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TITLE: Integration of Advanced Acoustic Log data, Images and NMR data with Conventional Petrophysical analysis for improved Characterization of a Dual Porosity System– A Case Study

Abstract

Porosity partitioning, characterization of rock fabric as regards fluid saturation and permeability, and bulk rock reservoir characterization are challenges faced while assessing potential of carbonate formations. A technique of porosity partitioning using Shear and Compressive Slowness integrated with conventional petro physical analysis is demonstrated wherein connected secondary porosity and isolated grain dissolution porosity are quantified. The porosity modelling is also validated with NMR Bin Porosity Distribution. The computation of the porosity components and properties of the rock fabric vital to understanding the potential of rock as a reservoir is demonstrated on an oil bearing Miocene Reservoir. From a field development perspective, realistic modeling of rock fabric in terms of porosity permeability and fluid saturation and rock compressibility is vital to prediction of reservoir dynamics over a period of exploitation of the reservoir as well as for effective response to (acid treatment) stimulation and therefore even enhanced productivity post stimulation. From a drilling perspective, apart from correcting fracture gradient and safe drilling window estimates conventionally arrived, especially for carbonates case, offset well modeling of secondary porosity allows for prior anticipation of size of grain dissolution through correlation and has implications to loss zone anticipation, the importance of which can hardly be overstated.

Introduction

The present case study communicates an approach towards addressing the challenge of carbonate reservoir characterization. In this case study, a technique of porosity partitioning using Shear and Compressive Slowness integrated with conventional petro physical analysis is demonstrated, wherein connected secondary porosity and isolated grain dissolution porosity are quantified. The methodology is demonstrated on an oil bearing Carbonate Reservoir of Miocene Age exposed in a well off the west coast of India as part of the case study.

The current approach to the problem of porosity partitioning is based on the Effective Medium Approach of modelling rock properties that include Elastic Properties, Electrical Properties and Permeability porosity and fluids saturation. Kuster-Toksoz Model of Acoustic Wave Propagation, Maxwell Garnett models of Electromagnetic Wave Propagation in media having discontinuities which incoherently scatter the wave fields, and the analogue of Maxwell Garnett Model for fluid transmissibility have been used in the work flow. Biot Gassmann Theory which is not an effective medium theory such as mentioned above, but a continuum theory, has been used for fluid substitution for forward modeling host properties needed. Quantitative grain dissolution porosity computed from electrical image analysis have been integrated into the work flow to successfully partition secondary porosity into connected and isolated grain dissolution porosity. Based on the partitioning, internal porosity permeability and fluid saturation of the rock matrix and bulk rock have been computed. This case study differentiates between grain properties and mineral properties while analyzing acoustic wave propagation. Also results of the Differential Effective Medium Theory perspective of acoustic wave propagation as reported by Berryman and other researchers have been used to obtain modeled grain properties from acoustic and petro physical data, in this case study. Salient features of the methodology adopted in respect of modeling, data and interpretation of the results obtained, are presented in brief, in the following.

Porosity modelling:

Pore space of rock has been modeled, as comprising macro - pore porosity (arising from macro pores having throat diameter greater than 5 microns and pore size in excess of 8 microns, meso pore porosity arising from meso pores having pore throat diameter between 0.1 microns and 5 microns and pore sizes in the range of 0.2-8.0 microns, and micro porosity. Micro porosity is considered as pore space arising from micro pores having pore throat dimension of 0.1 microns or less. The remaining porosity is modelled to comprise meso-pores. The upper half (size wise) of meso-pores class has been considered to principally comprise moldic pores and solution channels in addition to porosity contributed by the larger pores within leached pore porosity patches. The lower half the meso pore class has been considered to be populated by inter-granular pores of the preserved inter granular porosity of the rock. Micro pores are thought to be essentially the pore space represented as inter-crystalline porosity and small pores present within cemented areas of the rock.

Macro pores are essentially grain dissolution pores which start as moldic pores and solution channel pores. These, further increase in size and become more rounded, as surrounding matrix leaches out, giving rise to the macro pore class. Therefore, little control exists as far as pore to throat dimension ratio is concerned. On the other hand, micro and Meso-pores (esp, lower half) have little to do with grain dissolution as far as their genesis goes. Therefore the pore to throat ratio can be nearer to that observed in clastic rocks, which is around 3-4. Hence ~1.5-2 microns can be considered as Micropore diameter threshold. In the porosity model adopted for the current study macro-porosity is assumed to be present both within and outside leached pore porosity patches. It is an assumption of the model that as button current is not focused, when porosity histogram is generated from the normalized resistivity histogram, macro-porosity embedded within leached pore porosity patches has low likelihood of falling within macro porosity pore class. Hence, they are not very well differentiated from background conductivity whereas isolated macro pores or aggregates of macro pores tend to be well differentiated from background conductivity.

Thus VISO (representative of macro porosity) data is in fact essentially biased towards macro porosity situated outside leached pore porosity patches. On the other hand, for a propagating acoustic wave field, by virtue of extremely high contrast of elastic Modulus between the fluid and surrounding medium, incoherent scattering of acoustic wave-field energy occurs whether macro-porosity is located inside leached pore porosity patches or outside them. Similar reasoning applies for solution channels and larger moldic pores which fall within the upper half of meso pores classes. Thus any technique which cumulates the volume of incoherent scaterers acoustic wave field is biased towards returning an answer which is biased towards the bulk of secondary porosity.

We have excluded fractures or such events which are extensive across the borehole surface, as we know from images that there is negligible /do not exist. The bulk of the secondary porosity which comprises the incoherent scaterers of the acoustic wave, has been also called as “inclusion porosity”. The rest of the porosity is called as host porosity. In this work we have modeled the medium as a host in which inclusions which are of high aspect ratio occur, that represent secondary porosity development to a large extent (inter granular pores enhanced in size owing to leaching are not categorized under secondary porosity because they cannot be incoherently scattering discontinuities. The host is thus rock having micro pores, inter-granular pores, size-enhanced inter-granular pores moldic pores and solution channel pores which still merit classification as meso pores. The inclusion pore space is as discussed in the foregoing. Thus our rock model is as a bi-phasic composite of the host phase and the inclusion phase. From Resistivity Image analysis we have noted that rounded to oblate spheroidal pores mostly are representative of the macro pore class (and thus the inclusions phase). The symmetry axes of the elongate pores are seen to have random orientation in space mostly, making the rock eligible to be modeled as a macroscopically isotropic medium.

Integration of NMR data & Image Data:

The Size of vugs starts generally from 10 microns when they are well delineated on Images and therefore quantitatively represented by **VISO**. It is not unreasonable to consider vugular porosity as Spherical in shape. Images bring out that the vugs are ***equant*** pores which can be approximated to spherical pores. A vug having a size of 10 microns would be therefore approximated by a sphere of radius 5 microns. It is well known that micro-pores have diameters ~ 2microns and it is also well known that T2 cut off which differentiates micro from Meso-pores is defined by the following expression:

$$1T2\_micro = \rho\ 3r\_micro = \rho\ 31 \ \mu s/\mu m$$

The throat diameter of macropores starts from 5 microns and the ratio of pore diameter to throat diameter starts at 3-4 and can go up to 10. The minimum diameter a macropore can have is therefore 15 microns and the minimum radius a macropore can have would be 7.5 microns

$$1T2\_macro = \rho\ 3r\_macro \sim \rho\ 37.5 \ \mu s/\mu m$$

From the above two equation we get, $T2UT2L = 7.5$

The cutoff on T2 to differentiate micro-pores from the meso-pores is 100ms for Limestone. Thus T2L = 100ms. Therefore T2U = 750ms. We have started with a value of 700ms for T2U for exploring the T2 spectrum for estimating macro pore porosity.

In order to integrate the NMR data into the process of characterization of macro-porosity, we have (constrained by the bin structures into which T2 echos are processed and inverted or as shown in **Plate.1**) computed the porosity of bins beyond 700 ms to arrive at vugular porosity contribution.

The graphics shows that the porosity carried by the two bins beyond 700ms, which when cumulated, would represent an estimate of vugular porosity from NMR data. This is overlaid against VISO. The match is fair which indicated that the image derived vugular porosity and NMR T2 spectrum derived vugular porosity are in agreement. Hence VISO was used while calculating the **Sw_ig** (Sw of Host), as well as the Permeability.

The agreement between macro porosity from NMR as well from images brings out that most of the vugular porosity is indeed Isolated.

Forward Model of Host Electric Moduli:

Guided by the above observations Kuster-Toksoz theory for a host medium with near-spherical shaped inclusions has been adopted as the forward model for the acoustic wave propagation for this study. Again, based on the same observations referred to, Maxwell- Garnett Equation has been adopted as the

forward Model for calculating electrical conductivity from the bulk conductivity (from low frequency limit of general model of Maxwell – Garnett of electro- magnetic wave propagation).
Macro porosity outside leached pore porosity has also been designated as isolated porosity in this work.

The form Krief's equation has been adopted for modelling Host Shear Modulus. We assume rock G= G_{dry}, where G_{dry}, $=G_{grain}\ (1-\varphi)^{c/(1-\varphi)}$ (G_{dry}, G_{grain} respectively stand for dry frame and grain shear moduli) The parameter 'c' is usually assigned the value 3.0. This parameter is responsive to aspect ratio of pores and the equation is essentially true for medium with connected pores alone accounting for the total pore volume. When elastic moduli are measured from acoustic wave slowness measurements the representative orientation of the symmetry axes of the pores with respect to the direction of propagation of wave also matters. The value of 3.0 for the parameter 'c' works satisfactorily for the case of pore volume being made up of essentially rounded pores but can differ from the value of 3.0 when pore shape heterogeneity exists. Since the subject of study here has been carbonate rock, we have made c a free parameter. it is a parameter we have determined from actual data in our work. To determine this parameter, linear fit of Log of measured G against $(1-\varphi)^{1/(1-\varphi)}$ has been made for levels having sufficiently low φ (to rule out influence of secondary porosity on 'c') in order to obtain the value of the parameter c applicable for modeling host elastic moduli.
The texture of the carbonates analyzed is mainly wackestone packstone. The presence of Lime mud and the fact that rock may not be entirely grain supported imply that apparent grain moduli, of an equivalent (equivalent in the sense of rock mechanical properties) Biot Solid, is expected to be different from mineral elastic moduli. Consequently, grain moduli have been considered as (free) parameters to be elicited from filed date. Therefore log(G_{grain}) has been considered as the y-axis intercept of the linear fit line of measured G against $(1-\varphi)^{1/(1-\varphi)}$.

At Low-enough porosity values both K_{dry} and G follow relationships with respective grain moduli which have the form of Krief's Equation. It is also a known fact that ratio of dry frame moduli of carbonates as well as clastic rocks are independent of porosity. The above considerations imply that the ratio, K_{dry}/G_{dry} should essentially be independent of porosity and equal the ratio K_{grain}/G_{grain}. Therefore, for any rock having sparse isolated secondary porosity but good fraction of secondary porosity in accounted by pores occurring within leached pore porosity patches, K_dry can be modelled as (K_grain/G_grain)*G, since G_{dry}=G. The value of K_{grain}/G_{grain}=2.29 (Mavko et al) has been considered for the present study.
Maxwell-Garnett relation has been used to compute "host" electric conductivity from bulk electric conductivity. The basis of preference for this relation has been the fact that Maxwell-Garnet Theory treats scattering of Electromagnetic wave by spatially bounded conductivity-discontinuities (physically, conductive and resistive inclusions) in a way similar to the way Kustor-Toksoz theory treats the scattering acoustic waves by spatially bounded discontinuities within the host medium.
In the present work "host" conductivity computed from Maxwell-Garnet Relation has been inverted to "host" water saturation using Archie's Law since clay fractions is very low in the rock. Sxo has been obtained from Sw through standard power relation. Host Bulk Modulus K_{host} for the region of rock investigated by acoustic tools, has been calculated using Gassmann's Equation, assuming mud filtrate as the non-hydrocarbon component of the pore fluids composite. The above is valid save for minor error as rock can be considered a Biot solid to a fair degree of approximation in the narrow context of forward modeling K_{host} for modeling a parameter called Z_{host}. K_{host} thus calculated has been used only here and nowhere else, within the work flow to compute Z_{host} (see workflow). The possible error in V_{inc} computation arising from calculating K_{host} within the narrow context mentioned above, is considered negligible.
Computation of Sw host, an important aspect of reservoir characterization has been carried out as already discussed above.
Host porosity being interconnected, its permeability is amenable to computation through Timur-Coates relation, assuming S_{wirr} is close to S_w for the case rock occurring at depth levels well above contact. Such levels have been used to generate a porosity permeability regression model which has then been extended to all level for permeability prediction from porosity. The porosity -permeability regression has

been used to generate host permeability predictor below contact and for water zones. Extension of Maxwell – Garnett model to permeability results in bulk rock permeability predictor.

Discussion of Results:

Some examples of the evaluation of the parameter c of Krief's Equation, and evaluation of effective grain shear modulus are shown at plate 2. It is seen that both c and effective grain modulus applicable are respectively different from the value of 3.0 and calcite mineral Shear modulus of elasticity. The reason for this is that the value of c has sensitivity to grain shape, and packing and can be modeled. However it requires a large volume of data on grain shape and packing forward model of c, a macroscopic parameter, from microscopic attributes is difficult, which is why field calibration approach has been adopted here. The results indeed bear out the necessity of a field calibration approach as adopted here for proper inversion of shear and compressional slowness data into valid porosity partitioning, and quantitative fluids saturation of the host phase.

As a crosscheck of the pore space characterization and fluid saturation computation the computed water saturation of 'host' phase (S_{whost}) has been overlaid at track 6 of **Plate-3** with S_w from Petrophysical analysis in respect of two separate intervals (please refer collage appended at the end) and they conform well.

Porosity partitioning in respect of either interval is output at tracks 3, 4 of **plate-3**. From the results it is noted that a sizeable fraction of secondary porosity occurs within leached pore porosity patches (where conductivity contrast of the event is not high with respect to immediate surrounding rock)

Results of computation of host permeability have been presented as part of collage given in **plate-4**. The permeability is seen to lie within the range of 8mD - 100 mD. This range conforms to the flow rates observed during conventional tests. The permeability thickness from well test analysis when divided by the net thickness for the intervals perforated, gives answers which compare with the magnitude of host permeability computed. However, MDT permeability values are very low and lower than Perm-Host computed. Perm-Host is quite reasonable when examined with flowrates in conventional test against similar/same formation in the offset wells. The low permeability values from MDT is attributed to a combination of near wellbore formation damage and/or well cemented areas occurring inside 'host' being accessed by Formation Tester Tool's single probe. For carbonates, larger area of rock face of the rock volume involved in flow and build up experiment of formation tester techniques with single probe used, is required for obtaining host permeability. Dual packer deployment with pump- out, for a good amount of time preceding shut-in can give data of enough time history for host and overall permeability estimation. In the absence of this the current work flow is, as demonstrated, the best alternative to understand the prospectivity as a reservoir of porous carbonate intervals of hydrocarbon interest.

The modeling of rock as a bi-phasic system is a prudent optimized model. Here by modeling 'host' as essentially base rock with meso pore porosity and some microporosity the main control of flow zone index and reservoir quality index goes to the host which makes the model relatable to actual flow behavior in conventional tests as well as help streamline the information from electric images as well as post processing results from image analysis.

Conclusions

- A methodology of porosity partitioning of carbonates which is relatable to reservoir dynamics while at the same time based on a simple model of the rock is demonstrated.
- Modeling 'host' as essentially base rock with meso pore porosity and some microporosity and including moldic and solution channel porosity embedded within leached pore porosity patches, has proven to be productive (**Plate-4**). Host properties have the main control of flow zone index and reservoir quality index, in this approach, with the host modeled as defined. This approach renders, results arrived at from model based computations, relatable to actual flow behavior in conventional tests as well as help streamline the information from electric images (including post processing results from image analysis) for maximum synergy.
- Actual results validate the model based on Kuster-Toksoz Theory for rounded inclusions.
- The study underscores how integration of electric image data based partition of porosity with acoustic wave propagation analysis based porosity partitioning helps understand carbonate porosity with a reasonable degree of confidence attachable to the results.
- Integration of NMR with Images gives a valid estimation of isolated Macro-porosity. In this case study the vugular porosity from images and NMR match well. This suggests that most of the vugs are isolated ones.This study has brought out the value addition through integration of NMR and Images .
- However, the problem of systemizing pore throat / conduit dimensions to pore size ratio, calculation of attributes such as number of connected ports per pore continue to elude inversion while being central to deciphering fluid transport in heterogeneous carbonates.

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