Validation of Input and Output Parameters for Realistic Evaluation of Open Hole Logs Through Inverse Modeling

Lalaji Yadav*, Narayan Singh Rawat, Aloke Kr Bhanja and Kamaleshwar Rai
KDMIPE ONGC Dehradun

Summary

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. Global minimum for objective function is ensured 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. Imposition of geological and geophysical constraints on the solutions brings it to a finite but still too large to fix it for a unique set of parameters. Further, imposition of constraints from core measurements viz. porosity, mineral volumes and grain density and production testing results on input/output parameters, makes the parameters selection easier and more realistic in a particular geological setting. Hence, validation of input/output parameters becomes essential part of log data processing / interpretation with greater degree of authenticity, similar to calibration of logging tools prior to recording / presentation of logs.

All the inverse modeling packages are to be treated as weighted least square solver of approximate linear/nonlinear simultaneous tool response equations with geological and geophysical constraints imposed on the solutions and provide no means for model selection and verification. Validation of I/O parameters is to be ensured by its calibration against known lithologies like clean sand, limestone or shale/clay zones if available. Otherwise, log response parameters for the respective component has to be derived from partial effects seen on the log by using linear extrapolation technique on cross plots where log responses of the different constituents are defined as vertices of a multidimensional polygon defined by the number of available log measurements. Multidimensional polygon is visualized by generating cross plots for all the possible subsets/ planes viz. four log measurements will have six planes / cross plots. Vertices of the rock components are kept same on the entire cross plots.

In this article, a complete procedural approach for the validation of the I/O parameters has been illustrated with different field examples. These examples clearly show how an improper parameter selection can produce a meaningless paralogs, which may not corroborate at all with the geological model/ reservoir characteristics of the field. 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. Therefore the validation of I/O parameters is an essential requirement for meaningful formation evaluation with greater degree of confidence/ authenticity.silent but are misleading. These examples will suggest NMR as a unique solution provider and allow the neutron-density-sonic porosities to be redundant in such type of formations.

Introduction

Solving the simultaneous system of logging tool response equations through statistical approach by using weighted least square minimization technique performs inversion of open hole logs. 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. 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. Hence, validation of input/ output parameters becomes essential part of log data processing / interpretation with greater degree of authenticity, similar to calibration of logging tools prior to recording of logs.

Standard log response parameters for almost all type and group of known minerals are generally well published and available along with inverse modeling packages. 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 does not ensure the validity of parameters, for example a thick formation where ratio it self may be varying with depth.

Validation of I/O parameters is to be ensured by its calibration against known lithologies like clean sand, limestone or shale/clay zones if available. Otherwise, log response parameters for the respective component have to be derived from partial effects seen on the log by using linear extrapolation technique on cross plots where log responses of the different constituents are defined as vertices of a multidimensional polygon defined by the number of available log measurements.

All the inverse modeling packages are to be treated as weighted least square solver of approximate linear/non linear simultaneous tool response equations with geological and geophysical constraints imposed on the solutions and provide no means for model selection and verification. Minimum incoherence function ensured by packages for a particular combination of I/O parameters is a necessary but not the sufficient condition to have the meaningful results. 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. The log analyst has to achieve the meaningful results by fine-tuning the parameters within the uncertainties defined on the log measurements.

In this article, a complete procedural approach for the validation of the I/O parameters has been illustrated with different field examples. Both meaningless as well as meaningful paralogs, in geophysical and geological sense, are presented to highlight the problem of validation. These examples clearly show how an improper parameter selection can produce a meaningless paralogs, which may not corroborate at all with the geological model/ reservoir characteristics of the field. 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. Therefore the validation of I/O parameters is an essential requirement for meaningful formation evaluation with greater degree of confidence/ authenticity.fluids

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Basic concept of inversion of open hole logs

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

$$\sum_{j=1,n} r_j * v_j = L \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

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

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

$$R_{ij} * V_j = L_i \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where R_{ij} = Response parameter of i th log measurement of j th constituent

V_j = Volume fraction of j th constituent, L_i = i th log measurement

Equation (2) is the simplest representation of the simultaneous linear tool response equations, sometimes referred as universal logging tool response equations, where fluid is being treated as a rock constituent. These system of equations can be solved approximately through statistical approach by minimizing summation of squares errors f between measured and constructed logs by incorporating the uncertainties on measurements, generally known as weighted least square minimization technique;

$$f = \sum_{i=1,\,nom} (R_{ij} * V_j - L_i)^2 / s?_i^{\,2} \quad \text{.............} \quad (3)$$

where s?i represents total uncertainty on i th tool, parameter and response equation. nom denotes total number of log measurements. f represents a measure of lack of coherence between measured and constructed logs, it is generally referred as incoherence function, an indicator of degree of quality of model fit.

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..

$$Phi \{ rmf_i * Sxo + rh_i * (1 - Sxo) \} + R_{ij} * V_j = L_i$$

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

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

Where fluid components are excluded from constituents Vj. rmf 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.

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. Imposition of geological and geophysical constraints on the solutions brings it to a finite but still a very large number of combinations of input / output parameters. Further, 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.

Validation of input parameters

Simplest way to perform inversion/solution of simultaneous equation (2), through deterministic approach, is to invert response parameter matrix Rij to get inverse matrix of it. Multiplication of inverse matrix with right hand log response column vector Li provides the solution vector Vj. Basic condition for the existence of mathematically feasible solutions Vj is that response matrix Rij should be invertible or inverse of response matrix of Rij exists. To perform the inversion process, log analyst has to ensure the positiveness of the determinant of the response matrix before hand. This involves the unwanted computation of determinant of 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. 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. Knowledge of standard log response parameters can be used as guide to fix the value of parameters within standard range. For example, if mica mineral is representing a group of mica minerals, its density value should fall in within 2.87 to 3.2 gm/cc as indicated in standard mineral dictionary.

In case of lithofacie inversion of open hole logs, it is easy to validate the response parameters as facies are directly defined on logs. Examples presented in this article with log data processed through lithofacies inversion model, does not require validation of input response parameters. Pure facie interval can be easily seen on paralog, where volume fractions of other facies are close to zero except fluid. In case of multi mineral model, log response parameters for the respective component have to be derived from partial effects seen on the log by using linear extrapolation technique on cross plots where log responses of the different constituents are defined as vertices of a multidimensional polygon defined by the number of available log measurements. A complete procedure is presented by Yadav et al, 2002.

Validation of output 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. It ensures only feasibility of the mathematical solutions and minimum value of incoherence /error function. Minimum incoherence function is a necessary but not the sufficient condition to have the meaningful results. While high incoherence function indicates that model does not fit the data, a low one does not verify that the model is correct. For example, different models may fit the data equally well, but give different answers. The log analyst has to achieve the meaningful results by fine-tuning the parameters within the uncertainties defined on the log measurements. Meaningless as well as meaningful paralogs, in geophysical and geological sense, are presented to highlight the problem of validation. It is worth mentioning that correctness of the output reservoir parameters solely depends on the choice/selection of interpretation model/input parameters by the log analyst and it has nothing to do with the particular package.

1. Validation for the degree of quality of fit / incoherence function

Presentation of degree of quality of fit or incoherence function is necessary but not sufficient condition to meet the objective, it is an essential qualifying parameter to select or reject a paralog at first glance without going into other details. It is generally presented in the first track of the paralog. Any paralog without incoherence function obviously does not qualify for presentation.

2. Validation of mathematical/ physical 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 packages itself. Range of values available through core measurements further increases the confidence. Once total hydrocarbon volume defined by phi - phi*Sw, is zero, (or Sw is equal to unity), its movable or residual components can not be presented in paralog as shown in processed results of ELAN in Fig. No.1. It is a well known fact that accumulation of hydrocarbon is there only when basic entrapment condition is met i.e. impervious cap rock /shale exists at the top of reservoir. Presentation of a layer on paralog with better effective porosity, obviously permeable, as compared to the underlying reservoir, contradicts the basic condition of hydrocarbon entrapment (Fig. No. 2).

3. Validation of continuity constraints

Validity of parameters ensured by packages while performing level-by-level computation does not ensure the validity of upward or downward variations of these parameters according to geological setting. Log curves of a well from Lakhmani field are presented in Fig. No. 3. Log data is processed using inverse modeling package "APTWEL" (Yadav, L., 1988). A paralog shown in Fig. No. 4, is rejected as output parameters do not meet the continuity constraints i.e. output parameters cannot have better resolution than input logs itself. Many fictitious thin beds are generated which are not seen on logs. More over, boundaries of permeable beds are to be further confirmed on independent log measurements like SP. An example in Fig. No. 5 is indicating highest effective porosity in shale/ clay beds. ELAN processed results presented without any concept of permeable / non permeable beds, where effective porosity increases with clay volume/ shaliness.

4. Validation of Gelogical / Geophysical constraints

Validity of output response for geological reality has to be ensured through user defined local geological constraint equations i.e. phi and clay volume relationship for a particular geological setting. This relationship is derived from basic physical law of porosity and grain supported matrix system. In case of unit cube filled with steel spherical balls of equal sizes, maximum porosity is 47.6 %, which indicates the limiting value of porosity beyond which system will become fluid supported. Phimax for sandstone reservoirs is defined against clean sand layer and rest of the places it decreases in proportionate with sand matrix system of the rock. 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 (Mayer and Sibbit, 1980). Phi and Clay volume relationship for a particular geological setting is further illustrated in the table given below:

Vclay (%)	0.0	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0
Phi Laminated Model Phimax * (1 – Vcl)	30.0	28.5	27.0	25.5	24.0	22.5	21.0	19.5	18.0	16.5	15.0
Phi_Total ClayModel Phimax *(1-Vcl) ** 1.5	30.0	27.8	25.6	23.5	21.5	19.5	17.5	15.5	13.9	12.2	10.6

- In a volumetric approach, computation of Vcl is simultaneously performed on all the log measurements and depends only on the log response parameters of the clay, generally, defined as lithology line on cross plots. Effective porosity or interconnected porosity presented on paralog belongs to the sand matrix component of the rock system (1 - Vcl). There are several other logs viz. RT / GR / UB / K / TH, having more sensitivity than neutron-density and makes the clay volume computation independent of clay distribution as seen on conventional neutron-density cross plots. Magnitude of effect of clay distribution on logs as compared to its absolute volume is within the precision of log measurements itself and can not affect volume computation as in case of conventional neutron-density computations through sequential approach.

- An example of log and paralog for TS-1 of a well XXX from Lakhmani field, processed through ELAN Plus is shown in Fig. 6 and 7. Log porosity and core-derived porosity are nicely matched but basic fact is forgotten that Vclay value of around 30 to 35 % can not support a rock matrix system with 20 to 30 % porosity, as evident from the above table. Moreover, validation of input and output parameters goes together and linked with conventional basic concepts. For example, a 50% change in water saturation has to be linked either four times change of resistivity or two times change on porosity or a change of clay volume more than 25 %, depending on resistivity of clay, with other parameters constant. How this change on water saturation is seen on paralog Fig. No. 7, without any noticeable change on either of these parameters, is not understandable.
- APTWEL processed paralog for the same Lakhmani Well No. XXX is shown Fig. No. 8. It is also showing reservoir porosity in the range of 24 - 30 %, corroborating core measurements against this formation. Average reservoir grain density around 2.7 gm/cc, is also matching well with core measurement. Anomalous change on water saturation is not seen on this paralog. An examples in Fig. No. 9 is also contradicting the above basic concept of effective porosity which is increasing with increase of clay volume. At places, it is showing good effective porosity without sand matrix which is also meaningless.

5. Validation of grain density and porosity from core measurements

The paralog (Fig. No.10) for the log example shown in Fig. 3 should be rejected because clay volume is overestimated coupled with underestimation of average reservoir porosity and grain density. The final APTWEL processed paralog for this well shown in Fig. 11, is showing average reservoir porosity in the range of 24 - 30 %, corroborating core measurements against this formation. Average reservoir grain density around 2.68 gm/cc, is also matching well with core measurement.

6. Validation of water volume curve for depositional environment

Validity of water saturation (Sw) against water bearing layer is ensured by its value close to hundred percent. However, it does not ensure geological realism in hydrocarbon bearing zone. Variation of water volume (PhiSw) coupled with grain size variations indicates the geological veracity. For a producing reservoir or hydrocarbon charged formation, PhiSw, should be close to a constant value at an irreducible water saturation level or it may increase or decrease according to variation of grain size. In other words, more porosity will accommodate more oil. Transition zone is indicated by increase of PhiSw value with increase of depth. Variation of PhiSw with porosity or constant value of hydrocarbon volume (Phi - PhiSw), indicates:

- Oil-wet depositional environment for the reservoir or
- Water charged reservoir through water injection process or
- Mathematical or fictitious low Sw values computed due to overestimation of Vcl that overcorrects the Rt value in water saturation equation.

An example of SINMIN processed paralog of Lakwa Well No. X shown in Fig. No. 12, is indicating variable water volume curve. Water volume is more in cleanest portion of reservoir, where maximum porosity is 30 %. Constant value of hydrocarbon volume indicates water charging of reservoir or log analyst created oil wet reservoir. Presenting such paralog for known and producing hydrocarbon-bearing formation is meaningless because it is indicating that oil is occupying same fraction of pores both in big as well as small and is contradicting the basic concept of oil migration in known water wet reservoirs.

7. Validation of interpretation model to testing results / independent log measurement viz. CMR / MRIL, if available

A paralog validated for all the above-mentioned criterion, may not validate the interpretation model for testing results. An example of logs and GLOBAL results are presented in Figs. 13 for a Lakhmani Well No. X. This paralog may be rejected because it is showing well known producing low resistivity reservoirs at top as non reservoirs with Vcl > 35 %. APTWEL processed results that corroborate with the production testing results.

A constant value PhiSw value for a hydrocarbon column indicates that reservoir is hydrocarbon charged at irreducible water saturation level will produce clean hydrocarbon. This value in addition to residual hydrocarbon, must be in close agreement with corresponding immovable capillary fluid volume seen on lithology independent fluid volume provided on CMR / MRIL measurements. It is worth mentioning that clay bound water do not make part of fluid analysis volume track on paralog. It is a part of clay volume on formation analysis by volume track and is included in clay volume. In a hydrocarbon bearing zone free fluid corresponds to movable hydrocarbon volume. An example of APTWEL processed paralog and CMR recorded fluid volume fractions for LBS-1 sand unit of Laipling Gaon Well No. X, are presented in Fig. No. 14 . Hydrocarbon and water volumes computed through textural model using Assam equations and CMR predicted values are in close agreement within precision of porosity measurement.

Discussions

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). All the inverse modeling packages are to be treated as 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). Detailed methods are provided for use of these software packages, which cannot be treated as justification for realistic evaluation. Validity of output response for geological reality has to be ensured through user defined local geological constraint equations. 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. So, Output/paralog of a particular layer has 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. In case of lithofacie inversion of open hole logs, it easy to validate the input response parameters as facies are directly defined on logs. However, in case of multi mineral model, log response parameters for the respective component, have to be derived from partial effects seen on cross plots by fixing the endpoints of selected minerals. It ensures the existence of the inverse of response matrix as well as the existence of mathematically feasible solutions (Yadav et al, 2002).

Implementation of shaly - sand concept and method for selection of clay and silt parameters from neutron-density cross plots, presented by Poupon et al 1970, have not changed over several decades. Only basic approach of computation has changed with inverse modeling. In a sequential approach first total porosity is computed and then it is corrected for clay effect particularly bound water component to get effective porosity. However, computation of clay bound water component is a part of clay volume component and there is only effective porosity, which is computed as fluid volume. Whatever porosity is seen on paralog is effective porosity. So, shale/clay beds with zero SP cannot be presented as porous and permeable beds, contradicting to the basic shaly - sand concept. False effective porosity in clay beds are computed either in case of actual bad hole or log analyst created bad hole by selecting higher value of clay parameters towards dry clay point as compared to the actual value of the same seen on the logs.

There is a common perception that porosity computation is least sensitive to lithology logs viz. GR / UB / K / TH owing to its zero or close to zero value of gradient / first partial derivative with respect to porosity. However, in case of porosity computation through inverse modeling, computation of porosity and matrix component goes together where these logs become most sensitive for computation of matrix i.e. (1.0 - porosity). This is why sometimes these logs seem to be most sensitive for porosity computations, when clay/shale parameters are fixed on higher side. To be more specific, if GR value for clay is selected 100 API instead of 80 API, construction of GR log is complete without an error with combination of 80 % of clay volume and 20 % of false effective porosity. It is worth mentioning that RT log further complicates the situation. As least square or L2 norm is a mean estimator, false effective porosity will be estimated even if other response parameters like neutron and density are correctly selected conventionally on cross plot on zero porosity / SP line. So, it is meaning less to present false value of effective porosity or increase of interconnected porosity with increase of clay volume as indicated on almost all the paralogs processed through ELAN.

One should not get confused with solver and model. It is the log analyst who does the formation evaluation by defining his model for the solver (software package) not the solver itself. Outcome of any solver software is controlled by the log analyst through basic model parameters of evaluations provided by him. Once a softwares package is available, one can always " use" or "misuse" depending on his own perception of interpretation model and its parameters with or without standard cross plot techniques. So, 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.

Conclusions and reccommendations

All the inverse modeling packages are solver of simultaneous tool response equations with geological and geophysical constrains imposed on the solutions and provide no means for model selection and verification. In case of multi mineral model, log response parameters for the respective component has to be derived from partial effects seen on the log by using linear extrapolation technique on cross plots where log responses of the different constituents are defined as vertices of a multidimensional polygon defined by the number of available log measurements. It ensures the existence of the inverse of response matrix as well as the existence of mathematically feasible solutions. In case of textural model or lithofacie inversion of open hole logs, it is easy to validate the response parameters as facies are directly defined on logs.

Validity of output parameters ensured by packages while performing level-by-level computations, does not ensure the validity of upward or downward variations of these parameters according to geological setting. Paralog has to be validated for continuity, geological and geophysical constraints, and depositional environment from volume of water against hydrocarbon charged formation. Validation of paralog for average grain density and porosity from core measurements is most important as it also ensures real estimation of clay volume. Output parameters or paralog is a complete entity. Paralog is generally referred in isolation and not necessarily referred by log analyst only. Therefore paralog by itself should depict the true formation picture without associating any log suite. An improper parameter selection can produce a meaningless paralog, which may not corroborate at all with the geological model/ reservoir characteristics of the field. 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. Therefore the validation of I/O parameters is an essential requirement for meaningful formation evaluation with greater degree of confidence/ authenticity.

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