Integration of Open Hole Data with Flow Period Production Log Data as a Key for Sensing Reservoir Bounds of Permeable Layers Occurring not far from the Wellbore

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Summary

One of the hallmarks of certain depositional environments is the lack of covariance between permeability and thickness. Our study of a recent deep-water well offshore East Coast India, indicated such an environment. In addition, it was noted that Kh has poor covariance with inflow from a layer. It becomes possible, then, through orward models, to investigate whether or not pressure disturbance front during the flow period at the time of inflow investigation saw the classic radial flow at a microscopic level. We have noted that in case of some, though not all layers, the pressure front had inflow deviating from the classical radial flow (even when technical water reduction near sandface was not anticipated). Our thesis is that, this is due to radial and vertical variations in formation properties having been encountered by the pressure front, which, in turn, points to vicinity of a boundary to the pressure front. This is the most important insight gained. Possibility of time-lapse production logging allowing for more and more grading of sub layers in a commingled test and thereby better understanding of Reservoir Limit Test (RLT) results under such conditions exists. Additionally we have gained valuable insights that have a bearing upon testing zones.

Scope of work

The scope of the current work was to come up with a consistent methodology for sub-zone differentiation vis-àvis the geological setting. To this end the following workflow was adopted:

1. Conceptualization of a Static Model and constructing the same using Magnetic Resonance log data, Acoustic log data, Electrical, Nuclear log data and Electrical Images based quantitative Facies Differentiator data. Elements of the Model: Continuous porosity, permeability, fluid saturation and Elastic Modulii

2. Construction of Perforation model, viz. Construction of Dynamic model of fluids flow into perforation tunnel incorporating fluid flow, perforation process and tunnel cleanup, formation elastic properties, and finally culminating in a forward model single shot skin computation.

3. Constructing flow model and modeling inflow zone wise, from production log data.

4. Computation of Apparent Single Shot Skin from production log data

5. Comparison of forward model and apparent single shot skin

6. Interpretation of differences and implications in terms of formation geometry around wellbore region.

Static Model

Static model is essentially the framework of rock matrix that is devoid of fluid flow and associated properties, perse. The mineralogy, petrology and related characterization define the static model. Parameters like porosity, permeability, saturations of the various phases, volume open to flow, etc. are some of the basic parameters that constitute it.

Generally, data from the available sources are used to arrive at reliable values of all these parameters. In this case, Least Square Error Minimization inverse modeling was carried out using the high resolution data from resistivity, density-neutron, magnetic resonance, sonic, etc. tools to arrive at realistic values for saturation of various fluids (essentially Gas and Water) and at volumes of the rock constituents. Thus volume open to flow was clearly described. Effective porosity was derived integrating data from magnetic resonance logs after applying appropriate corrections.

Our main area of focus was derivation of a reliable permeability dataset from the available formation evaluation data and, finally, calibrate it with drawdown permeability as measured by the formation tester. A later section of this paper details the steps carried out in order to arrive at a robust permeability dataset using Images to resolve facies and then characterize each facies separately using the Kozeny -Carman treatment of permeability estimation, which takes into account, among other parameters, the tortuosity of the flow path in the reservoir rocks, and pore surface to volume ratio of pore spaces. Formation bulk elastic modulii were obtained by inversion of shear and compressional slowness data, and fluid modulii were obtained by using appropriate mixing laws, and total compressibility as evaluated by using Gassman model.

Fluid Make Up

Dry Gas is known to be the only hydrocarbon phase. The properties of dry gas are well documented for these reservoir conditions1. Gas gravity, formation temperature and pressure have been computed from Pressure test data. Transport properties for the given gas gravity, pressure and temperature have been accessed from standard documentation.

Dynamic Model

The dynamic model comprises of modeling of transport properties of the rock into the static model for the different fluids. The transport is modeled as pressure and flow velocity using radial equation. The environment is modeled as a cylindrical borehole with an altered zone near the sand face. This altered zone is considered as a part of the total skin. The other part of the skin includes deviation from radial flow, turbulence, azimuthal disturbance of entry points, etc., and last-but-not-the-least, apparent skin due to liquid saturation near sandface.

In this study, we have also considered the fact that the combination of Kv and radially limited geometrics would lead to the disturbance front sensing non-radially and possible azimuthally anisotropic. Pressure and flux distribution are also accounted as apparent skin. The altered zone would entail variations in properties

1. Due to drilling induced damage
2. Damage due to cementation
3. Crushed zone created during the perforation.
4. Liquid saturation near sandface.

As shall be seen later, the well selected was subjected to minimal alteration due to factors 1,2 above. Modeling factor 3 mentioned above, is a part of our workflow. Factor 4 is considered by its expected covariance with texture, which is represented by a texture parameter derived from Electrical Image Tool button current data. However, the specific well studied has low liquid saturation near sandface as texture indicator is high and also the same is corroborated by log responses.

In addition to the texture indicator from Images, Density Neutron separation indicates low near-sandface water. Even so, comparison of differential skin (difference between IMASSS and FMSSS, explained in the ensuing sections) has been carried out for equal texture indicator values from Images.

The exposed litho section investigated meets the condition of low silt content in reservoirs, by which we mean that actual reservoirs are well resolved by Images and that other logs cannot fully resolve some of these. This condition is essential for near sandface liquid saturations not to drive the difference between IMASSS and FMSSS, and thus, boundary effects solely manifest themselves as the differential skin.

It would be prudent to mention here that the dynamic model is no way a comprehensive model but is an inflow profile model. Similarly a static model is basically based on wireline measurement and no attempt has been made to integrate it with the earth model.

Computation of Inverse Model Apparent Single Shot Skin (IMASSS)

The dynamic model has been used to compute a notional skin built during the perforation process using the ample production logging data available. This computation consists of three parts, all of which are considered in the apparent skin calculator, described in the body of this paper.

In the first part, Production Log data is inverted to inflow rates[2]. This inverse modeling uses standard Multiphase fluid flow models for flow through tubulars available in accredited commercial algorithms used by us.

In the second part, the inverted inflow rates are converted to apparent skin using conventional gas testing analysis and, subsequently, to single shot skin for a given drawdown. If the apparent skin is within bounds, a single shot skin is computed, else the Production Log data inversion is refined, and the process repeated till residual error, if any, is stable and lowest. Correction is given to inflow data to make total residual error summed over the number of zones minimal and close to zero. Finally zone wise inverse model apparent single shot skin is computed.

Computation of Forward Model Single Shot Skin (FMSSS)

The computation uses inputs from the dynamic model. The single shot theoretical construct for perforation and initial tunnel clean up, is an approach given by Larry Behrman[3]. We have adopted a specific usage of this methodology derived using thick zones, which are expected to have boundaries far away from sand face as calibration points, to account for systematic errors in the inversion of Production Log data to inflow rates. The corrected data has been used to compute crushed zone permeability by a technique described in this paper. This broadly entails plotting IMASSS and Perforation Systematics for calculating a notional ratio of zonal permeability to crushed zone permeability for thick zones. The crushed zone permeability is now inputted as a parameter into the forward model skin calculator described in this paper. The associated assumptions have also been stated alongwith.

Candidate well selection

We have selected a well drilled in the Deep waters off the East Coast of India for this study as this study was germane to the issue concerning reservoir characterization in this environment. The well section offers a unique opportunity not only in respect of completeness of data set, but also in fact, it has been noted that in this area, static reservoir properties have no relation with reservoir thickness exposed in the well section. This could be confirmed also from inflow study using production logs acquired in the well. Hence, this well was an ideal candidate for our study. We could confirm that layer wise dynamic behavior (fluid inflow performance) of different layers (from the Production Logs) followed the trend that the static behavior anticipated.

Since thicker layers are normally expected to be aerially more extensive than thinner ones, Forward Models of inflow can differentiate them in sense of property variations being near or far away from a pressure disturbing edge during flow. Layer wise skin rather than productivity Index has been taken as the inflow key parameter because flow environmental conditions such as choke size, tubing size, etc reduced sensitivity of drawdown to flow rates.

Dataset

The data for the said analysis was derived from various open and cased hole logs acquired in the candidate well. The open hole logging suite comprised of the state-of-theart high resolution formation evaluation tools, which are enlisted below:

- High resolution Density, Neutron and Resistivity logs
- Dipole Shear-Sonic Imager logs
- Elemental Capture Spectroscopy measurement
- Nuclear Magnetic Resonance measurements
- Formation Micro Images
- Modular Formation Dynamics Tester

The high resolution of the formation evaluation logs facilitated identification of thin beds commonly encountered in such geological settings. Moreover, the condition of the hole was conducive for logging the aforementioned tools, primarily because of usage of KCl Polymer based mud during drilling.

Also, during production testing of the candidate well, a comprehensive Production Logging suite was carried out with the objective of identification of fluids being produced from different perforated zones and quantification of the respective contributions. The interpreted results were integrated into the study together with the Production Testing results.

Methodology

The methodology followed to build the static models, compute the transport properties, and compare it with result obtained from the dynamic model has been illustrated further in Figure 1. The following section deals with explanation of the different steps undertaken.

Facies Characterization Using Image Logs

An Image based analysis of the well section for characterization and classification of different facies in the clastic deposit is a central feature of the Forward model. In this method, the high-resolution textural information from borehole electrical image log and mineralogical information from borehole spectroscopy log are combined to derive the lithofacies.

The elemental yields of the principle elements observed in the borehole spectroscopy log are converted

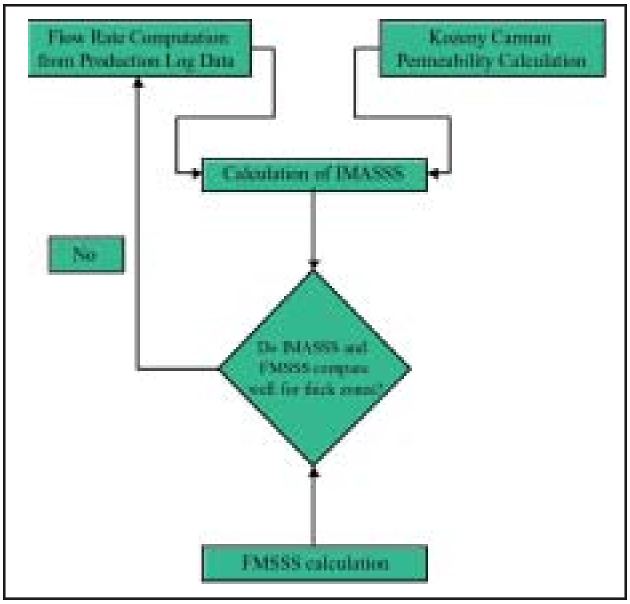

Fig. 1: Flowchart for calibration of the IMASSS using FMSSS for thick zones.

into dry weight percentages of total clay, total quartz-feldspar-mica, total carbonate, total evaporates, total pyrite, total siderite, total coal, and total anhydrite. Then, the mineralogical information is combined with textural information in the image log for defining facies. As this interval is devoid of non-clastic deposits and the rock texture is well represented in the image log, the lithofacies are well descriptive of the grain size variations within the studied section. Six major lithofacies, viz. 1) claystone, 2) shale, 3) sandy shale, 4) shaly sand, 5) sand and 6) clean sand, were identified using this method. The facies 1 to 6 are in the order of increase in sand content and decrease in the clay content. Hence, a general increase in the proportion of courser grains is represented in the facies 1 to 6. As it is a well-transported deep marine deposit, overall sorting, roundness and shape of the grains are presumed to be uniform across the various classes of the grain size fractions, i.e. facies.

Computation of Forward Model Permeability

We have compared Timur Coates, Timur, and Kozeny Carman approaches and have found that Kozeny Carman approach was most suitable. It is also the most basic. The surface to volume ratio of connected pore space and the hydraulic tortuosity of the pore space are critical parameters in this approach. We have seen that this can be amalgamated into a parameter akin to Kozeny Carman constant. However, we have realized that this can have a high covariance with the rock texture.

In our study, for the first time, we have taken advantage of this covariance which we have established, by cross plotting a textural class qualifier (an index available from proprietary inversion software which uses electrical button resistivity of Formation Micro Imager tool to device the textural class qualifier) against computed Kozeny Carman coefficient from formation test permeabilities to obtain valid forward model Kozeny Carman coefficient as a continuous curve. We used only some of the formation tester data for the exercise and used the remnant formation tester data as a check/validation. The fit is of good quality (See Figure 2). Further sections of the paper detail the technique more elaborately.

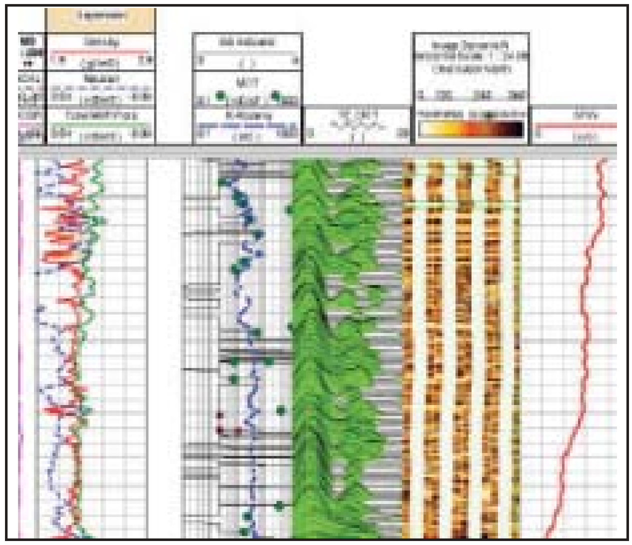

Fig. 2. Comparison of the raw permeability from the Timur-Coates equation and the Grain size indicator using Images and Capture Spectroscopy.

Dynamic Model Skin Computation

In the dynamic model, the perforated intervals were subdivided into numerous zones. These zones were demarcated on the basis of points of inflexion in the flowrate channel derived from the interpretation of production logging data for a particular choke size. Other parameters like permeability, porosity, and water saturation etc. were averaged using pertinent mathematical methods. Using these parameters, skin values were calculated for various zones as explained earlier in the section on “Computation of IMASSS”.

Forward Model Skin Computation

The broad methodology has already been described. The main features of the dynamic model are now given.

1. Shock decompression of fluid and frame post perforation create pressure differential pulse propagation. The effects of these are not considered, apart from the fact that tunnel debris is produced.
2. The above effect in water is more a mechanism in producing tunnel debris, while that in gas has a lesser role to play.
3. Debris cleanup is mainly through Technical water flow and secondary through Gas flow, because viscous drag force due to flow of water is many orders higher than that due to flow of gas.
4. It has been reported in literature that computer simulations indicate effects of (point 1 above) to be high for Gas, which is our case, but we have not considered effects of differential pulse propagation.
5. Drawdown is maintained during initial period (clean up of tunnel).
6. Flow is considered to be laminar.
7. Crushed zone grains are assumed to maintain packing while fluid flows through their intervening spaces. Main cleanup takes place by viscous drag experienced by crushed zone tunnel wall, by virtue of axial flow of fluids through the crushed zone tunnel.
8. Drag comes from velocity of fluid, which in turn depends on "Effective Pore Radius" of any element of tunnel and "Pressure Differential" across that element. Hence, for grain dissolution in tunnel, minimum velocity to be achieved which for given effective pore radius, depends on the drawdown.
9. Debris/crushed zone gets reduced and a tunnel grows to equivalent diameter leading to the following consequences:
   a. Equivalent Dia. = Formation Entrance Hole Dia. =>no debris
   b. Equivalent Dia. < Formation Entrance Hole Dia. => Debris present

The crushed zone permeability is an important parameter in the FMSSS calculation as explained earlier. Figure 3 illustrates the plot between IMASSS and Perforation Systematics for calculation of the notional ratio between thick zone permeability and crushed zone permeability.

It was also seen that in the plot of IAMSSS and Perforation Systematics, scatter is much more for low underbalance case (16 psi) than for initial (high) underbalance of 500 psi. This brings in an important consideration that systematics of clean up is not followed when underbalance is very low, which has implications on pros and cons of phased opening of zone(s)/zone addition etc. Post perforation (i.e. additional perforation) data for 16 psi underbalance perforation has not been considered in this study.

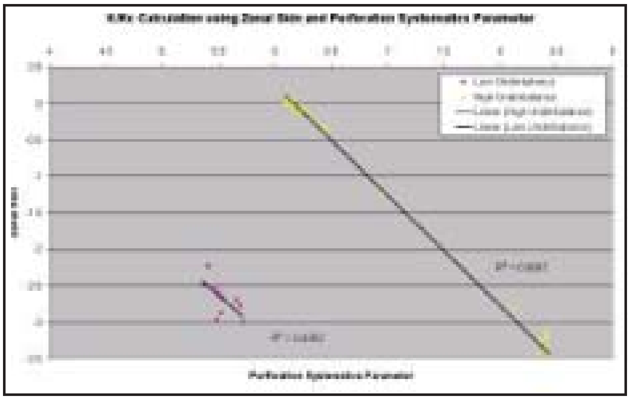

Fig. 3: Plot between IAMSSS and Perforation Systematics.

Comparison of IMASSS and FMSSS

Referring back to the Dynamic Model, it is clear that drilling induced and cementation damage are minimal in this well (See "Candidate Well Selection"). Apparent skin representing spatial distribution of perforation tunnels and crushed zones are accounted for in our work and forms a part of our forward model. Therefore the difference between IMASSS and FMSSS can arise due to near a) near sandface liquid saturation; and b) other reasons discussed below.

In addition to the texture indicator from Images, Density Neutron separation indicates low near-sandface water. Even so, comparison of Differential Skin (between IMASSS and FMSSS) has been carried out for equal texture indicator values from Images.

The exposed litho section investigated meets the condition of low silt content in reservoirs, by which we mean that actual reservoirs are well resolved by Images and that other logs cannot fully resolve some of these. This condition is essential for near sandface liquid saturations not to drive the differential skin, and thus, boundary effects solely manifest themselves as the differential skin. Hence, differential skin has been interpreted vis-à-vis texture indicator number.

We have seen that difference between IMASSS and FMSSS in most thick zones, and some thin zones, is negligible and these have low silt index (from image button data inversion). The few thicker zones that have low silt index but difference between IMASSS and FMSSS are interpreted to be having bounds near well bore in some direction.

Zones having high silt index are expected to have some retained technical water near sand face, which contributes to difference between IMASSS and FMSSS, beyond reasonable uncertainty expected. Normalizing from silt index, residual difference may be attributed to pressure disturbance pulse being in vicinity of a boundary.

Zones having low silt index, but a difference in IMASSS and FMSSS, are interpreted as zones bounding off not far away from the well bore in certain directions.

Conclusions

1. Owing to the importance of the wells drilled in the area under study in respect of the exploration program and criticality of the data acquired from these wells for efficient future exploitation of the reserves, a fairly comprehensive acquisition program was implemented in open hole & flow studies were carried out in well-cemented cased hole.

2. From the study of various logs acquired in the wells drilled in this area, it was observed that the static reservoir properties in the zone(s) of interest have no covariance with the reservoir thicknesses.

3. A robust forward model was established for continuous permeability, and was well validated with formation tester permeability data.

4. A robust model for inflow was developed, which provided insight for zone differentiation based on IMASSS vis -à-vis FMSSS. This differentiation was actually realized beyond reasonable uncertainty.

5. This differentiation has been found to be in consonance with FMI image interpretation results (See Figures 4 to 7).

6. Production Logging data can be used for zone differentiation in a commingled environment. This, however, is not possible from RLT data due to time constraints and techno-economical considerations.

7. Important input on facies extent from this method may be taken back to static reservoir characterization.

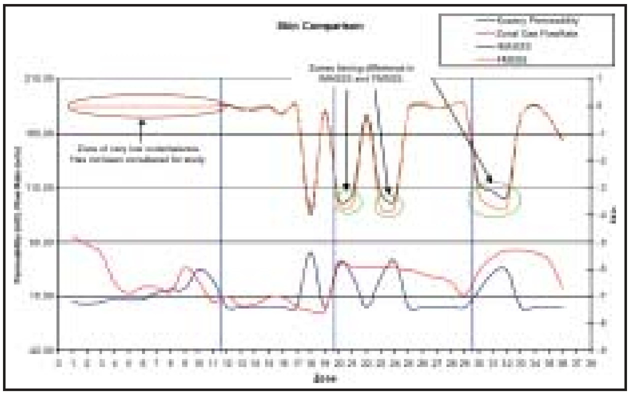

Fig. 4: Comparison of IMASSS and FMSSS (Secondary Y-Axis) for different Zones (X-Axis) across the perforated interval.

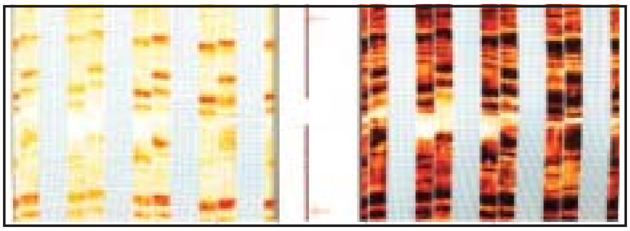

Fig. 5: Static (left) and Dynamic Images of the interval encompassing Zones 20 to 21. Silt -laminated thin sands –May not be extensive.

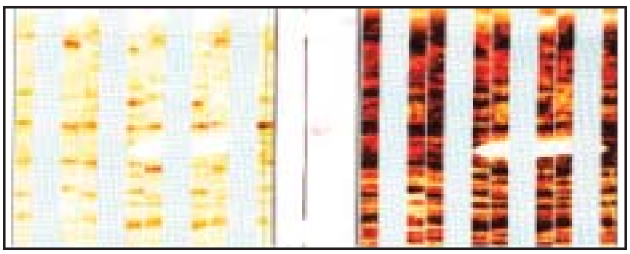

Fig. 6: Static and Dynamic Images of the interval encompassing Zones 23 to 24. Silt -laminated thin sands –May not be extensive.

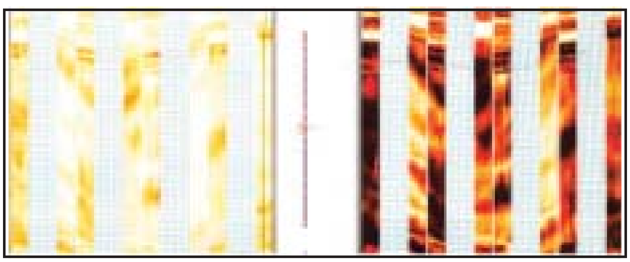

Fig. 7: Static and Dynamic Images of the interval encompassing Zones 30 to 33. High angle erosional cut - fill. Well likely to be located not far from cut-edge.

8. This method of integration and analysis of various static and dynamic measurements, especially production logging data, leads to in-depth dynamic

characterization of producing zones of varied thicknesses, and is an important complement to RLT.

9. Our work has indicated that systematics of the tunnel debris cleaning have consistency only when a minimum, albeit low, underbalance is ensured. This has important implication or pros and cons of zone addition, phased opening of zones vis-à-vis optimal production enhancement.

Directions of Future Work

1. Integration of Seismic Attributes into current work would allow us to label the nature of boundaries encountered by results.

2. Recording Production Logs with time lapse would help further differentiation of zones.

3. We can build an appropriate single well simulation model around the current work, which will integrate open hole log data, electrical images, NMR, acoustics and production logging and other flow data to predict the production performance of the well in future.

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