plots, is suggested by using this stage. This stage provides computation of exact mineral / matrix response parameters for a known set of mineral volumes and porosity in a water bearing zone. Mineral responses Rij are optimized through optimization of incoherence function **f**.

This stage exploits the statistical theory that least square estimations are mean estimations. For matrix parameter optimization, only mean values of logs in a particular water bearing horizon are used as observed values and constructed logs from expected values of volumes are optimized for mineral parameters. Computation of response matrix parameters is performed through least square error minimization using Truncated Newton Technique of non-linear constrained (bound) minimization. Parameters of first mineral, which is treated as basic mineral (viz. Quartz, Calcite etc) and water are not changed. However, parameters for the rest of the minerals are changed up to a maximum of +/- 20 % of initial values given by the user.

Stage – 2:: Volumetric Computation Level by Level

APTWEL software package initially solves the equations using weighted linear least square technique by minimizing the error objective function ***f*** of equation (3) by imposing non negative constraints on unknowns (Lawson and Hanson, 1974; Haskell and Hanson, 1981). Due to its averaging nature of least square technique (L2 Norm), some times it leads to unrealistic situation, particularly in case of bad hole or malfunctioning of a logging tool in a particular interval. In such cases L1 Norm technique gives better as well as realistic solutions by discarding most anomalous log as an outlier. To deal with such situation a provision is made in the package to look for solutions from constrained minimization through L1 Norm technique at each level. Selection of the solution from either of the technique is made on the basis of deviation of the solution from previous level.

Solutions from these techniques or previous level, whichever is better one is used as starting values for solving the system of equations (3) and (4) using non linear optimization technique by incorporating all the geological and geophysical constraints. Values of all the output parameters i.e. reservoir parameters (phi, rock volume fractions, Sw and Sxo) between zero and one, Sxo greater than or equal to Sw, are ensured through mathematical constraints imposed on these parameters in the software package itself. In case of laminated type of clay, porosity is less than or equal to Phimax * Vsand or Phimax * (1 –Vcl). However, in case of total clay volume computation, porosity should be less than or equal to Phimax * (1 – Vcl) ** 1.5 is also ensured through constraint equation (Mayer and Sibbit, 1980).

Stage - 3 :: Computation of aRw, Rcl and "m"

In this stage, slow parameters Rw, Rcl and "m" are calculated through least square minimization of square of error between actual and constructed resistivity log through equation (5) in a water bearing zone defined by the user. Vcl and Phi are the mean values of clay volume and porosity respectively in water bearing section of the horizon. Twenty percent up and low bounds are put as constraints on the solutions as in the case of mineral response optimization. This stage also uses the statistical property that least square estimators are mean estimators. So, optimization is performed only for mean values. Computation of is performed through least square error minimization using Truncated Newton Technique of non- linear constrained (bound) minimization. This stage is equivalent of picket plot where outliers are not considered for fitting the Rt and Phi values corrected for Vcl. This stage uses Rt, Vcl and Phi i.e. results of stage 2 as input data for least square fitting.

Applications of APTWEL to Reservoir Evaluations of Indian Basins

On-line Mineral dictionary from published literature along with their log response parameters were also incorporated in APTWEL, to provide the on-line standard parameters to users. All the minerals are available in 14 broad groups and each group is further divided into several minerals. There is no restriction on selection of number of minerals from same group. User can select several clay minerals from clay group at the cost of other mineral components of rock matrix. Actually, lumping of the minerals is guided by availability of number of logs, which should preferably be kept equal or more than the number of minerals in order to have mathematically feasible solutions. Concept of dummy logs and minerals are also available to take care of future logs and user defined minerals. Facility of user defined restrictions/ranges on the mineral volume fractions are also available as in case of other commercial packages.

APTWEL provides a very wide and flexible environment to log analyst for the evaluation of a wide spectrum of reservoirs. Processed results from various interpretation models for different types of reservoirs including complex lithology, low resistive complex lithology, low resistive naturally fractured carbonates, carbonate with various lithofacies, are presented in **Figure Nos. 1 to 4** (Yadav, et al. 2000, 2002). Examples of inversion of open hole logs recorded in coal beds are presented by Yadav et al 2001. Inversion of open hole logs are regularly being performed by APTWEL in ONGC and unpublished reports issued since 1988.

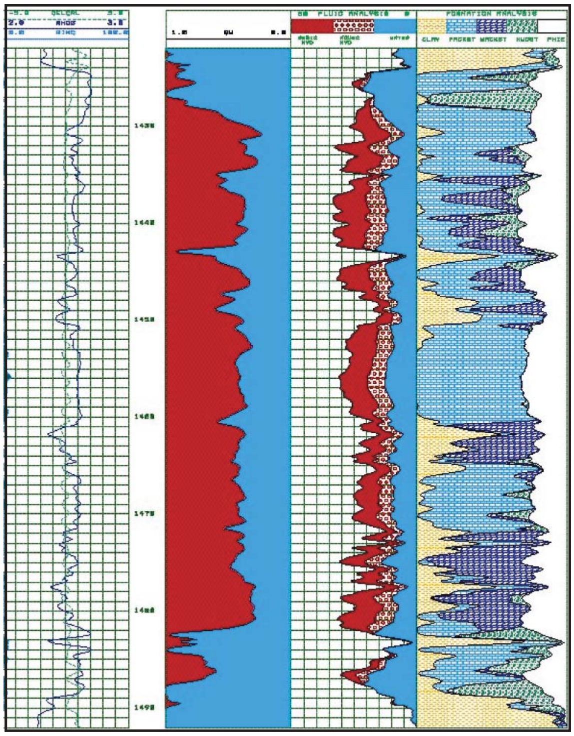

Fig. 1: APTWEL Processed Results of carbonate ReservoirsThrough “ *LITHOFACIES INVERSION*”

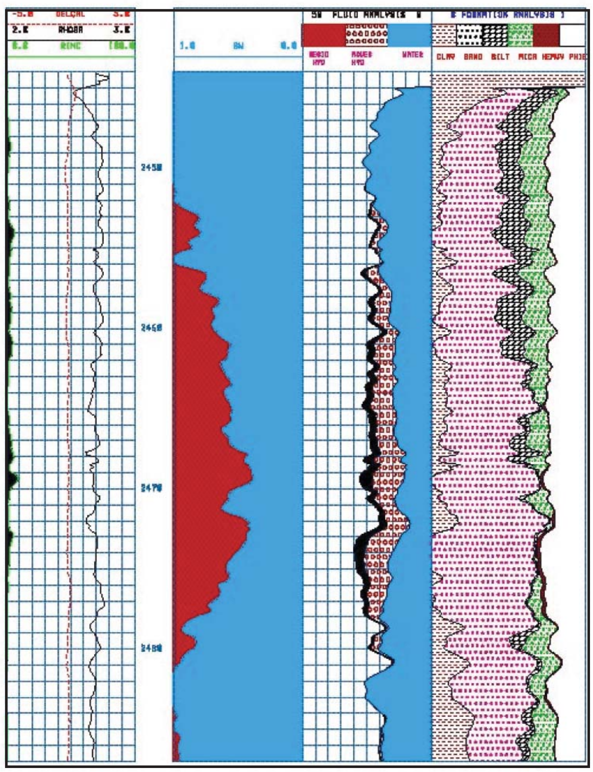

Fig.2: APTWEL Processed Results in Complex Lithology Through “*FOUR MINERAL MODEL*”

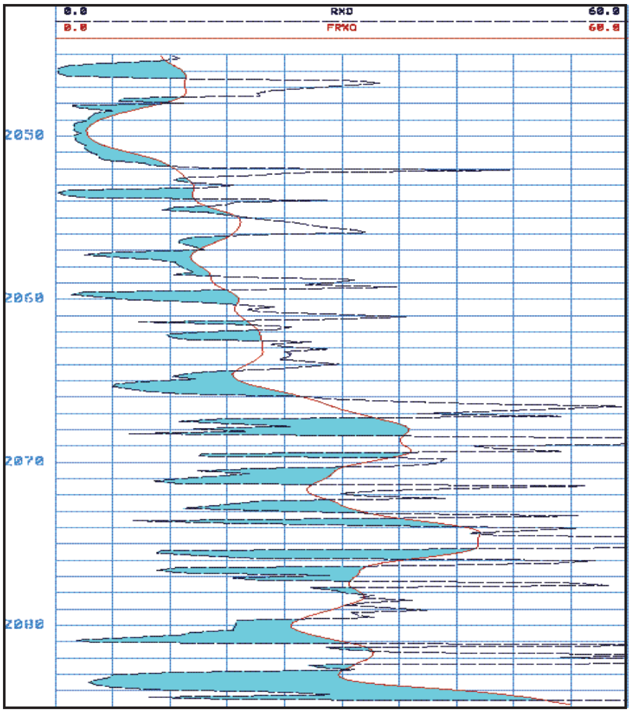

Fig.3: Identification of fractures / Vugs in Carbonates

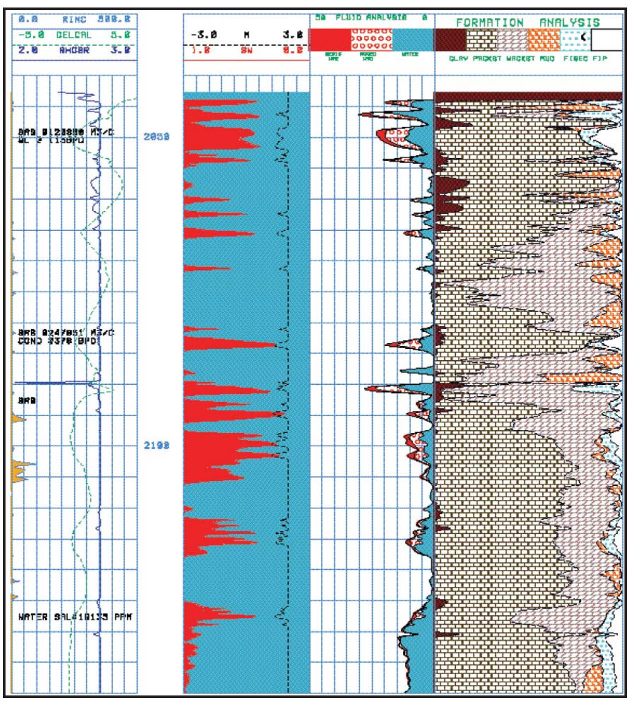

Fig. 4: APTWEL Processed Results of Low Resistive Fractured Reservoirs Through Variable " m"

Discussions and Conclusions

Inversion of open hole logs is performed by solving the *simultaneous* system of logging tool response equations through *statistical approach* by using weighted least square minimization technique. The main advantage of the inversion technique over conventional approach mainly lies in many folds.

- All the log measurements are seen simultaneously with their uncertainties. However, a deterministic model provides a sequential approach to see a log independently in isolation without knowledge of other log measurements.
- It provides a wide and flexible environment to log analyst as compared to the fixed models using limited number of log measurements in conventional techniques.
- Its ability to incorporate local geological/geophysical knowledge and core measurements through constrain equations.

The use of over determined system of equations incorporates flexibility in *simultaneous* solving of tool response equations. In statistical terms it is known as degree of freedom defined as difference between the number of equations (log measurements) and number of unknowns (number of minerals). Fluid component comes from additional unity equation i.e. summation of all rock constituents is equal to unity. Degree of freedom is the parameter, which incorporates the statistical sense to the solutions by keeping its value more than one. For example, fitting of a line through only two data points do not have any statistical sense. There is only a unique condition exist to join two points. Role of statistics come into play only when there are more number of data points. Similarly, log analyst has to keep number of minerals minimum as far as possible to provide statistical meaning to the inversion of open hole logs where uncertainties on both input as well as out put exist

There are several inverse modeling packages available in the industry viz. GLOBAL, ELAN, ULTRA, OPTIMA etc. (Mayer and Sibit, 1980, Alberty and Hashmy, 1984, Mezzatesta, et al., 1986 and Geysen and Hashmy, 1987). The basic concept of inverse modeling techniques has not been changed much during last twenty years; only efforts have been made to make the software packages more efficient and faster. All the inverse modeling packages are basically weighted least square solver of approximate linear/ non linear simultaneous tool response equations with geological and geophysical constrains imposed on the solutions and provide no means for model selection and verification (Quirein et al., 1986). Global minimum for objective function is ensured only for a particular combination of input and output parameters. Detailed methods are provided for use of these software packages, which cannot be treated as justification for realistic evaluation. Despite general agreement that statistical techniques produce more accurate answers, these techniques have been slow to replace the conventional approaches. The main reason behind it is that statistical techniques are difficult to use because of subtle interrelationships of formation parameters (e.g. cementation factor "m" affecting porosity value etc.), which occur when solving for all parameters simultaneously (Mitchell and Nelson, 1988).

Validity of output parameters ensured by packages while performing level-by-level computation, do not ensure the validity of upward or downward variations of these parameters according to geological setting. Output/ paralog of a particular layer have to be validated for continuity, depositional environment from volume of water against hydrocarbon charged formation. Validation of paralog for average grain density and limiting porosity established through core measurements is most important as it ensures real estimation of both clay volume and porosity. Degree of authenticity of an output results depends mainly on the log analyst rather than the type of software packages used and for which validation of I/O parameters is an essential requirement otherwise the evaluation of formation parameters will be highly subjective or meaningless in geological sense.

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