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Generating Continuous Logs of Matrix and Shale Acoustic Properties for Improved Formation Evaluation

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Introduction

In previous publications (Holmes and Holmes, 2005) Rock Physics models of Gassmann (1951) and Krief (1990) were combined with petrophysical modeling, to derive pseudo acoustic logs – both compressional and shear – from other standard open-hole logs.

Rock Physics, when linked with Petrophysical Modeling, has a wide range of applications:

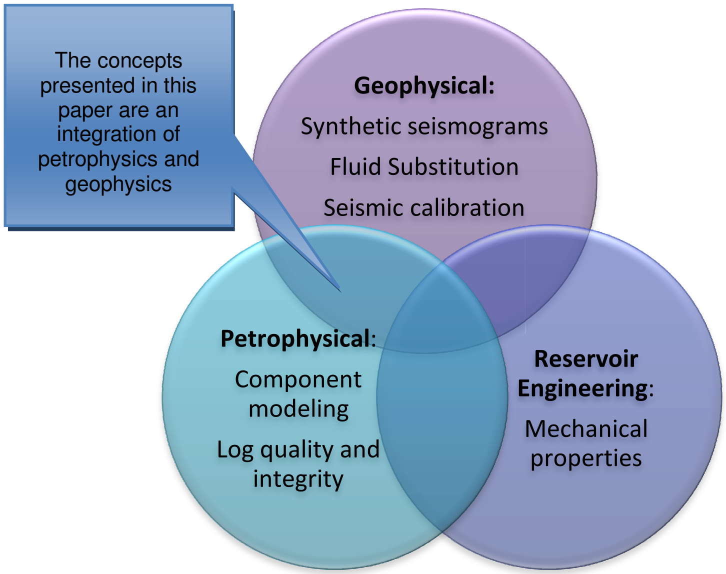


Figure 1: Examples of Rock Physics and Petrophysical modeling applications

A procedure is described whereby continuous curves of ***solids*** – the ***matrix*** and ***shale*** components of rocks – can be generated for :

- Compressional acoustic data DTP
- Shear acoustic data DTS
- Density log data RhoB

The deterministic calculations are based on Krief rock physics modeling procedures, which are similar to the Gassmann approach. Validity of the results can be verified by reconstructing pseudo logs and comparing with original data.

Output from the calculations are a series of curves, showing variation with depth of:

- DTP ***matrix***
- DTP ***shale***
- DTS ***matrix***
- DTS ***shale***
- RhoB ***matrix***
- RhoB ***shale***

From these curves, it is possible to calculate, by depth, each of the three log responses contributed by:

- ***Shale***
- ***Matrix***
- Porosity

Method

Equations used in the Krief model are included below. For a petrophysical solution, V_P and V_s are replaced by reciprocal velocity – interval transit time, or acoustic slowness – DTP and DTS:

$$V_p^2 = \frac{K + {}^4\!/_3\,\mu}{\rho_b} \; and \; V_S^2 = \frac{\mu}{\rho_b}$$

$$K = \rho_b\, V_p^2 - \rho_b\, {}^4\!/_3\, V_S^2$$

The Biot model equations are written as follows:

$$K = K_{ma}(1 - \beta_b) + \beta_B^2\, M_B$$

$$\mu = \mu_{ma}(1 - \beta_B)$$

$$\frac{1}{M_B} = \frac{\beta_B - \varphi_e}{K_{ma}} + \frac{\varphi_e}{K_f}$$

$$1 - \beta_B = (1 - \varphi_e)^{m(\varphi_e)}$$

While substituting:

$$m(\varphi_e) = 3/(1 - \varphi_e)$$

$$\frac{\varphi_e}{K_f} = \frac{\varphi_e S_{xo}}{K_{mf}} + \frac{\varphi_e(1 - S_{xo})}{K_{hc}}$$

$$DT_p = (1 - \varphi - V_{SH})DT_{Pma} + V_{SH}DT_{Phs} + \varphi_e DT_{Pf}$$

$$\frac{1 - \varphi_t}{K_S} = \frac{1 - \varphi_e - V_{SH}}{K_{ma}} + \frac{V_{SH}(1 - \varphi_{SH})}{K_{SH}}$$

$$\frac{1 - \varphi_t}{\mu_S} = \frac{1 - \varphi_e - V_{SH}}{\mu_{ma}} + \frac{V_{SH}(1 - \varphi_{SH})}{\mu_{SH}}$$

Where:

$$\varphi_t = \varphi_e + V_{SH}\varphi_{SH}$$

and making use of the following relations:

$$\frac{1}{M_B} = \frac{\beta_B - \varphi_t}{K_s} + \frac{\varphi_t}{K_f}$$

$$(1 - \beta_B) = (1 - \varphi_t)^{\frac{3}{(1-\varphi_t)}}$$

Symbol	**Definition**
DTP	Interval transit time of compressional wave
DTS	interval transit time of shear wave
RhoB, ρ_b	density of the formation
φ_e	effective porosity of the formation, exclusive of the pore-space water associated with the shale fraction
φ_t	total porosity, including pore-space water associated with the shale fraction
S_{xo}	water saturation of the filtrate-flushed zone
S_w	water saturation of the uninvaded zone
μ	shear modulus (S wave propagation)
K	elastic modulus (body waves)
β_B	Biot compressibility constant
V_{sh}	volume shale
M_B	Bulk elastic modulus
Subscript	**Definition**
X_{ma}	matrix (solid phase exclusive of clay fraction)
X_{mf}	mud filtrate
X_{hc}	Hydrocarbons

Table 1: Listing of symbols used in the Krief equation, and their definitions

In our petrophysical solution to the Krief equations, porosity, shale, and saturations are calculated using non-acoustic logs. Then, using the Krief equations, together with published information on bulk and shear moduli, pseudo DTP and DTS curves are generated for a full range of fluid substitution – oil/water and gas/water systems. Assuming the entire modeling procedure is perfect, the pseudo acoustic curves should match the measured logs for the saturation values that exist in the reservoir. One might speculate that, for the DTP and density logs the satuation is S_{xo}, whereas for the deeper reading DTS logs it is S_w.

A generalized model of porous rock is shown:

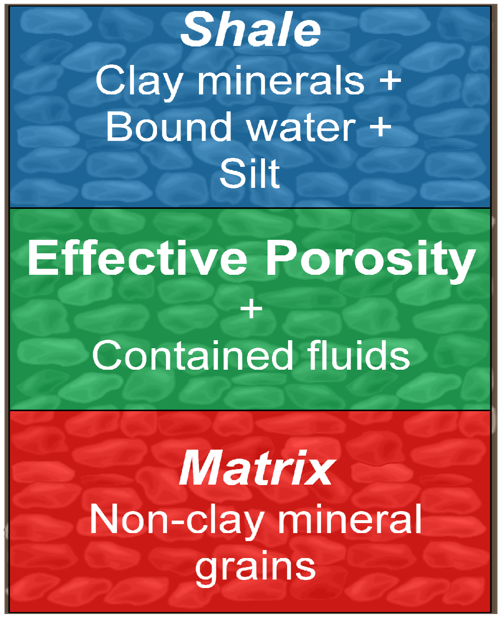


Figure 2: Generalized model of porous rock

As defined here, ***shale*** is composed of clay minerals, with associated bound water, and silt. Silt is made up of very fine grained clastic and/or calcareous material often about 50% of the shale volume. From a petrophysical viewpoint, silt is difficult to distinguish quantitatively from clay. ***Shales*** have mostly high gamma ray responses. ***Matrix*** is defined as the non-clay mineral grains and probably includes silt-sized material similar to the silts associated with clays in ***shales***.

Effective Porosity and contained fluids make up the remainder of the rock. The contained fluids consist of water and other fluids, mostly oil and/or gas.

As defined in this paper, ***shales*** + ***matrix*** = ***solids***.

One of the important results of this study is the ability to define, for each of the DTP, DTS and RhoB curves, the contribution of each of the 3 major components to the total log response.

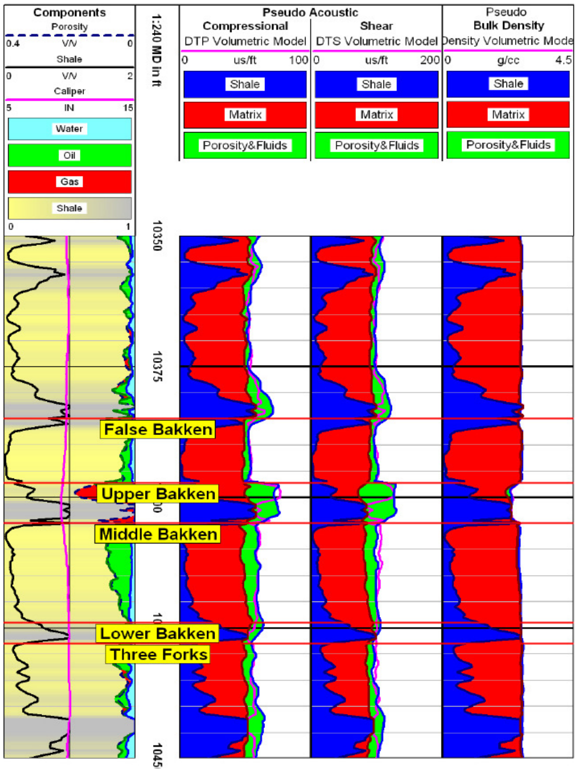


Figure 3: Example of porous rock model with actual data from the Bakken oil reservoir

An important observation is that the porosity contribution of acoustic responses to total response is much higher than for the density log. Percentage ***shale*** response is about the same for all 3 logs. Percentage ***matrix*** response is higher for the density log as compared with acoustic logs.

Calculation Procedures

Initial petrophysical processing consists of standard deterministic calculations:

- Shale Volume – frequently from a gamma ray log, or from a density/neutron combination (but not in gas reservoirs)
- Total Porosity – best from a density/neutron combination, because results are least affected by fluid content and changing matrix properties
- Effective porosity – by subtracting clay bound water from total porosity
- Water saturation – from any one of a number of equations. Often the calculation that is the least reliable

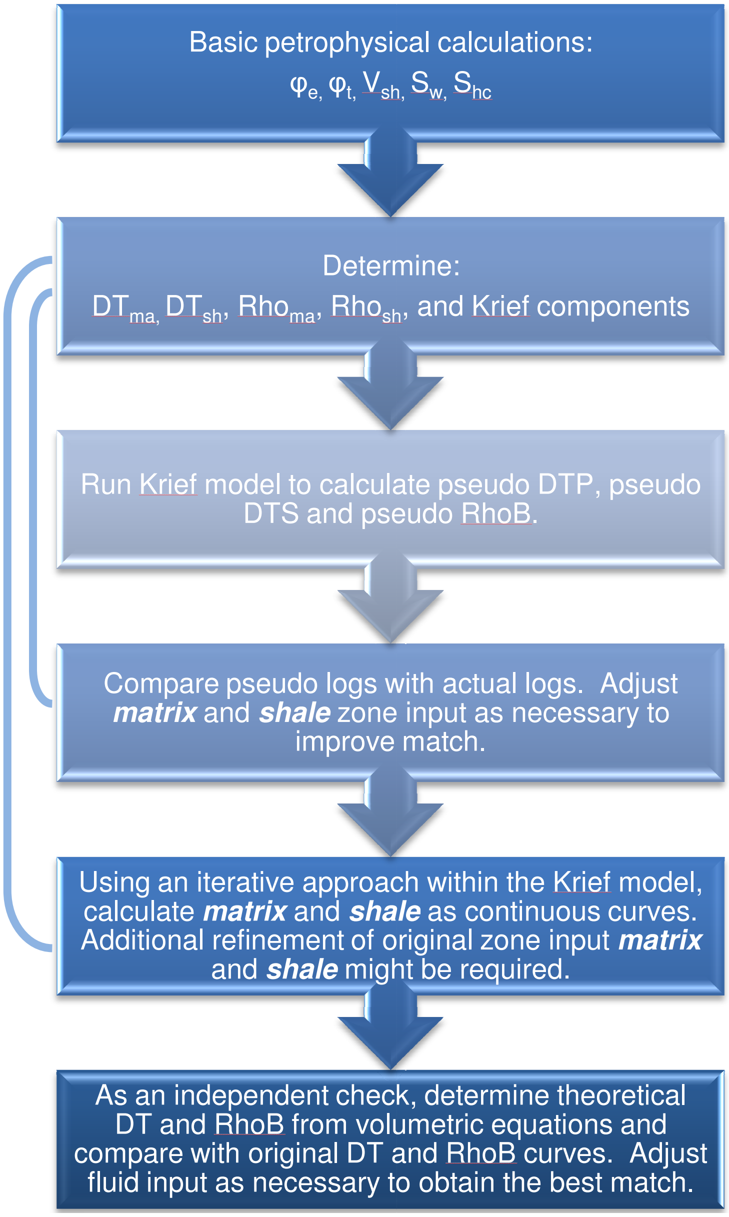
The second stage involves solution to the Krief model, to calculate pseudo acoustic and density logs. By comparing the pseudo logs with measured data, zone parameters of the solids can be adjusted to minimize differences.

A third procedure, again involving the Krief model, is employed to generate continuous curves of the ***solids***. Using zone values as a starting point, and on a level-by-level basis, an initial ***matrix*** value is used to predict a shale value, to minimize differences between pseudo and actual data. This ***shale*** value is in turn used to predict the ***matrix*** value. The procedure is iterated until differences are minimized. The end result is continuous curves of ***matrix*** and ***shale.***

To avoid the problem of non-convergence, permissible curve ranges for the solids are restricted to ± 50% of the original input. The final curves from this procedure are recognized as the “Krief reconstructed”.

A final check on validity of the reconstructions is through calculations of reconstructed volumetric porosity logs.

$$\begin{gathered} \mathit{Reconstructed\ Volumetric\ Porosity\ Log} = \\ (\mathit{Shale\ Response} \times V_{sh}) + \\ (\mathit{Water\ Response} \times \varphi_e \times S_w) + \\ (\mathit{Hydrocarbon\ Response} \times \varphi_e \times S_{hc}) + \\ (\mathit{Matrix\ Response} \times (1 - V_{sh} - \varphi_e)) \end{gathered}$$



Basic petrophysical calculations: φ_{e}, φ_{t}, V_{sh}, S_{w}, S_{hc}

Determine: DT_{ma}, DT_{sh}, Rho_{ma}, Rho_{sh}, and Krief components

Run Krief model to calculate pseudo DTP, pseudo DTS and pseudo RhoB.

Compare pseudo logs with actual logs. Adjust ***matrix*** and ***shale*** zone input as necessary to improve match.

Using an iterative approach within the Krief model, calculate ***matrix*** and ***shale*** as continuous curves. Additional refinement of original zone input ***matrix*** and ***shale*** might be required.

As an independent check, determine theoretical DT and RhoB from volumetric equations and compare with original DT and RhoB curves. Adjust fluid input as necessary to obtain the best match.

Figure 4: Flow chart of calculation/iteration procedure

Examples

1. Oil reservoir: Teapot Dome, Wyoming
2. Oil Reservoir: Bakken Formation, Montana
3. Shale Gas Reservoir: Western Canada
4. Tight Gas Sand: Piceance Basin, Colorado

The following template is used for data presentation of all examples:

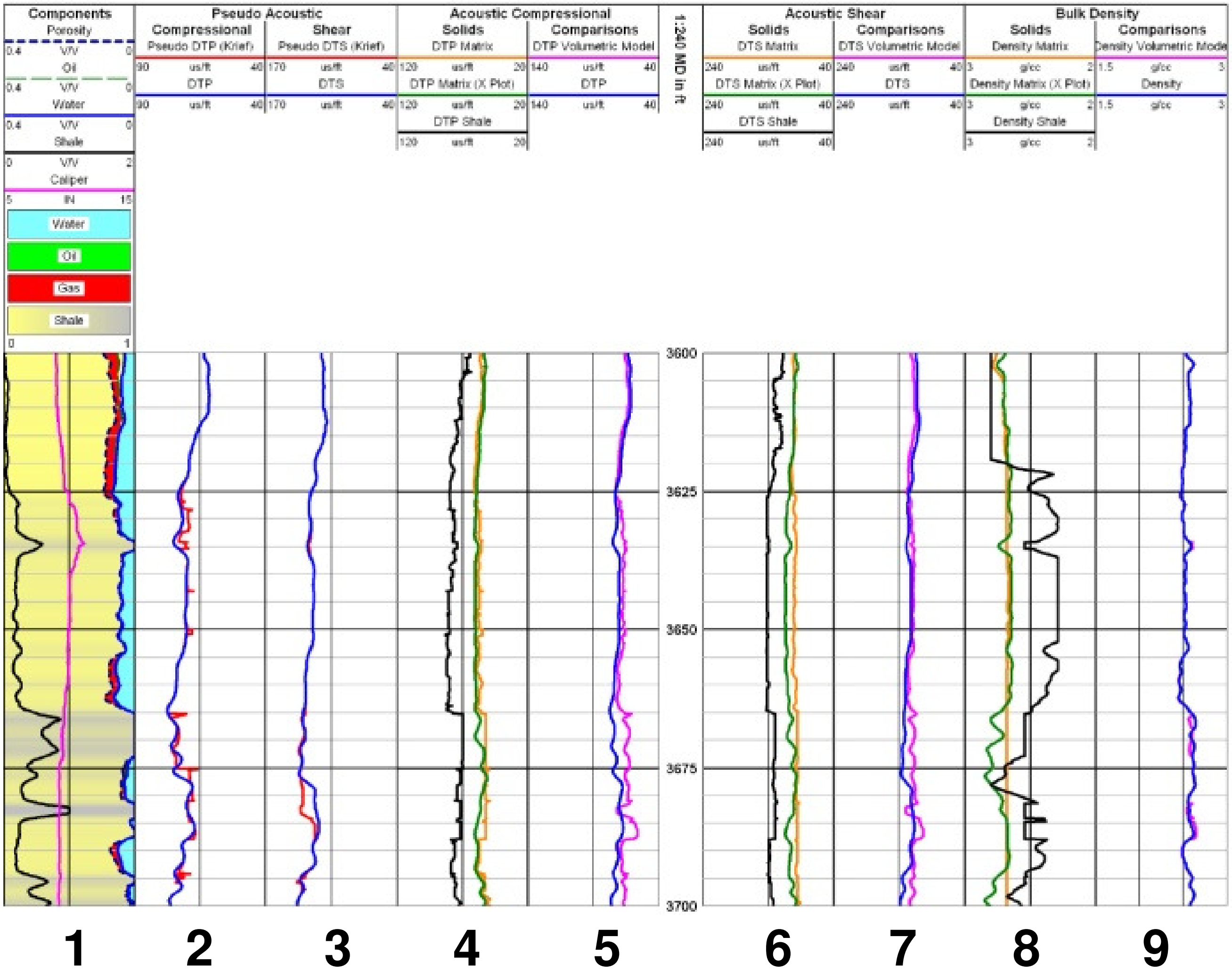
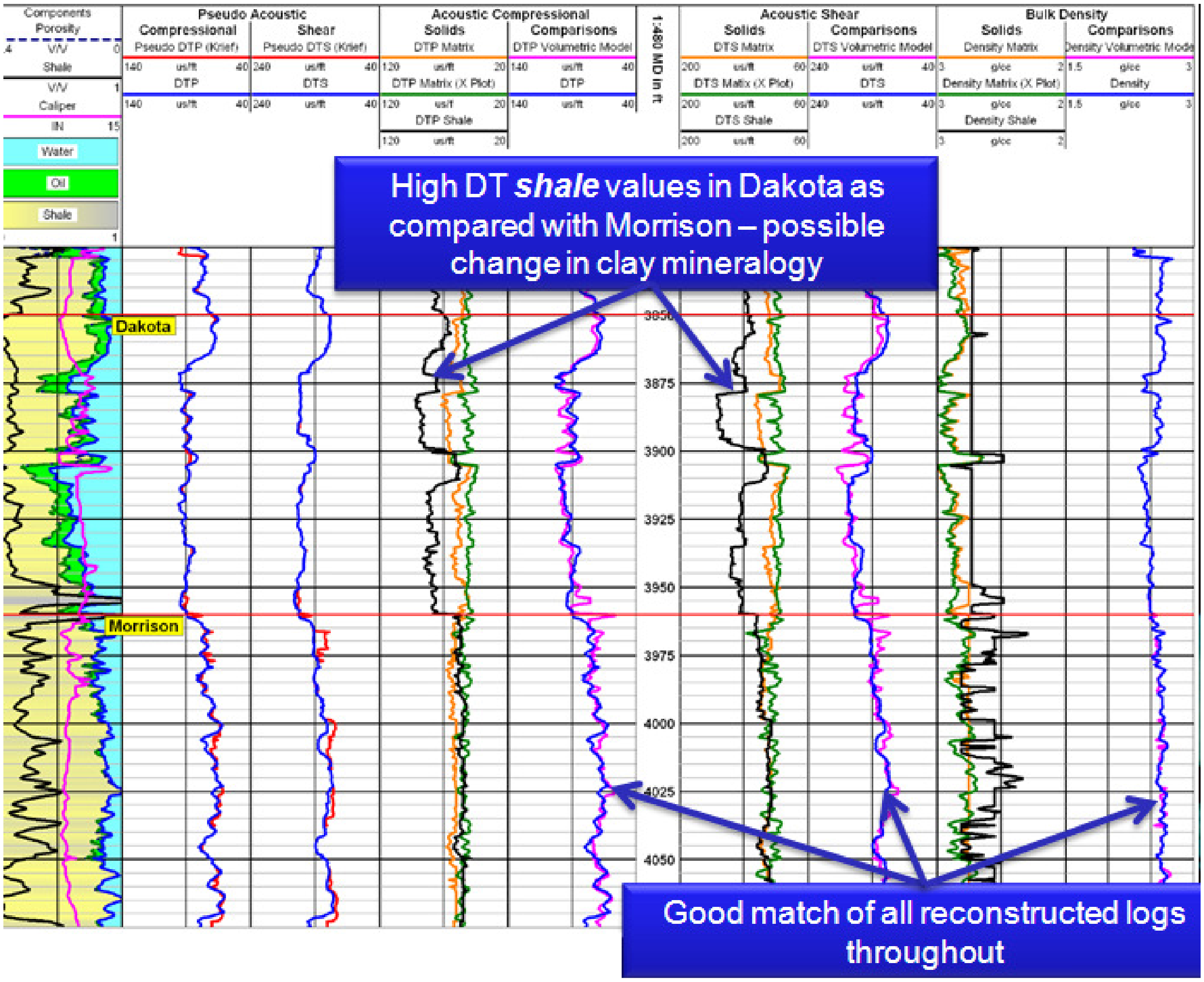


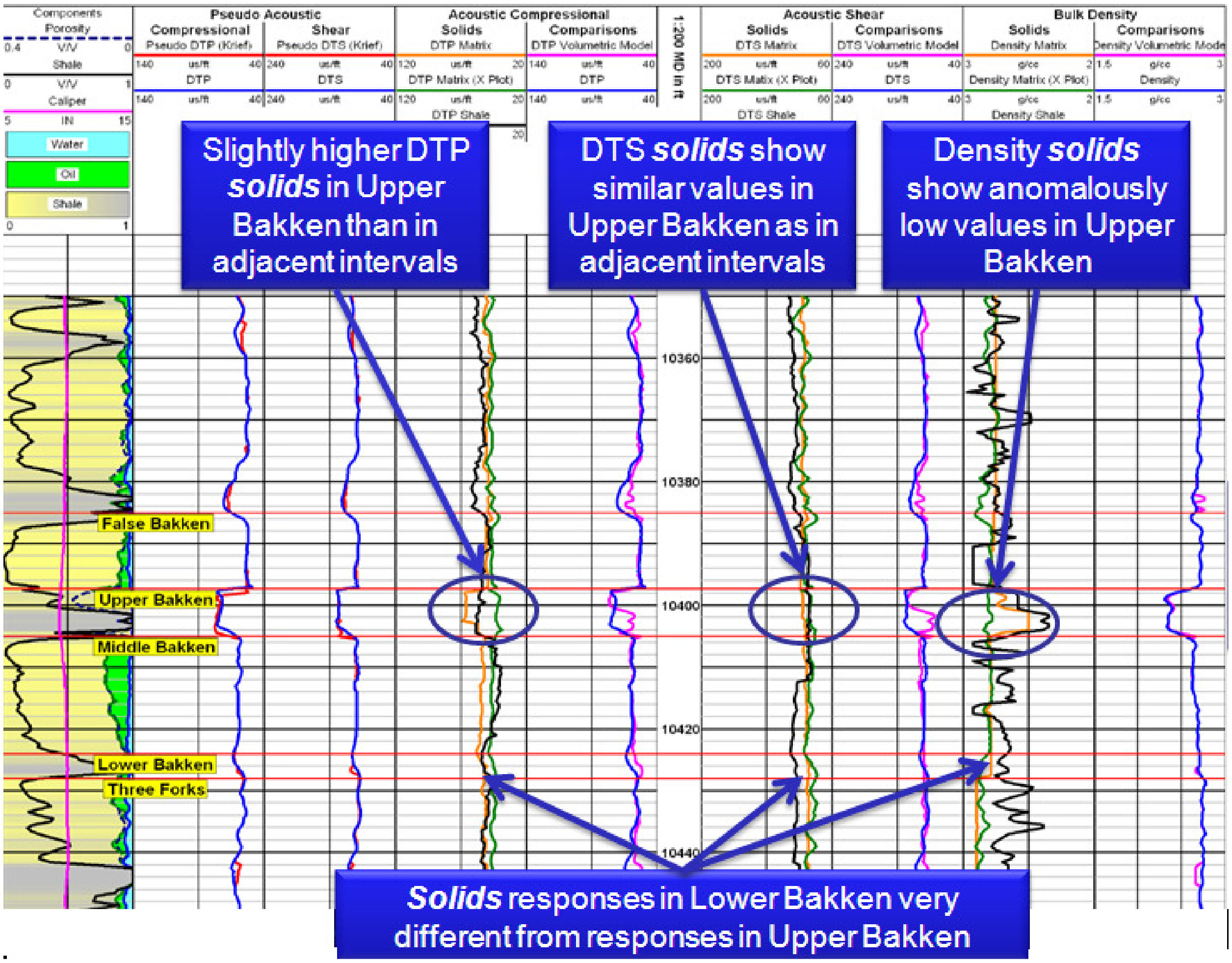
Figure 5: Description of template used for examples:
Track 1: Petrophysical φ_e, V_{sh}, S_w, S_o or S_g
Tracks 2 and 3: DTP and DTS original and pseudo curves (Krief Modeling)
Tracks 4 and 5: DTP solids and DTP comparisons – volumetric modeling
Tracks 6 and 7: DTS solids and DTS comparisons – volumetric modeling
Tracks 8 and 9: RhoB solids and RhoB comparisons – volumetric modeling



High DT *shale* values in Dakota as compared with Morrison – possible change in clay mineralogy

Good match of all reconstructed logs throughout

Figure 6: Example from an oil reservoir, Teapot Dome, Wyoming



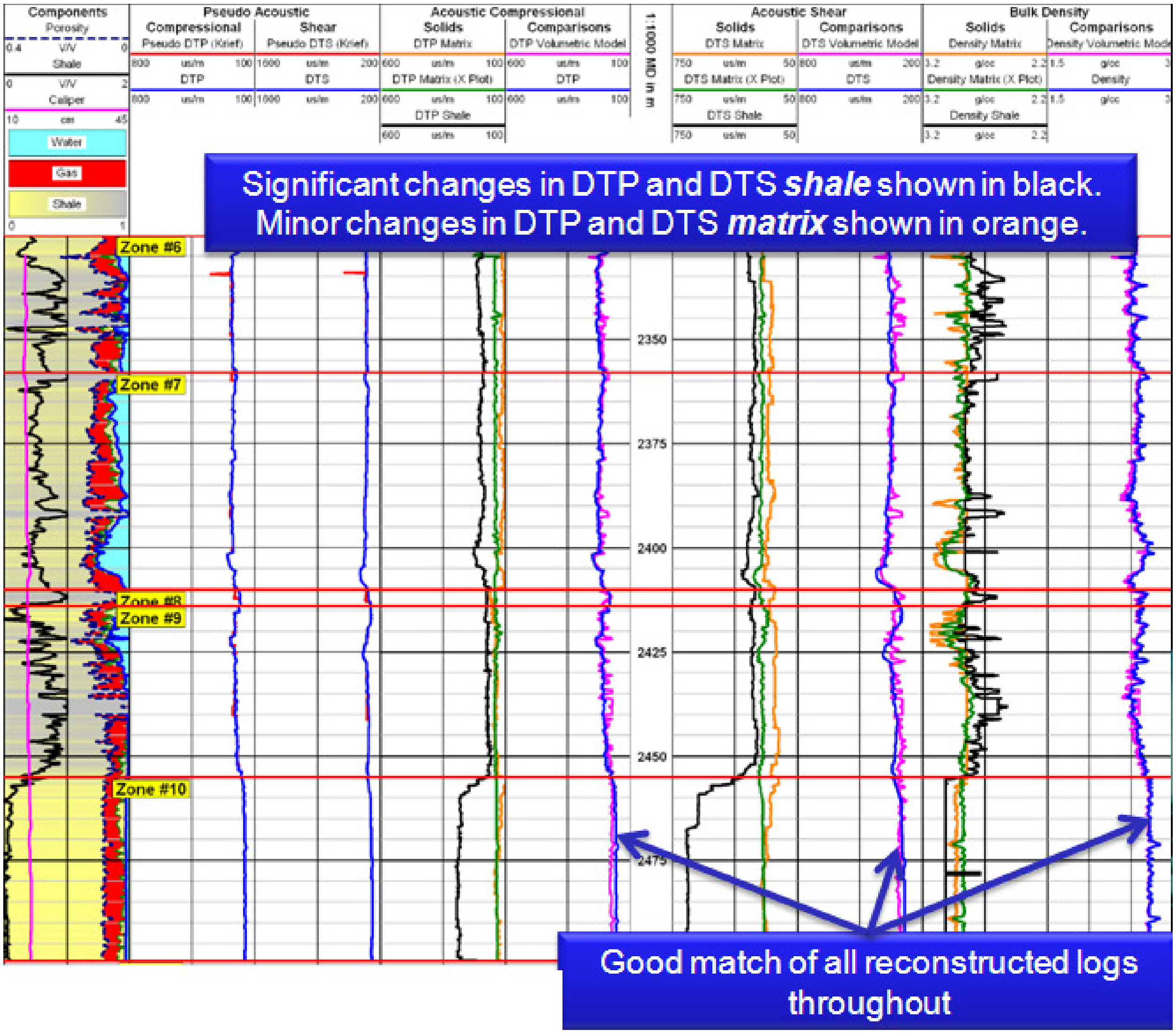
Slightly higher DTP ***solids*** in Upper Bakken than in adjacent intervals

DTS ***solids*** show similar values in Upper Bakken as in adjacent intervals

Density ***solids*** show anomalously low values in Upper Bakken

Solids responses in Lower Bakken very different from responses in Upper Bakken

Figure 7: Oil reservoir, Bakken Formation, Montana



Significant changes in DTP and DTS ***shale*** shown in black.
Minor changes in DTP and DTS ***matrix*** shown in orange.

Good match of all reconstructed logs throughout

Figure 8: Example from a shale gas reservoir in Western Canada

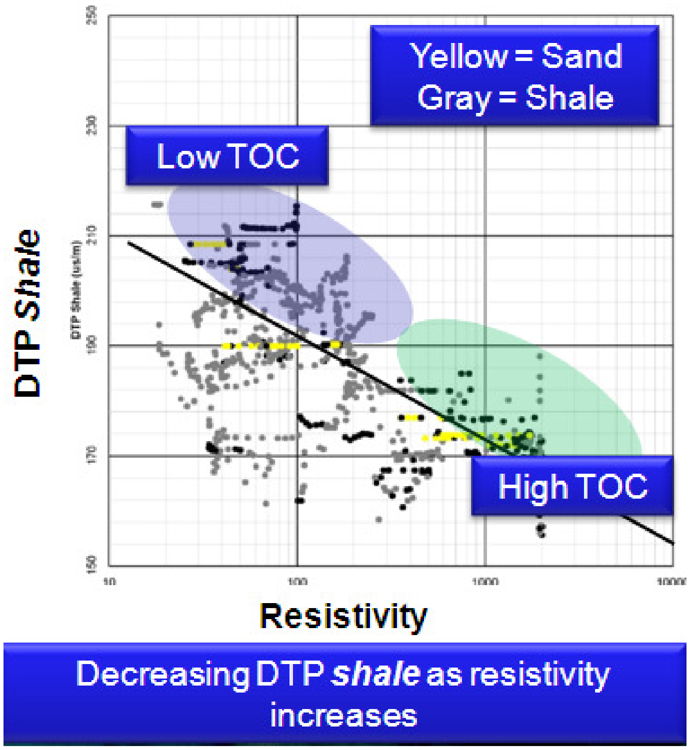


Figure 9: DTP *shale* vs. resistivity from a shale gas reservoir in Western Canada

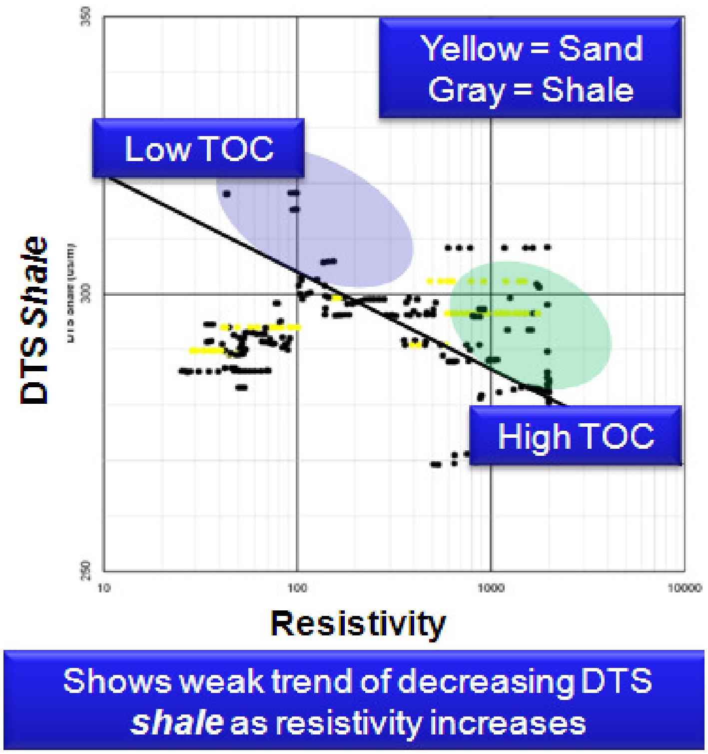
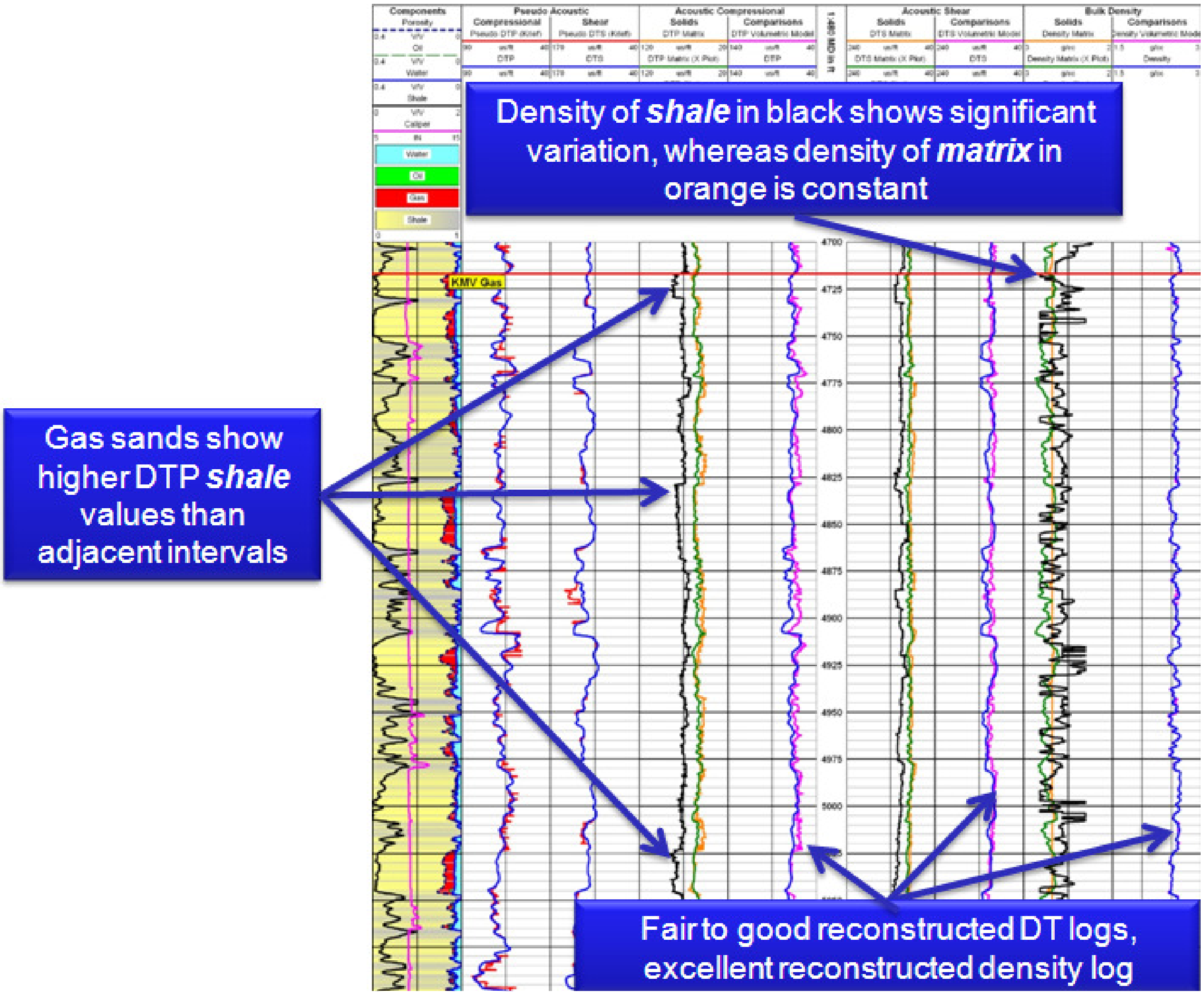


Figure 10: DTS *shale* vs. resistivity from a shale gas reservoir in Western Canada



Density of ***shale*** in black shows significant variation, whereas density of ***matrix*** in orange is constant

Gas sands show higher DTP ***shale*** values than adjacent intervals

Fair to good reconstructed DT logs, excellent reconstructed density log

Figure 11: Example from tight gas sand in the Piceance Basin, Colorado

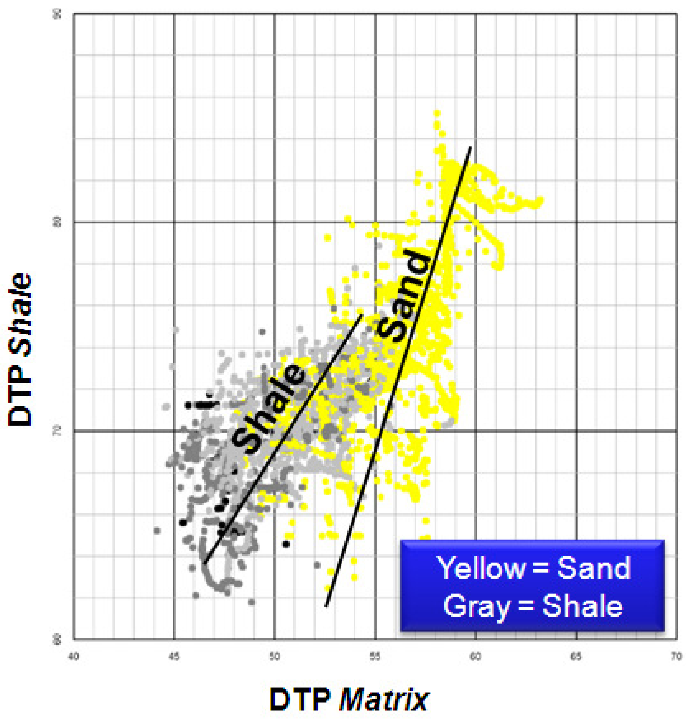


Figure 12: DTP *shale vs.* DTP *matrix* from tight gas sand in the Piceance Basin, Colorado

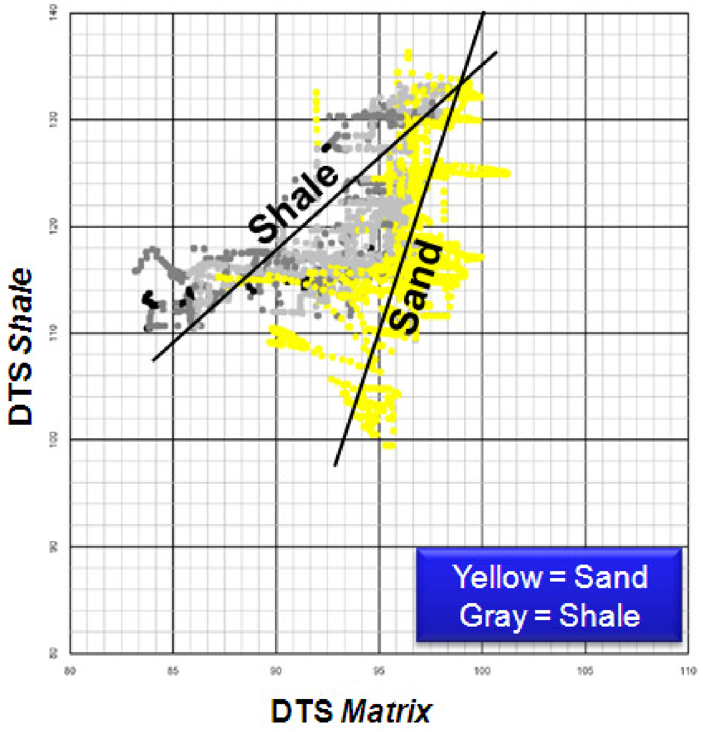


Figure 13: DTS *shale vs.* DTS *matrix* from tight gas sand in the Piceance Basin, Colorado

Conclusions

The technique allows for distinction between ***shale***, ***matrix***, and free porosity, together with their fluid content, in contribution to log responses for:

- DTP
- DTS
- RhoB

Examination of changes with depth of ***shale*** and ***matrix*** properties helps in understanding changing rock properties with depth.

The reconstructed logs, when compared with original log measurements, will indicate whether or not the solids curve calculations are correct. Mismatches can mean one of three possibilities:

- Incorrect calibration of properties which influence log responses
- An incorrect basic model
- Inconsistencies among logs used in the calculations

A suggested geophysical application is to use the ***solids*** curves as a starting point, and then add porosity and contained fluids at specified levels to generate a series of theoretical acoustic and density profiles. This procedure could be used to model different degrees of porosity development, and then apply to defining seismic signatures.

References

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