

OPTIMIZATION OF DRY FRAME MODELING USING REALISTIC APPROACH AND ITS IMPACT ON FLUID SUBSTITUTION: A DEEPWATER CASE STUDY

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ABSTRACT

Fluid saturation is time dependent in a mature field which is undergoing water injection. Forward models of elastic properties of rocks having partial saturations are important for modeling of porosity as fluid pressure and saturation changes with time. Hence, fluid saturation is a critical component of modeling the behavior of reservoir rocks not only as reservoir entities but also as elastic rocks during production and enhancement.

The current work is a case study of fluid substitution in a deep water gas-bearing clastic reservoir using a dry frame optimization technique. Even though this is an example from an exploratory well, the technique showcased here is extremely relevant and applicable for the wells in brown field as well. A field calibration approach was used towards effective grain properties of the principal grain mineral (quartz). The work assumes that the Poisson's ratio of dry rock is independent of porosity.

Firstly the effective grain properties are found in case of shale free sand stone employing a technique described in detail in the paper. This method effectively takes into account the grain-to-grain contact properties and the Krief's exponent was modeled. Then the effective grain properties of shaly sand are modeled using Voigt-Reuss averaging. The exponent(s) of the grain volume used in the relationship that links grain volume to the dry frame properties are modeled from values obtained from a sophisticated log data inversion technique resulting in a high degree of confidence in dry frame properties.

Once the dry frame properties have been modeled, level-by-level fluid substitution is carried out using Gassmann's equation and the mixing law for the fluid properties, which has been fine tuned. Additionally the saturation from this approach is compared with the hydrocarbon saturation from a conventional petrophysical log inversion method. Finally an attempt has been made to model the Effective Aspect Ratio (EAR) from estimated critical porosity as explained in this paper.

This case study demonstrates the utility, validity and portability of such an optimization approach using dry frame properties with fluid substitution and describes the implications for understanding the acoustic tortuosity in relation to compressibility and the grain properties.

INTRODUCTION

Dry frame properties of reservoir rocks are critical components for fluid saturation estimation. Additionally, fluid saturation changes with time and a good control on dry rock frame properties plays a crucial role in estimating partial saturation through forward modeling with higher confidence.

The present case study involves an offshore well in the East Coast deep-water in India. The reservoir analyzed is a gas-bearing reservoir. The well section has acoustic well-log data in addition to other conventional logs and electrical images. The litho-facies is blocky as well as finely laminated sandstone facies. The current work is spurred by a desire to investigate if acoustic based methods for optimization of dry frame property modeling, which could result in valid and robust water saturation computation. The aspiration is that the method is applicable in cases

where variation in intercalated or inter-laminated clay volumes could mask the signature of fluid saturations or fluid-type changes in resistivity and thus clarify the contact definitions. An integrated approach has been used by using saturation from substitution in elastic moduli in addition to conventional resistivity based saturation analysis. Results are quite encouraging and promise not only the alternative validating mechanisms but also detection of hydrocarbon saturation using non resistivity well-logs in deep-water environment. Finally an attempt was carried out to model the effective aspect ratio.

THEORY AND METHODOLOGY

A workflow is used to optimize the dry frame rock properties followed by a realistic computation of fluid saturation. First effective grain properties of the rock was carried out by considering the fact of grain-to-grain contact properties and the Krief’s exponent. Fluid bulk modulus has been determined and used for acoustic saturation determination using the mixing law (Brie et al., 1995). Finally using the dry frame elastic properties critical porosity has been estimated, which are related to the effective aspect ratio of grains.

Effective grain properties from the clean zones:

Effective medium theories that model dry frame properties and saturated frame properties rely on grain properties while not explicitly modeling grain to grain contact elasticity.

In order to account for all factors including the above, an effective G_{grain}^{clean} and an effective K_{grain}^{clean} have been obtained

For clean zones the following relationships have been used.

$$G_{dry}^{clean} = G_{grain}^{clean} \left(\frac{\Phi}{1-\Phi} \right)^c \quad \dots (1)$$

$$K_{dry}^{clean} = K_{grain}^{clean} \left(\frac{\Phi}{1-\Phi} \right)^c \quad \dots (2)$$

Where, Φ , is total porosity and c is a constant independent of total porosity.

G_{grain}^{clean} has been evaluated as the intercept of a line fitted to the $\log G_{bulk}$ versus $(1/1-\Phi_i) * \log(1-\Phi_i)$ plot, on the G_{bulk} axis with c having been evaluated as the slope of that line.

Since VP/VS of dry gas bearing rock is a constant (Brie at al., 1995), The implication is that K_{dry}/G_{dry} has to be independent of Φ_i and therefore

$$K_{dry}/G_{dry} = K_{grain}/G_{grain}.$$

From the values reported for VP/VS in consolidated dry gas bearing sandstones (Brie et al., 1995), K_{grain}/G_{grain} is deduced to be 1.14, and hence

$$K_{grain}^{clean} = 1.14 * G_{grain}^{clean} \quad \dots (3)$$

Dry frame properties with shale present

K_{grain} has been computed using Voigt and Reuss method as below

$$K_{or} = \frac{1}{\left(\frac{V_{sh}}{K_{sh}} \right) + \left(\frac{V_{quart}}{K_{quart}} \right)}$$

$$K_{ov} = (K_{sh} * V_{sh}) + (K_{quart} * V_{quart})$$

$$K_{ovrh} = (a * K_{or} + bK_{ov})/2 \quad \dots (4)$$

Where a =1, b=1

K_{dry} has been computed as

$$K_{dry} = K_{grain} *(1 - \Phi_t)^p \quad \dots (5)$$

Where,

$$p = p_c + p_s$$

where, *c* stands for compliant pores and *s* stands for stiff pores (Keys and Xu, 2002).

When the calculations were carried out it was noted that when V_{clay} was less than 25% p_s was less than p_c . The compliant pore volumetrics p_c was modeled from clay bound water and stiff pore volumetrics from $\Phi_t - \Phi_c$. Clay bound water has been computed as the minimum of clay bound water from petrophysical inversion through a least square optimization and implemented through a robust multiminer model of rock and micro porosity from micro-porosity bin of NMR T_2 inversion. Total porosity has been considered by averaging Φ_t by the afore-mentioned petrophysical processing result and density nuclear magnetic response (NMR) derived method.

Consequently K_{dry} has been modeled as

$$K_{dry} = K_{grain} *(1 - \Phi_t)^{c/(1 - \Phi_t)} \quad \dots (6)$$

Where ‘*c*’ obtained from clean reservoir data as discussed in the foregoing has been used.

It is worth noting here that the methodology discussed (namely obtaining ‘*c*’ and G_{grain}^{clean} from clean formation leads to most likely values of G_{grain}^{clean} to be used. Thus preferring this over $K_{dry} = G_{dry} * (K_{grain}^{clean} / G_{grain}^{clean})$ has been deliberate, since K_{grain}/G_{grain} has derived from $(K_{grain}^{clean} / G_{grain}^{clean})$, even when volume of clay is low, whereas ‘*c*’ is applicable for a clayey formation is still close to ‘*c*’ obtained from analysis of clean formation, where V_{clay} is less than 25%.

Fluid properties

The properties of mud filtrate and formation water at formation temperature and pressure conditions have been computed from standard correlations. The gas composition is known and accordingly the compressional modulus has been computed.

Computation of K_{fluid}

The value of K_{fluid} has been computed as follows:

$$\frac{K_{bulk}}{(K_{grain}) - (K_{bulk})} = \frac{K_{dry}}{(K_{grain}) - (K_{dry})} + \frac{K_{fluid}}{\phi_t [(K_{grain}) - (K_{fluid})]} \quad \text{Or,} \quad \dots (7)$$

$$\left\{ \frac{K_{fluid}}{(K_{grain})} \right\}^{-1} = \left\{ \left[\left(\frac{K_{bulk}}{(K_{grain}) - (K_{bulk})} \right) \left(\frac{K_{dry}}{(K_{grain}) - (K_{dry})} \right) \right] * \phi_t \right\}^{-1} + 1 \quad \dots (8)$$

Finally K_{fluid} can be written as

$$K_{fluid} = \frac{(K_{grain})_{composite}}{\left(1 + \left(\frac{1}{\phi_t * A} \right) \right)} \quad \dots (9)$$

Where, A can be defined as

$$A = \frac{K_{bulk}}{(K_{grain}) - (K_{bulk})} - \frac{K_{dry}}{(K_{grain}) - (K_{dry})} \quad \dots (10)$$

Computation of water saturation using Voigt and Reuss mixing law for dry frame grain properties

The water saturation in the zone affected by acoustic wave fields, denoted as S_{xo} sonic has been calculated from inverting K_{fluid} , in accordance with the mixing law (Brie et al., 1995), valid for the frequency range relevant to the acoustic tools used (namely 5 to 18 kHz).

$$S_{xo} = \left[\frac{(K_{fluid} - K_{gas})}{(K_{water} - K_{gas})} \right]^e \quad \dots (11)$$

The above mentioned relationships are used in a work-flow shown in Fig. 1

After computation of the water saturation, an attempt has been carried out to compute the critical porosity for lithologies. Dry frame properties have been used in addition to the proportion of stiff and compliant pore proportions to compute the critical porosities for different lithologies. (Xu-White, 1995).

Firstly a component R was computed using the following equation,

$$R = \frac{3\mu}{(3K - 4\mu)} \quad \dots (12)$$

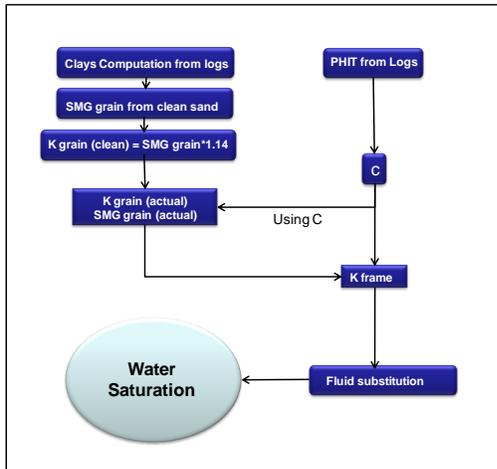


Fig. 1: Work flow for saturation from sonic data

Then, F1 and F2 were computed using equations as reported in Keys-Xu (2002), which quoted the equations given by Kuster and Toksoz (1974) and Xu and White (1995).

Finally T_{ijij} was evaluated as

$$T_{ijij}(\alpha) = \frac{3F1}{F2} \quad \dots (13)$$

It is known that T_{ijij} is related to the exponent “p” of the relationships

$$K_{dry} = K_{grain} * (1 - \phi)^p \quad \dots (14)$$

and

$$G_{dry} = G_{grain} * (1 - \phi)^p \text{ by } \dots (15)$$

$$p = 1/3 * \sum_{l=s,c} v_l T_{ijij}(\alpha_l)$$

The critical porosity for sands and shale have been computed using the relationship

$$\phi_c = \frac{1}{p} \quad \dots (18)$$

The depth-wise variation of the critical porosity for sand and shale respectively shows tight clustering around values, which are closed to such critical porosities reported in literature (Keys and Xu, 2002).

Effective Aspect Ratio (EAR):

Finally the Effective Aspect Ratio (EAR) was determined using the continuous critical porosity curve derived by using the steps mentioned earlier.

RESULTS AND DISCUSSION

The methodology allows for dry frame properties estimation under conditions of continuously varying clay volume. The variation of the exponent of the equations 1 and 2 is modeled in a robust manner. The integrated approach, which integrates state-of-the-art petrophysics with rock physics results in accurate modeling of clay type and clay content crucial to refined dry frame property modeling.

The methodology differs from conventional approaches which concentrate on clean reservoirs by two important ways. Firstly, the grain properties modeling is based on Voigt and Reuss averaging and Wood’s mixing law. Secondly, the acoustic equivalent of Archie exponent, which is represented as “p” in this paper, is modeled using the approach of Keys and Xu (2002) equations. These encompass the aspect ratio of grains, which is the main reason why the approach is robust. As far as fluid properties modeling is concerned, the equations appropriate to the acoustic frequency of the data have been used. As a result of the approaches described, the computed saturations of gas are found to be realistic and well validated by petrophysical results, which in turn have been demonstrated to be realistic through formation testing. This included straddle packer testing with long flow and long build up (not presented in the present paper).

This approach is found to be particularly suitable for deep water deposits because the laminated shale is more dominant than disseminated shale, in the fractional representation of the total shale, while the sequence of lamination is such that individual lamina dimensions are much smaller than the vertical resolution of acoustic tools used. Consequently, dry clay parameters are stable and can be taken from standard mineral values. Clay properties have been taken as weighted average properties of montmorillonite, illite, kaolinite and mixed-layer clays with mixed-layer clay properties approximated to be close to those of illite. The effect of non-radioactive heavy minerals such as pyrite and siderite as well as thorium minerals associated with radioactive heavy minerals have been neglected, because their volumetric representation is very low. Acoustic logs were recorded approximately 20 hr after the stoppage of circulation in the study well. Because the zones investigated are permeable gas-bearing zones, it was expected that S_{x_0} sonic would be closer to S_w (water saturation in virgin zone).

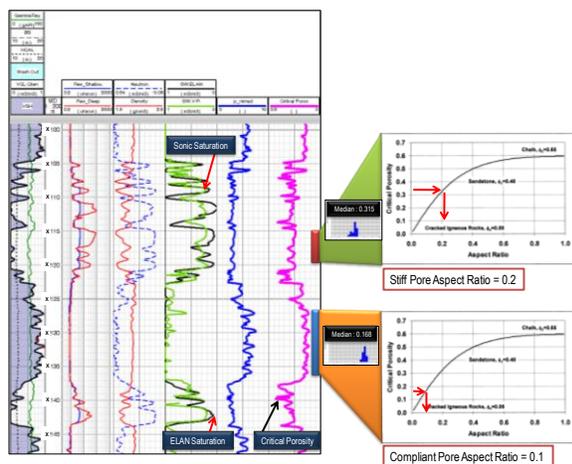


Fig. 2 : Composite plot with saturation from sonic data, continuous values of “p” and critical porosity. The histogram over the top zone (red in the right track) shows a median value of critical porosity of 0.315, which leads to a pore aspect ratio of 0.2. The histogram over the bottom zone (blue bar in the right track) shows a median value of critical porosity 0.168, which leads to a pore aspect ratio of 0.1

Both S_{xo} and S_w were computed from regular petrophysical analysis using a realistic multi-mineral model. Comparison of traditional water saturation computed from resistivity method has been plotted with S_w sonic (Fig. 2). The overlay brings out the validity of the technique used to compute water saturation through the workflow mentioned earlier.

The exponent “ p ” was determined using the methodology described earlier. It has been found that

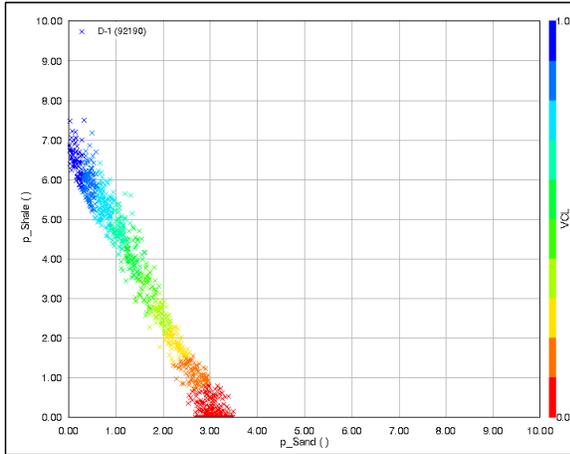


Fig. 3 : Z-Plot of p-sand, p-shale and clay volume (VCL)

the value of “ p ” in clean sand are range from approximately 2.5 to 3.0, where-as in pure shale “ p ” ranges from approximately from 5 to 7 (fig. 3). A continuous p curve was then generated using a mixing law. Critical porosities were computed as a continuous curve using the “ p ” values. It was observed that the critical porosity in clean sands is

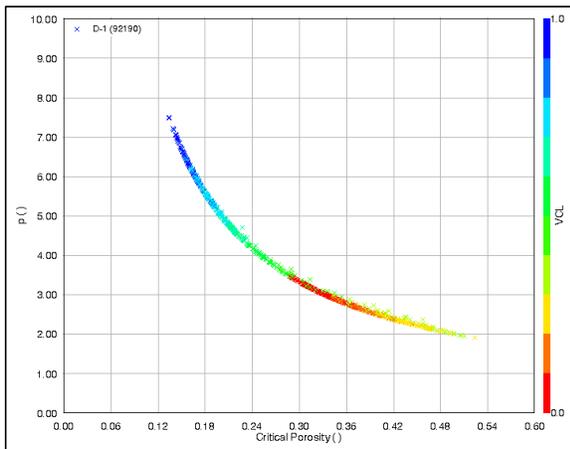


Fig. 4: Z-Plot of p with critical porosity and clay volume (VCL)

ranges from approximately 0.3 to 0.4, where-as in shale “ p ” ranges from approximately 0.12 to 0.18 (fig. 4). The critical porosity of shale is higher than the normally expected value, because the shale in this well falls in the category of silty-shale. Based on the critical porosity values, aspect ratio over clean sand (X115 to X120m) was found to be around 0.2, whereas over a shale section (X126.5 to X136m) the aspect ratio was found to be around 0.1 (fig. 2).

CONCLUSIONS

The present approach demonstrated in the paper for water saturation determination reveals a good degree of accuracy. In the case of a detailed acoustic method, judgment needs to be exercised while interpreting the water saturation as being that of the flushed zone or nearer to that if it is a virgin zone. Because permeability was good and sufficient time lapse was available between stoppages of circulation recording of logs, the saturation came close to water saturation in the present work. Starting with assumed standard aspect ratios for sand and shale grains and deriving the dry frame properties (and also fluid saturations there from through realistic fluid substitution regimens) has yielded encouraging results.

Effective Aspect Ratio (EAR) can be defined as aspect ratio of pores of a fully water saturated rock, whose elastic moduli would be computed from compressional and shear velocity fields.

EAR can be computed from the exponent of $(1-\Phi)$ (this exponent “ p ” would be the acoustic equivalent of Archie cementation factor) in the relationship between grain volume, grain elastic modulus and the corresponding dry frame slowness. With porosity known at well point and also calibrating seismic-derived porosity in the three dimension volume, the dry frame properties computed from velocity field can be used to compute “ p ” and hence EAR.

This application can be further refined if at well point the effective aspect ratio is inverted into stiff pore aspect ratio, and thereby sand grain aspect ratio, and compliant pore aspect ratio and there-by shale grain aspect ratio, using information about the relative proportions of different clays and quartz in the solid regime.

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REFERENCES

1. Brie, A., Pampuri, F., Marsala, A.F., and Meazza, O., 1995, Shear sonic interpretation in gas-bearing sands, SPE paper-30595, presented at the SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, 22–25 October.
2. Keys, Robert G. and Xu, Shiyu, 2002, An approximation for the Xu-White velocity model, *Geophysics*, **67**, pp. 1406-1414.
3. Kuster, G.T., and Toksoz, M.N., 1974, Velocity and attenuation of seismic waves in two phase media: Part 1: Theoretical formulation: *Geophysics*, **39**, pp.587-606.
4. Xu, S. and White, R.E., 1995, A new velocity model for clay-sand mixtures: *Geophysical Prospecting*, **43**, pp. 91-118.