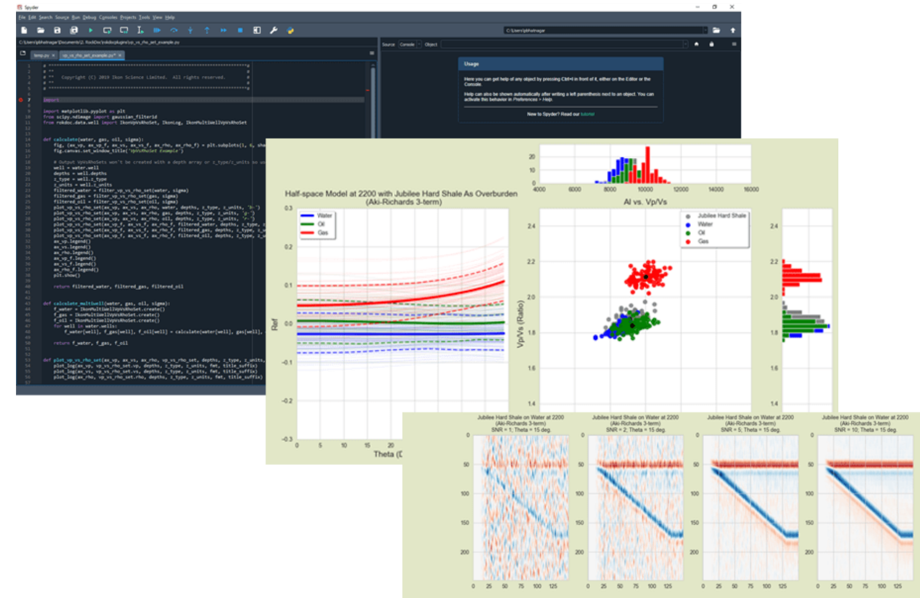

Rock Physics Analysis, Gassmann's Fluid Substitution and AVO (using RokDoc software)

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Rock Physics Analysis

Work Flow

1 Starting Up Application (RokDoc)

- Creating a directory
- Opening the RokDoc software
- Checking the Global Project Settings
- Creating a Project

2 Importing Data

- Importing well data
- Importing Wireline logging data
- Importing Markers
- Importing position settings
- Importing Check-shot

3 QC Data and Display

- Display Setting (Size, Color etc.)
- Creating Working Interval
- Creating Cross plot identifying and Removing spurious data

4 Generating New Logs

- Vs log from Vp log (using sand parameter, **Formula 1**)
- Vs log from Vp log (using shale parameter, **Formula 2**)
- Composite Vs log using GR API Value (**Formula 3**)
- AI log from Vp and Rho (**Formula 4**)

5 Rock Physics Analysis

- Plotting Different Cross-plot
- Observing and Categorizing the data based on rock physics

Greenberg & Castagna(1992) Relationship between Vp and Vs:

For sandstone parameter: Vs= 0.8042Vp – 0.8559

For shale parameter: Vs= 0.7697Vp – 0.86735

- More than 70 GR API is considered as shale whereas the value below 70 API is Sand.
- GR API = 8 × Uranium concentration in ppm + 4 × thorium concentration in ppm + 16 × potassium concentration in percent (Schlumberger Oilfield Glossary).

Formula Used In Our Study:

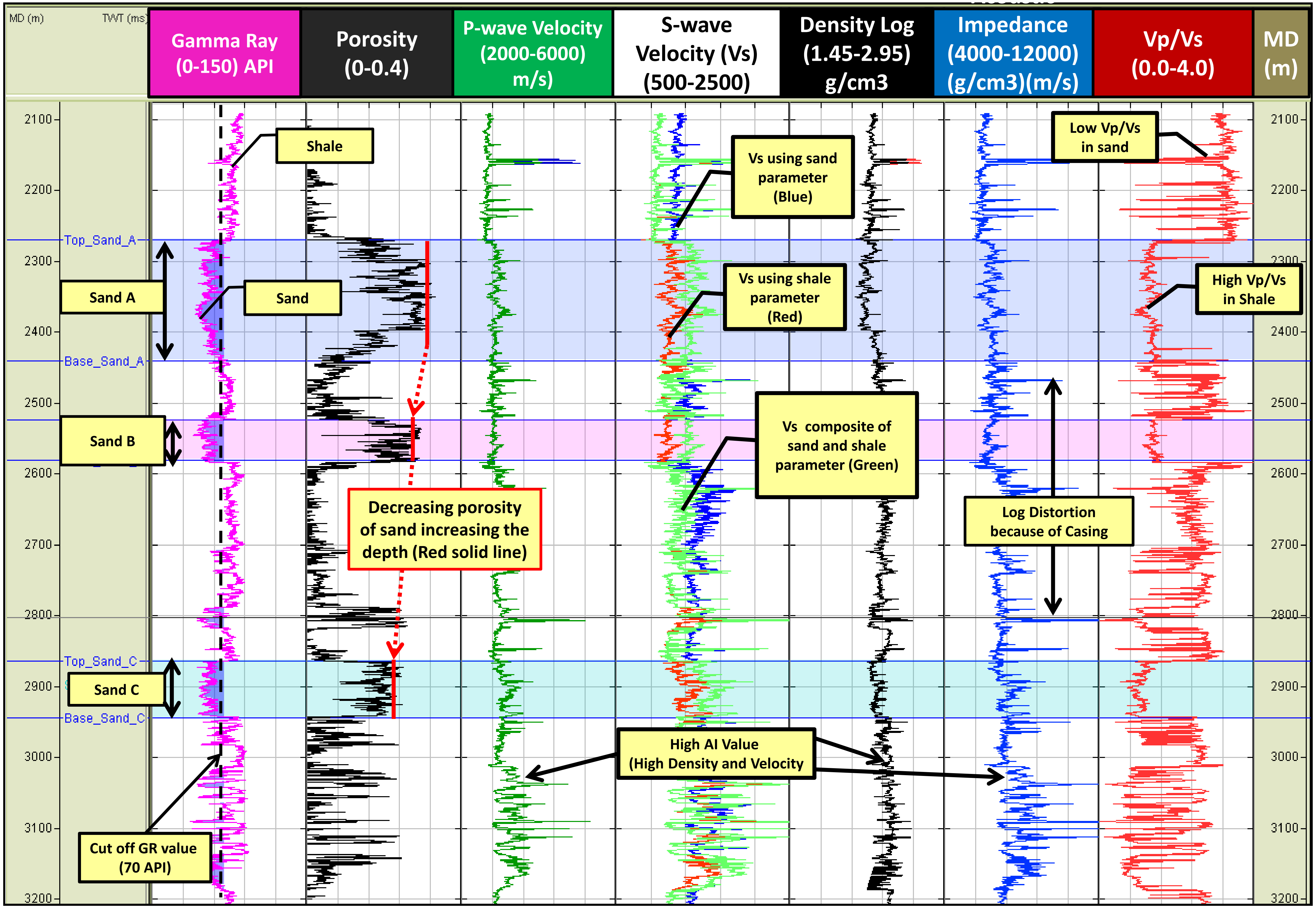
For shale parameter: Vs= 0.7Vp – 0.9 → (1)

For sandstone parameter: Vs= 0.75Vp – 0.8 → (2)

Composite Vs Log :
IF [Curve] GR < [Constant] 70.0 THEN [Curve] Vs (From Sand Parameter) ELSE [Curve] Vs (From Shale Parameter) END. → (3)

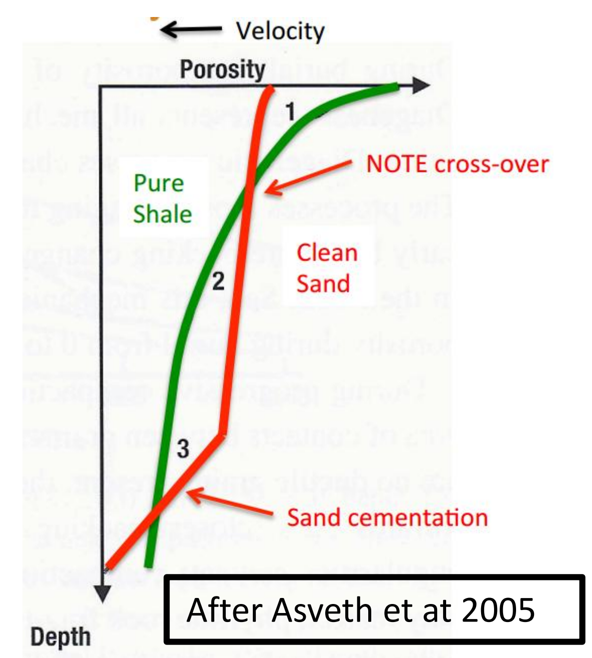
AI= Velocity*Density → (4)

Well Log Viewer Summary



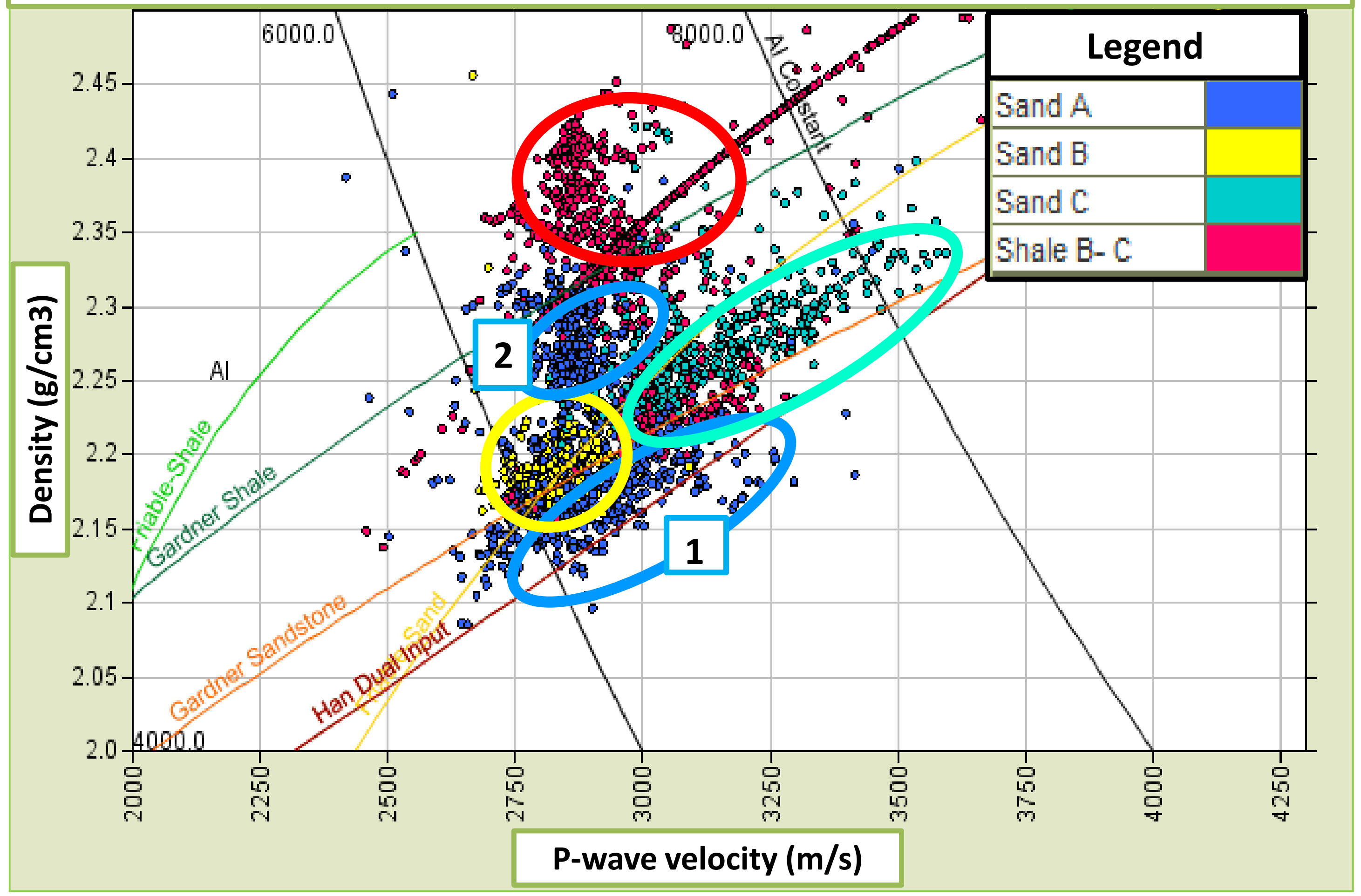
- Cut off GR value is 70 API (< 70 API is Sand and > 70 API is Shale).
- Porosity reduction related to sorting , compaction and digenesis.
- Porosity reduction associated with compaction and digenesis (cementation) are directly related to burial depth.

Compaction Trend for Sand and shale



Rock Physics Analysis

P-wave velocity-Density cross-plot



In Density P-wave velocity plot, Gardner Shale/Sand trends and Working interval color code are applied to analysis the lithology of data. It's a empirical rock physics model are derived from experimental result.

Gardner's Relation:

$\rho_{bulk} = dV_p^f$ (d, f are constant);

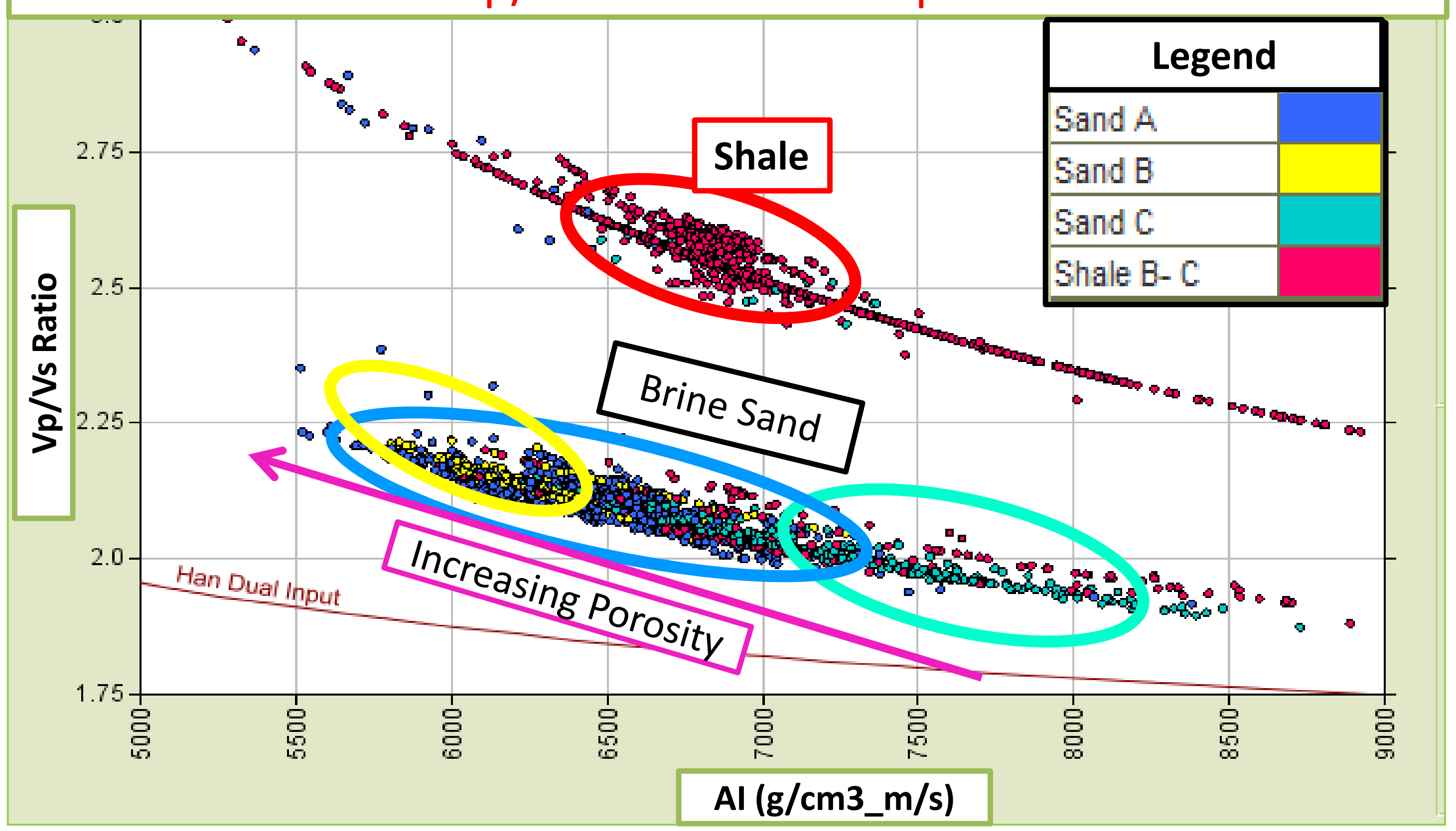
For sand trend: d=1.66 and f=0.261;

For shale trend: d=1.75 and f=0.265; **[Gardener et al (1974) Geophysics 39, 770-780]**

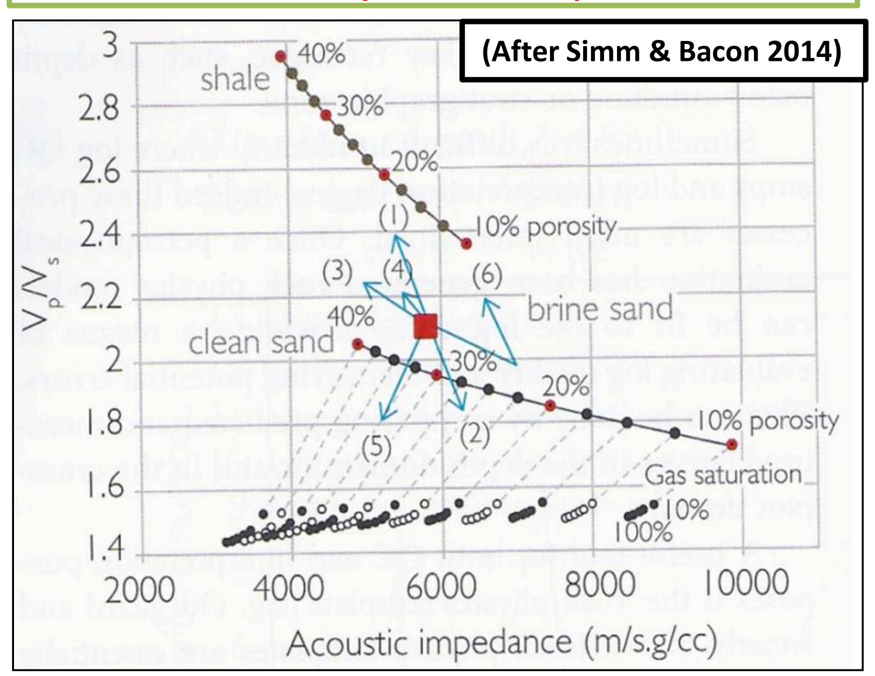
Based on this plot the lithofacies of the well has being classified into four type which are high clean sand, shaly sand, sandy shale and shale:

- **Sand A (1):** Clean sandstone; Relatively low density (2.1 -2.23 g/cm3) and low to intermediate velocity (2600-3200 m/s)
- **Sand A (2):** Sandy shale ; Intermediate density (2.24 -2.3 g/cm3) and Relatively low velocity velocity (2700-3000 m/s)
- **Sand B:** Shaly sand; Intermediate density (2.16 -2.23 g/cm3) and relatively low velocity around 2800 m/s
- **Sand C:** Shaly sand; Intermediate to high density (2.2 -2.35 g/cm3) and ; Intermediate to high velocity (2900-3600 m/s)
- **Shale B-C:** Shale; High density (2.3-2.45 g/cm3) and relative low to intermediate velocity (2700-3100m/s)

Vp/Vs Ratio -AI cross-plot



Rock Physics Template

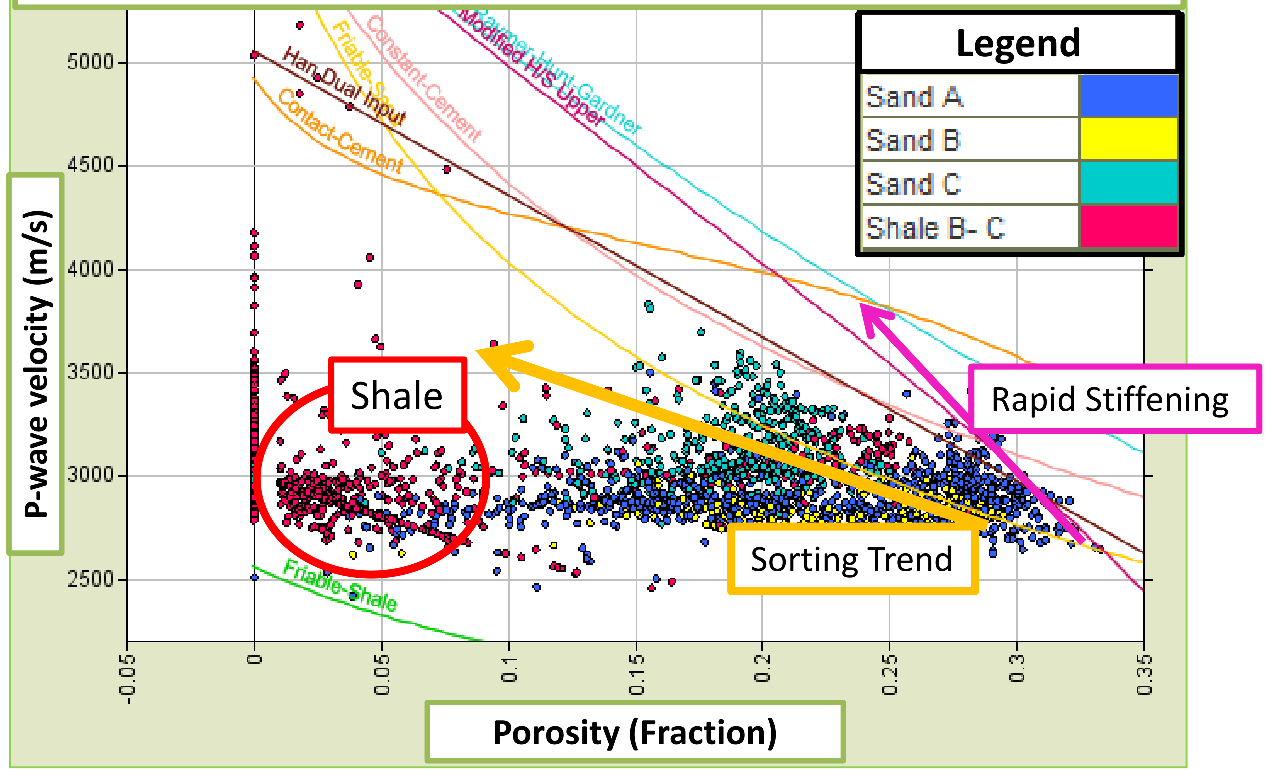


1) Increasing laminar shale 2) Increasing cementation
3) Increasing Porosity 4) Decreasing effective pressure
5) Increasing H-C content 6) Increasing Dispersed shale

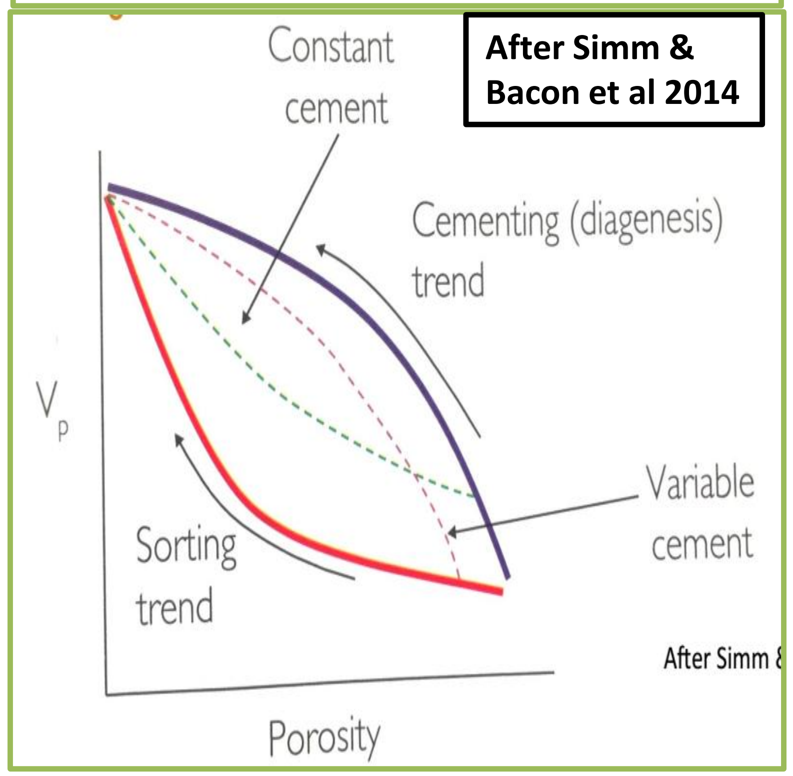
- Vp/Vs is a key parameter to differentiate lithologies, fluid saturation and pore fluid type.
- Sand A, B and C are **brine sand** and **no hydrocarbon content.**
- Porosity in Sand B> Sand A> Sand C

Rock Physics Analysis and Summaries

P-wave velocity-Porosity cross-plot

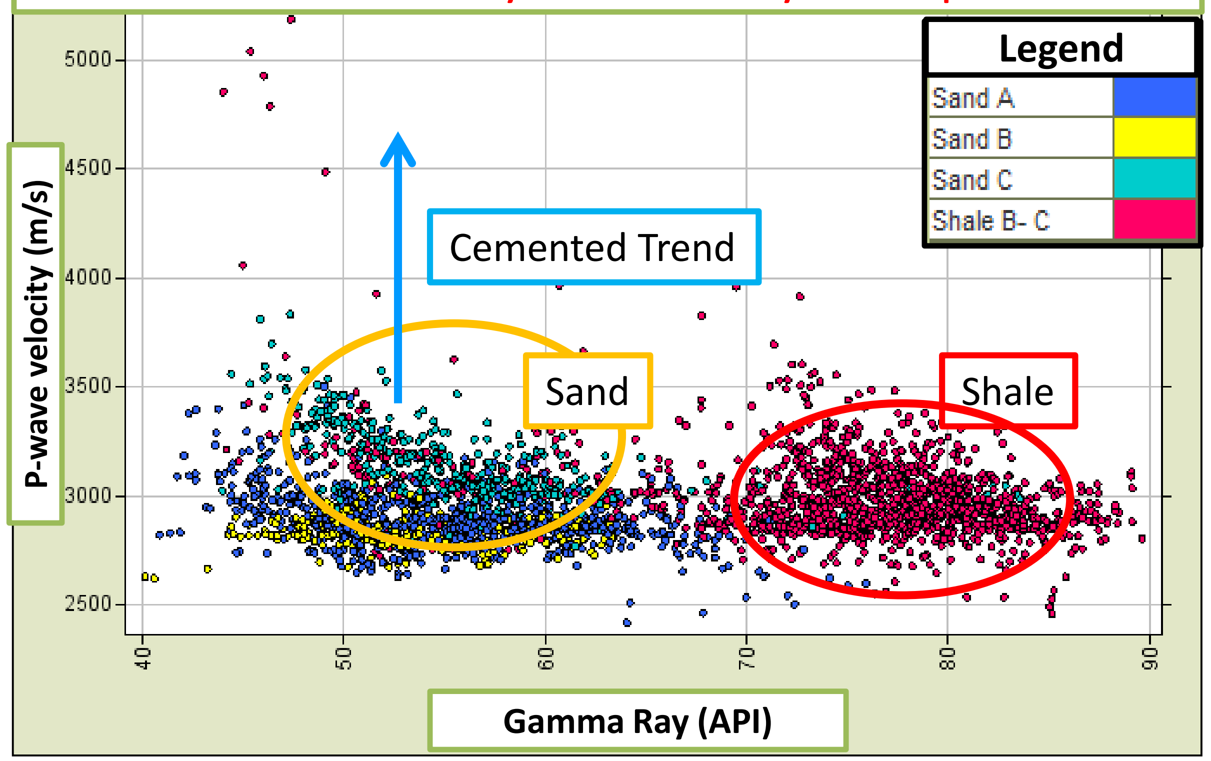


Sorting and cemented Trend

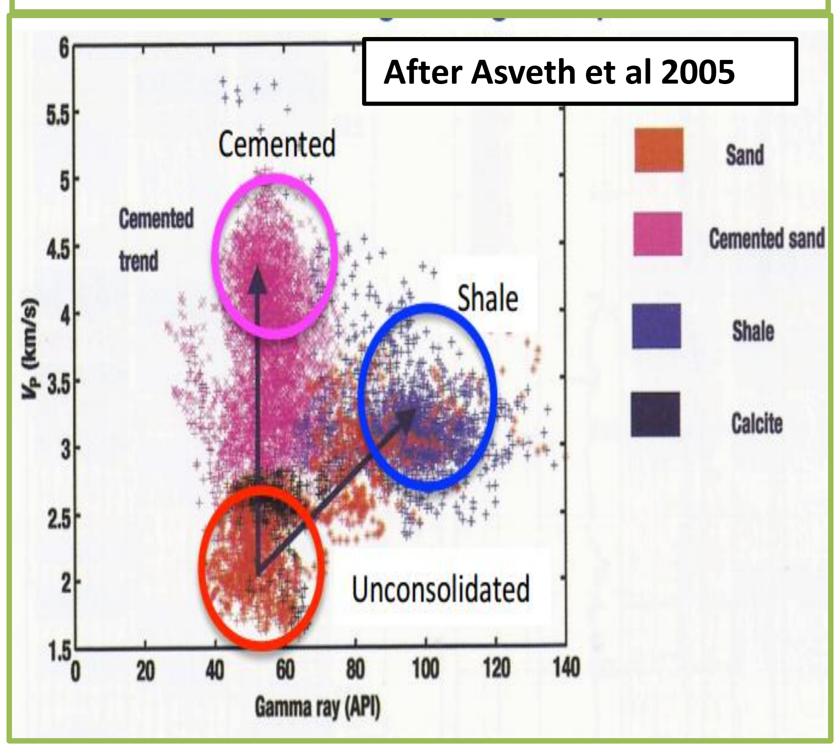


- Shale B-C has very low porosity and poorly sorted.
- Based on porosity-Vp plot and Hashin Shtrikman bounds, Sand A can be considered to have a wide range of porosity which is around 15-33%. The porosity for Sand B is about 12-33% whereas Sand C has about 17-23% porosity.
- Sand A and Sand B are ranging from clean sand to shaley sand as the trend of the sand moves toward HS lower bound (Decreasing sorting; Increasing clay content)
- Sand C has higher P wave velocity which indicates higher bulk modulus (K) and it also closer to the modified HS upper bound line. Therefore, it can be said that Sand C is more compacted compared to the other flow units.
- From Porosity-Vp plot, clean sand having porosity around 25 to 30% whereas the porosity for shaley sand, sandy shale and shale are 15-24%, 7-15% and 0-5% respectively .

P-wave velocity-Gamma Ray cross-plot



Jizba (1991) model for cemented sand



- Jizba(1991) modified the Marion model to predict velocity of cemented Sands.
- Sand C is move forward to cemented trend and very high velocity (3.2-3.5 km/s)
- Sand A and B partially cemented.
- GR value for Sand A,B and C have below 70 API and for Shale more than 70 API

Gassmann’s Fluid Substitution and AVO

Executive summary

- A demo well is provided to perform the analysis using IkonScience's RokDoc software. Using existing log (Gamma Ray, Sonic Velocity, Density log etc.) generate Shale Volume (Defining shale base line GR = 68 API and sand baseline GR = 45 API) and Shear velocity log (using Greenberg-Castagna equation).

- Three formation are introduced for each sand working interval to observe the fluid substitution effect(100% water saturated sand, 80% oil saturated sand and 90% gas saturated sand). Gassmann's algorithm was used for fluid substitution.

- Fluid substitution enables prediction of P-wave velocity (Vp), S-Wave velocity (Vs) and Density values for rocks saturated with different fluids. Having these values, pre-stack attributes (AVO and elastic parameters) can be calculated.

- AVO response shows that Sand A and B have similar response in all three cases. 80% oil and 90% gas saturated sand have relatively high zero incident reflectivity R(0) (-0.07 to -0.09 for oil and -0.15 to -0.17 for gas) which are classified as Class III AVO and flow the unconsolidated hydrocarbon trend. In Sand C, R(0) for 100% water saturated is about 0.02 (Class IIP AVO) flow cement with brine trend.

- Among 13 elastic contrast analyzer parameter Lambda-Rho (λρ) and Lambda-Mu(μλ) shows very high elastic contrast different between different fluids type. In Sand C, λρ change dramatically (for 100% water -0.05 and for 90% gas -0.43).

- Mu-Rho (μρ) value doesn't change a lot due to the change of fluid type, because it is not affected by rigidity (μ) but affected by the density a little bit. On all sands change of μρ from 100% water saturation to 90% gas saturation around 5%.

Work Flow

1 Starting Up Application (RokDoc)

- Read the different log

(Import well data, Import log data, Import marker, Import Position, Import Check-shot data and Display setting etc.)

- QC analysis

(Identifying and Removing spurious Data)

- Set working interval

2 Manipulation of data

- Set volume fraction using GR curve value.

For sand= 45 API
For shale=68 API

- Set mineral properties

(In this study have shale and sand; select Quartz for complement log)

- Saturation Set

(Assume that study well is water saturated Sw=1)

3 Blocky Model

- Vs prediction using Greenberg Castagna method **(R-1)**. **1**

- Deriving average set for working interval Sand A,B,C and Shale B_C.

Cut-off value for sand <0.3
Cut-off value for Shale >0.7

- Blocking the logs

(block-out the Vp, Vs and density parameters for 100% water sands)

4 Fluid Substitution

- Set up the initial and final fluid substitution Parameter.

Saturate sand with 80% oil
Saturate sand with 90% gas

- Calculate rock modulus changes with a change in pore fluids using Gassmann's (1951) Equation **(R-2)**. **2**

5 Fluid substitution and AVO response Analysis

- Create AVO response

(effects of Oil and Gas saturation on the reflectivity)

- Create AVO gradient cross plot

- Analyzing the elastic contrast

[contrast in Acoustic Impedance(AI), Shear Impedance(SI) and Elastic Impedance(EI)]

1

Greenberg & Castagna(1992) Relationship :

$$Vs = a_{i2}V_P^2 + a_{i1}V_P + a_{i0}$$

(a_{i2}, a_{i1} and a_{i0} are constant)

For sand : $a_{i2} = 0, a_{i1} = 0.77$ and $a_{i0} = -0.867$
For shale : $a_{i2} = 0, a_{i1} = 0.804$ and $a_{i0} = -0.856$

2

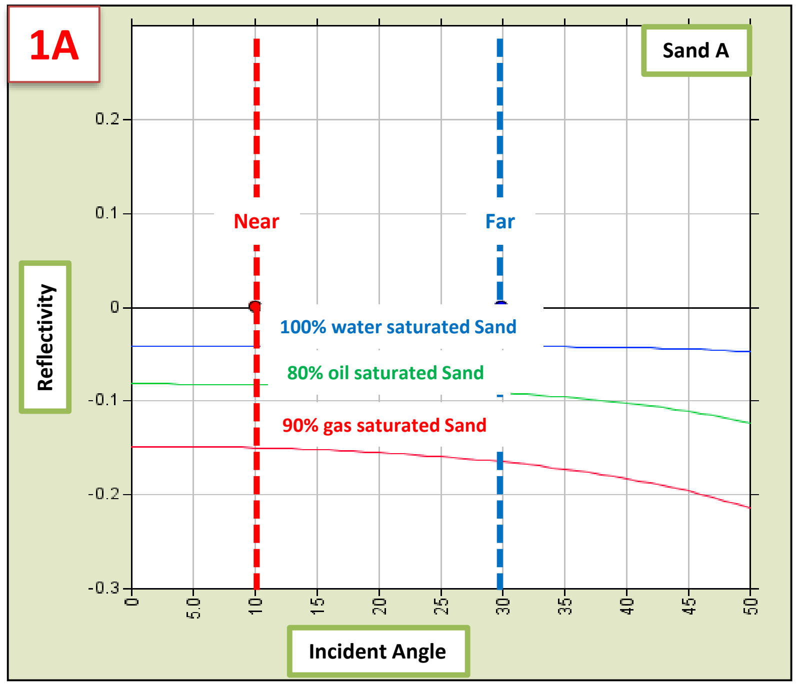
Fluid Substitution Steps:

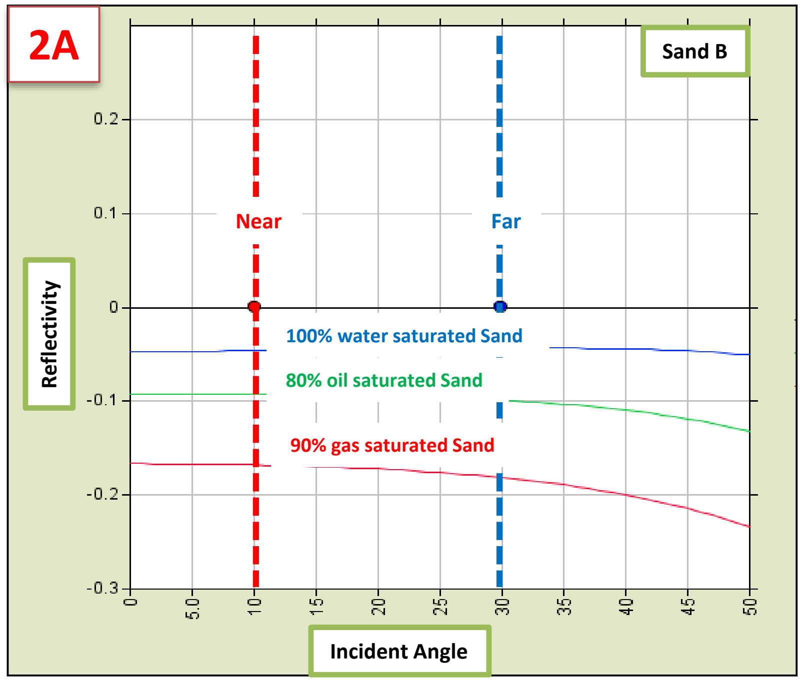
- Input Parameter: → V_P, V_S, ρ
- Calculate bulk and shear moduli of rock saturated with original fluid: → $K_1 = \rho\left(V_p^2 - \frac{4}{3}V_s^2\right), \quad \mu_1 = \rho V_s^2$
- Rearrange Gassmann'sin terms of K_{Dry}: → $K_{Dry} = \frac{K_1}{K_{matrix} - K_1} - \frac{K_{fluid1}}{\emptyset(K_{matrix} - K_{fluid1})}$
- Transform the bulk modulus substituting into Gassmann's Equation's for K_{Dry}: → $\frac{K_1}{K_{matrix} - K_1} - \frac{K_{fluid1}}{\emptyset(K_{matrix} - K_{fluid1})} = \frac{K_2}{K_{matrix} - K_2} - \frac{K_{fluid2}}{\emptyset(K_{matrix} - K_{fluid2})}$
- Shear modulus: → $\mu_1 = \mu_2$
- Reassemble the velocities (Rock with another fluid): → $\rho_2 = (1 - \emptyset)\rho_{matrix} + \emptyset\rho_{fluid2} = \rho_1 + \emptyset(\rho_{fluid2} - \rho_{fluid1})$
- Transform density: → $V_P = \sqrt{\frac{K_2 + \frac{4}{3}\mu_2}{\rho_2}}, \quad V_S = \sqrt{\frac{\mu_2}{\rho_2}}$

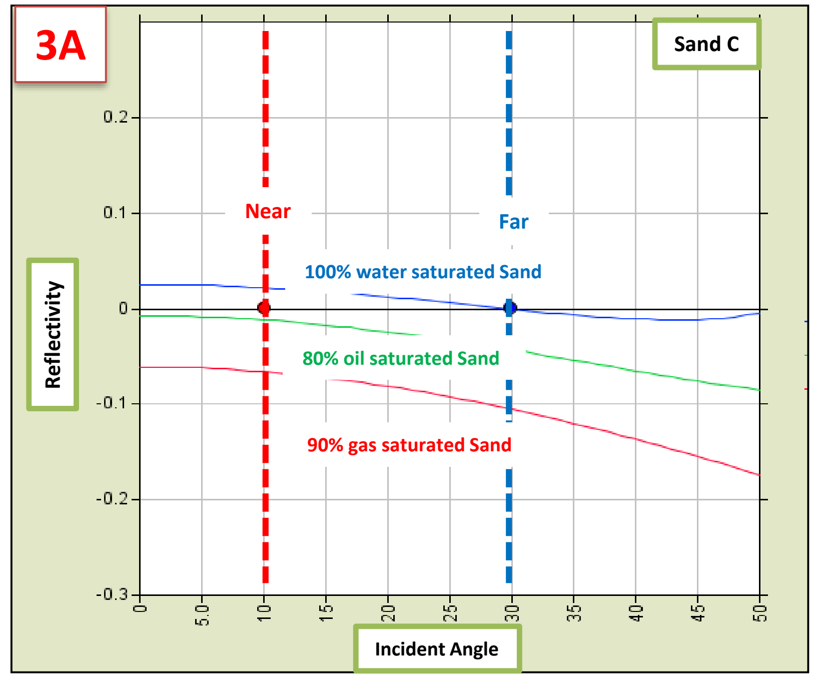
R-1: Greenberg, M. L., and J. P. Castagna, 1992, Shear-wave velocity estimation in porous rocks: Theoretical formulation, preliminary verification and applications: Geophysical Prospecting, 40, 195–209.

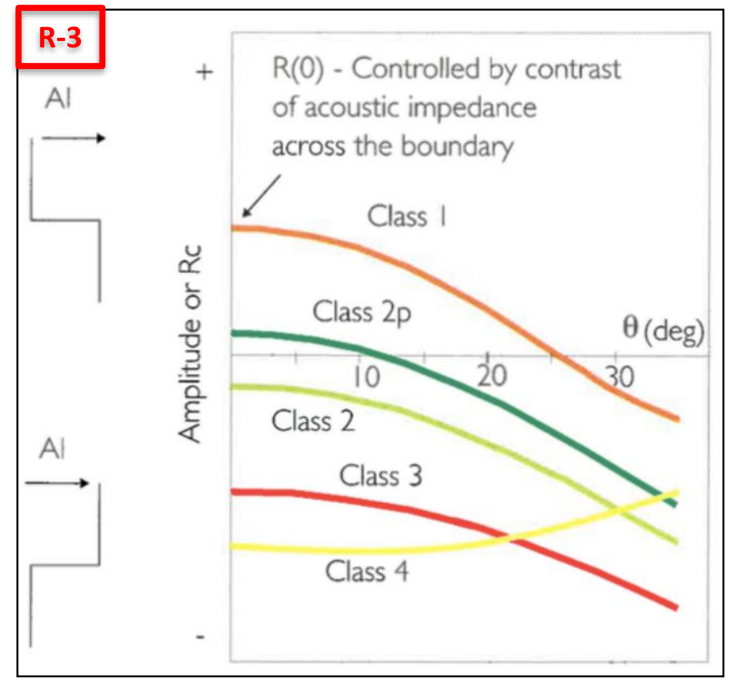
R-2: Simm and Becon, 2014, seismic Amplitude-An Interpreter's Hand Book

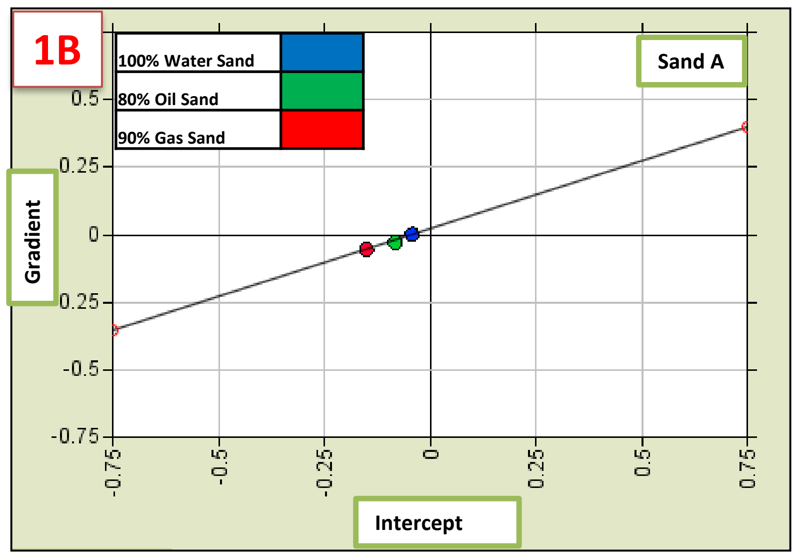
Fluid Substitution Effect on AVO response

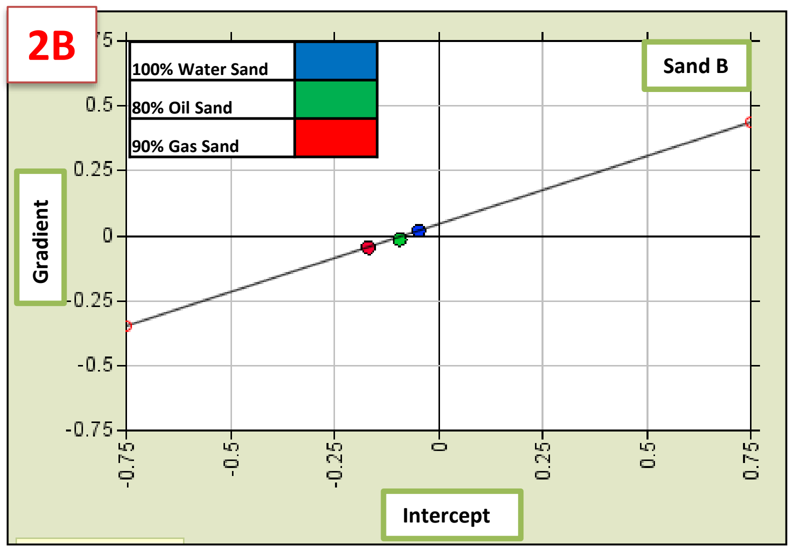


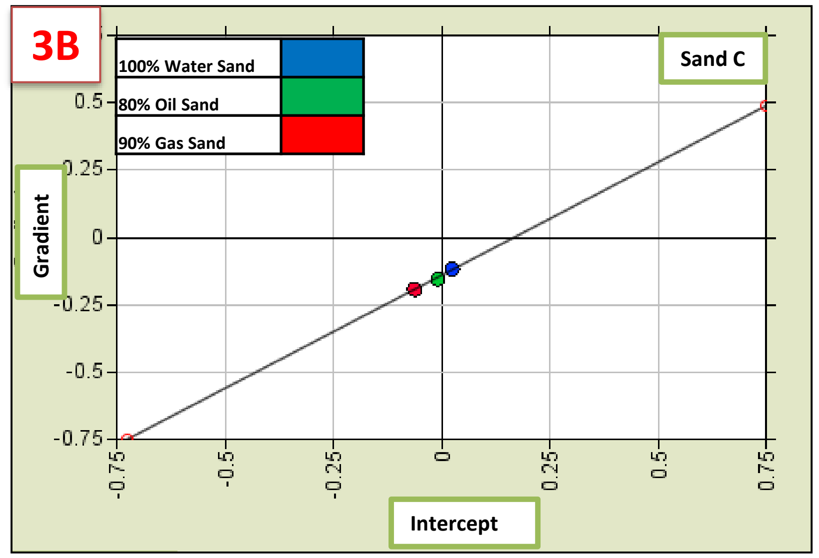


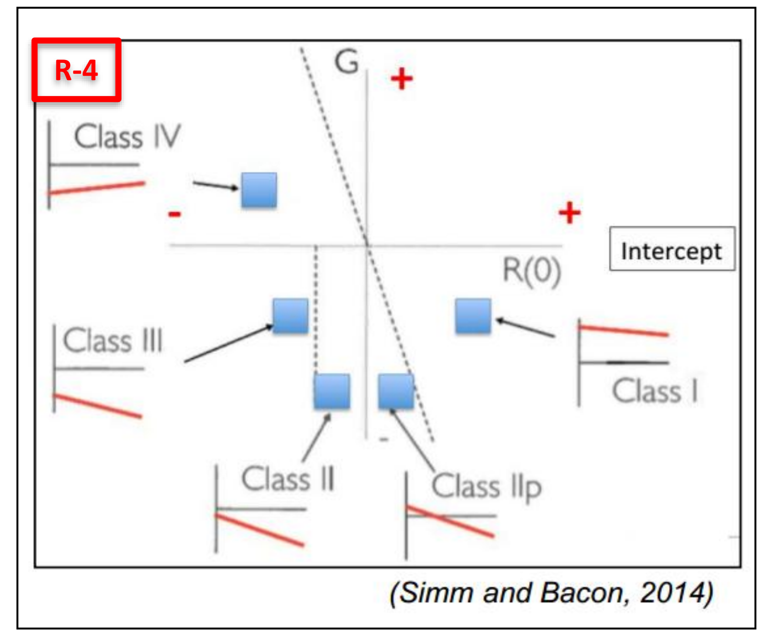


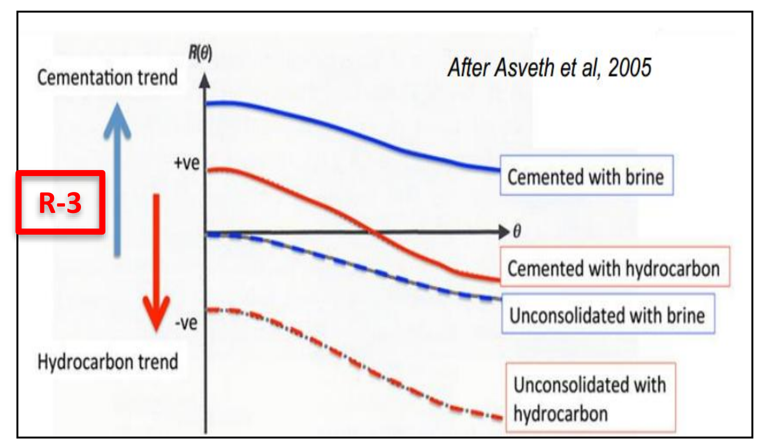








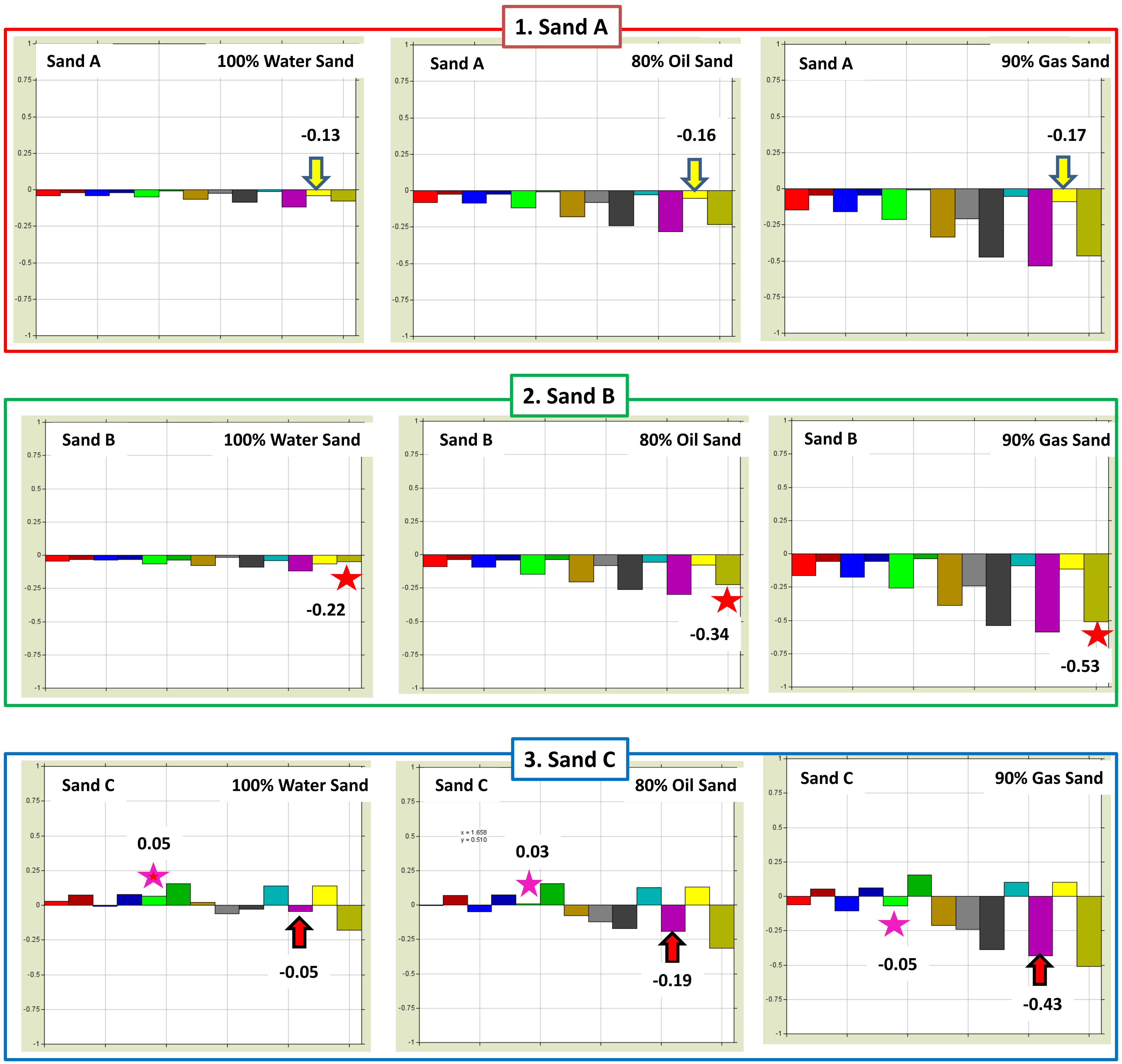


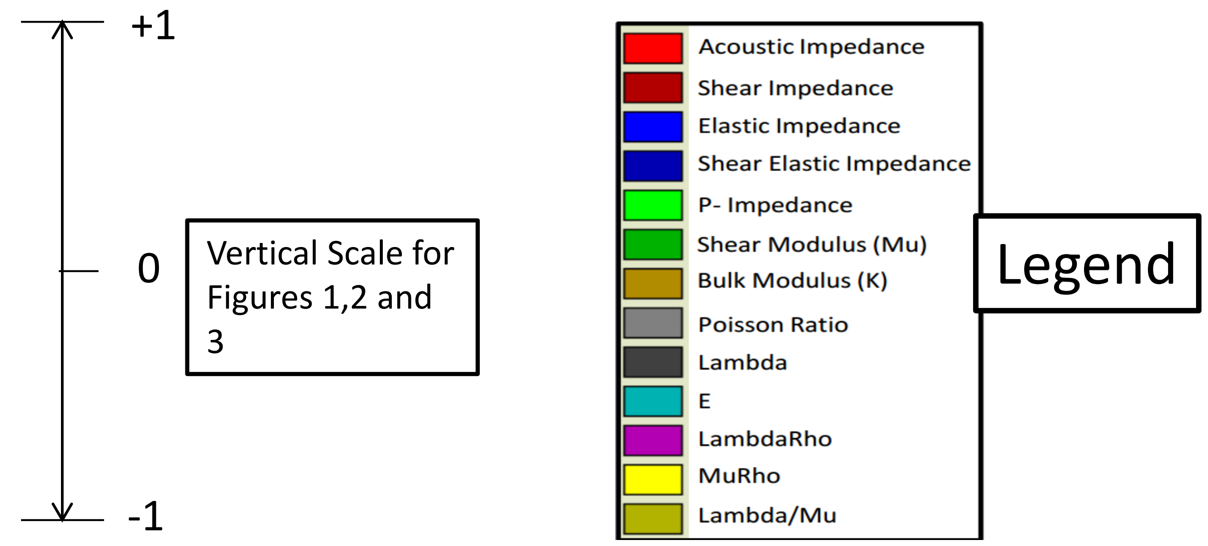


- Sand A and Sand B have similar AVO response for Three cases. For 100% water saturation Sand A And Sand B have low amplitude at zero incident angle R(0) About o.4 and R(near) is greater than the R(far). Water saturated Sand A and B Class II AVO (Figure 1A and 2A).
- 80% Oil and 90% gas saturated sand on Sand A an B have relatively high R(0), 0.08 to 0.09 in oil saturated sand and 0.15 to 0.17 in gas saturated sand ; Both of these may be Class III AVO (Figure 1A and 2A).
- In Sand C, 100% water saturated R(0) is positive, very low magnitude (about 0.02) and phase reversal. so, water saturated sand in Sand C is Class 2P (Figure 3A).
- For 80% oil saturation Sand C is Class ll AVO (very low amplitude at R(0) around 0.01 and negative gradient). Besides, In 90% gas Sand C is Class III AVO (R(0) is relatively high about 0.07) .
- Intercept for 100% saturation on Sand A and Sand B are negative about 0.05. on the other hand for Sand C gradient is positive and near to zero Which is classified as Class IIP AVO (Figure 1,2,3 B).
- Shale overlying gas sand case shows the highest amplitude change from near to far offset, followed by oil sand and brine sand case. For 90% gas sand: Sand A= 0.16; Sand B=0. 15 ; Sand C= 0.17; For 80% oil sand: Sand A= 0.09; Sand B=0.09; Sand C=0.09; For 100% water saturated Sand : Sand A=0.03; Sand B=0.03; Sand C=0.02;
- On all sand, It has been observed that reflectivity for hydrocarbon saturated sand is more negative towards the far offset angle and Gradient for are increased when sands are saturated by hydrocarbon (Figure 1,2,3 A).

R-3: Avseth, P., Mukerji, T. and Mavko, G., 2005. Quantitative seismic interpretation, Cambridge University Press.
R-4: Simm and Becon, 2014, seismic Amplitude-An Interpreter's Hand Book

Elastic Contrast Analyzer





- There are 13 elastic parameters presented but just 4 are observed to be significant – Mu-Rho, Lambda-Rho, Lambda-Mu, and P-Impedance.
- Sand A and B show almost similar elastic contrast behavior (Figure 1 and 2). In contrast, Sand C provides different behavior compared to the other sand (Figure 1).
- Mu-Rho (μρ) value doesn't change a lot due to the change of fluid type, because it is not affected by rigidity (μ) but affected by the density a little bit (Figure 1, Marked by **Yellow Arrow**). For Sand A, this value water sand is -0.13 which is slightly increased (-ve) to -0.17 for 90% gas saturation.
- Lambda-Mu has decreasing trends as we move from brine to gas sand case. This property also shows high contrast between hydrocarbon and non-hydrocarbon zone (Figure 2, marked by **Red Asterisk** Sign).
- The Lambda-Rho (λρ) values gives the best attribute differentiate among the types of pore fluid because it gives the highest contrast. In Figure 3 (marked by **Red Arrow**), (λρ) for 100% water is -0.05, for 80% oil -0.19 and for 90% gas -0.43 (about 9 times garter compare to value for 100% water).
- Some attributes change from positive contrast to negative contrast as we move from brine to gas sand case (P-impedance and bulk modulus). In Figure C , P-Impedance marked by **Purple Asterisk** Sign (for 100% water saturated sand +0.05 and for 90% gas saturated sand -0.05).

Conclusion

- Trough AVO model fluid substitution effect easily observed using different predicted AVO response. Sand A and B gives same response for three cases. For 100% Water saturation , Zero incidence reflectivity is about 0.4 and gradient is near to zero. These sand are Class II AVO and Unconsolidated brine sand.

- In Sand C, AVO response are Quite different from other two. 100% water sand follows phase change for far angle, has very low positive (about +0.02) zero incidence angle with positive intercept (about +0.03). This Classified as Class IIP AVO.

- All 90% gas saturated sand, with relatively high (-ve) gradient (0.10-0.20), classified as Class III AVO. In addition, gas sand case shows the highest amplitude change from near to far offset (bout 0.15 t0 0.17).

- Like as AVO response Sand A and B show almost similar elastic contrast behavior and Sand C has quite different behavior compared to these sands.

- Among 13 elastic contrast analyzer parameter Lambda-Rho (λρ) and Lambda-Mu shows very high elastic contrast different between hydrocarbon and non-hydrocarbon saturated formation. In Sand C, λρ change dramatically (for 100% water -0.05 and for 90% gas -0.43).

- Effect of fluid type on Mu-Rho (μρ) value is negligible , but affected by the density a little bit (Figure 1, Marked by Yellow Arrow). For Sand A, this value water sand is -0.13 which is slightly increased (-ve) to -0.17 for 90% gas saturation.