UNIVERSITÀ DEGLI STUDI DI TRIESTE

Laurea Magistrale in Geoscienze

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PETROFISICA INTEGRATA II MODULO

UD5
AVO, AVA e INVERSIONE SISMICA

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REFLECTION SEISMIC: AMPLITUDE ANALYSIS

QUANTITATIVE/PETROGRAPHYCAL ANALYSIS

New analysis/interpretation techniques were implemented to obtain more affordable results to:

Discriminate between gas, oil & brine saturation;

Localize major rock lateral/vertical variations (sand and clay content, porosity changes, …)

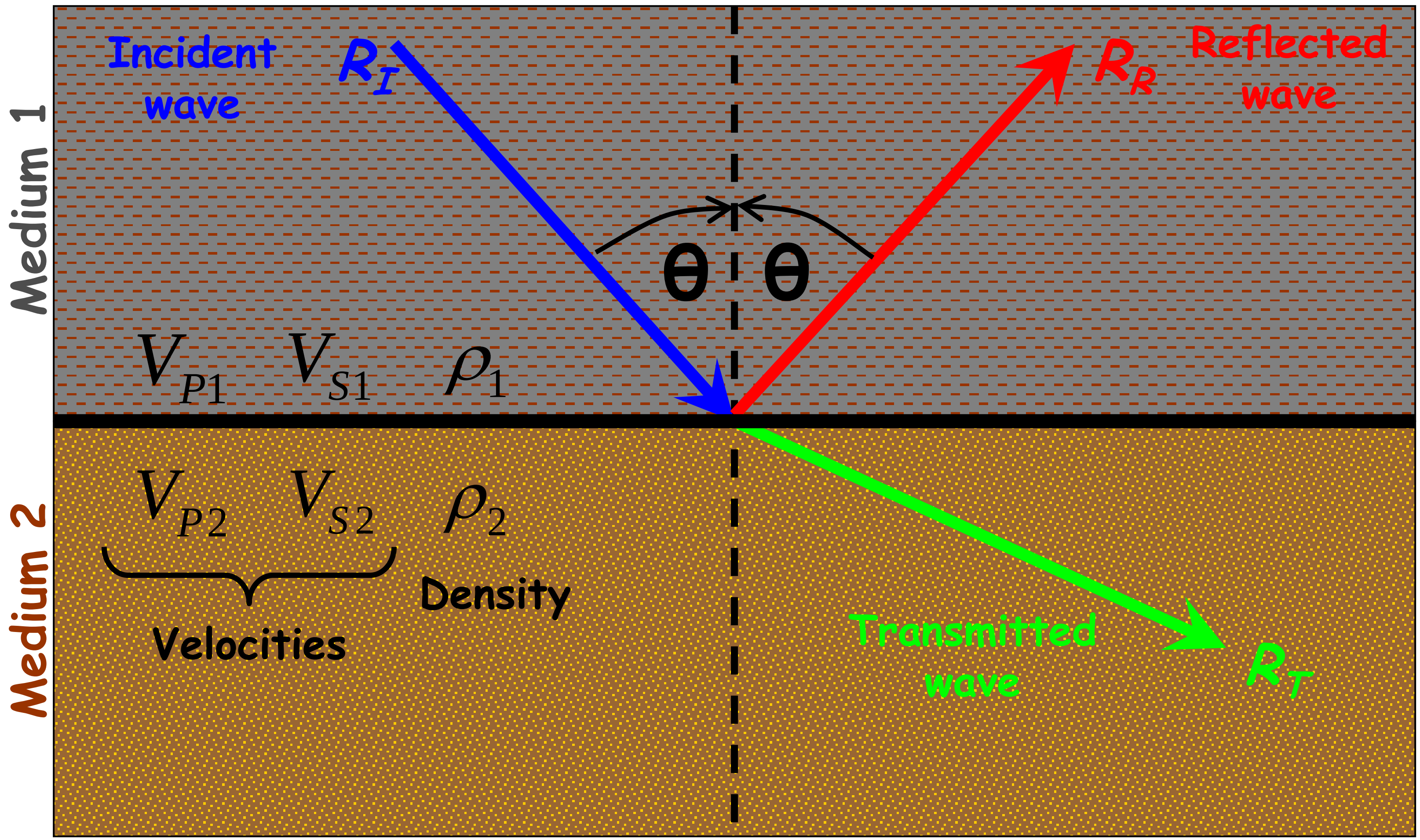
Estimate main petrophysical parameters

AMPLITUDE VERSUS OFFSET – AVO

AMPLITUDE VERSUS AZIMUTH - AVA

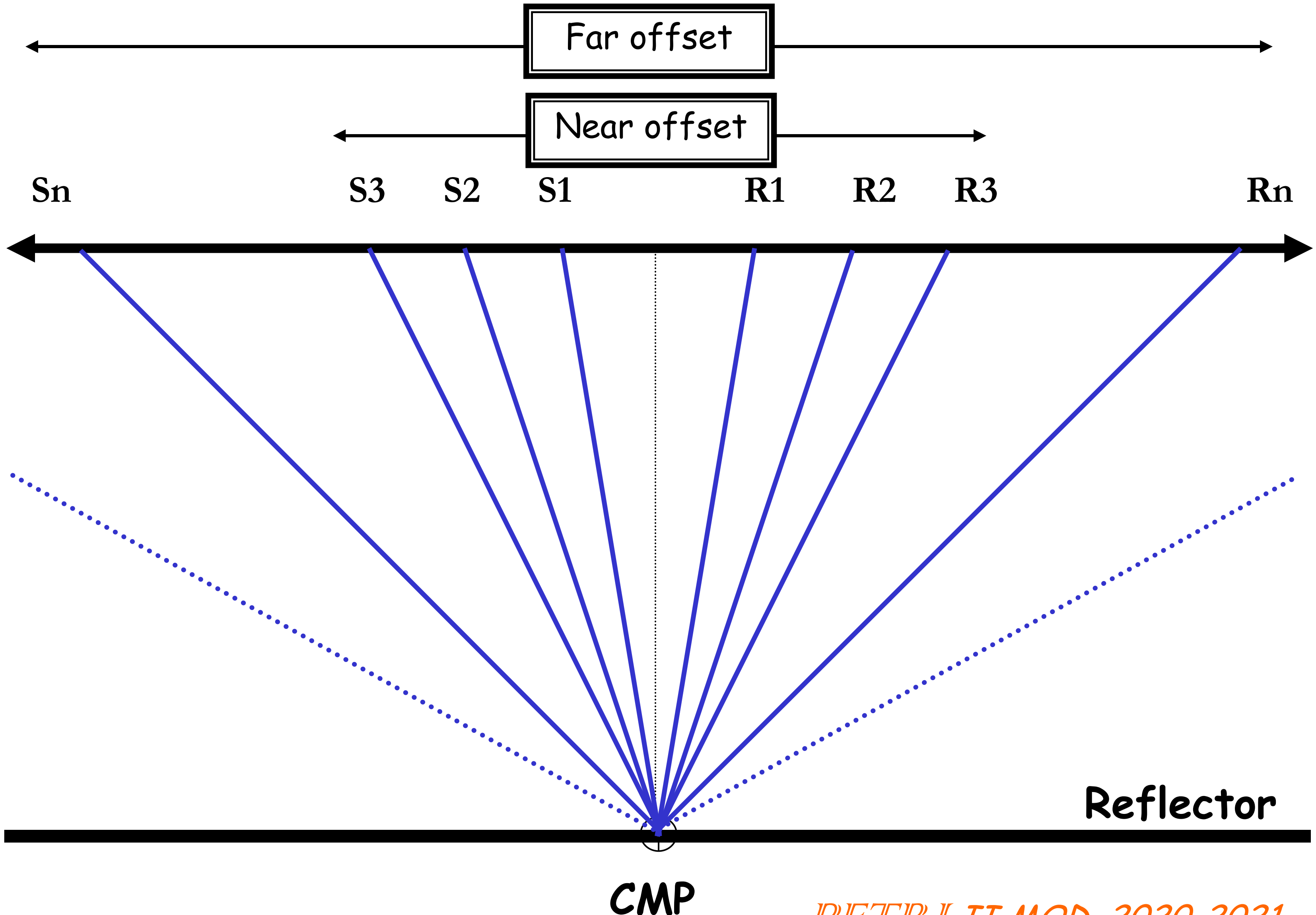
REFLECTION SEISMIC: AMPLITUDE ANALYSIS

Reflection Amplitudes R_R, R_T, are determined by the ***contrast*** *in rock properties V_P, V_S, ρ and* ***angle of incidence θ***



REFLECTION SEISMIC: AMPLITUDE ANALYSIS

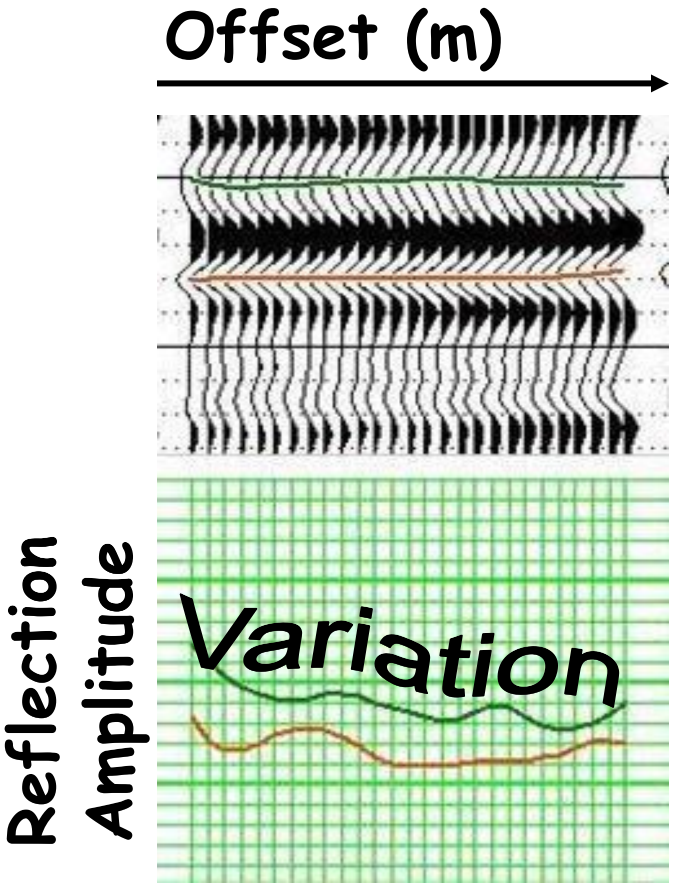
Information on the same point from several different OFFSETS



REFLECTION SEISMIC: AVO

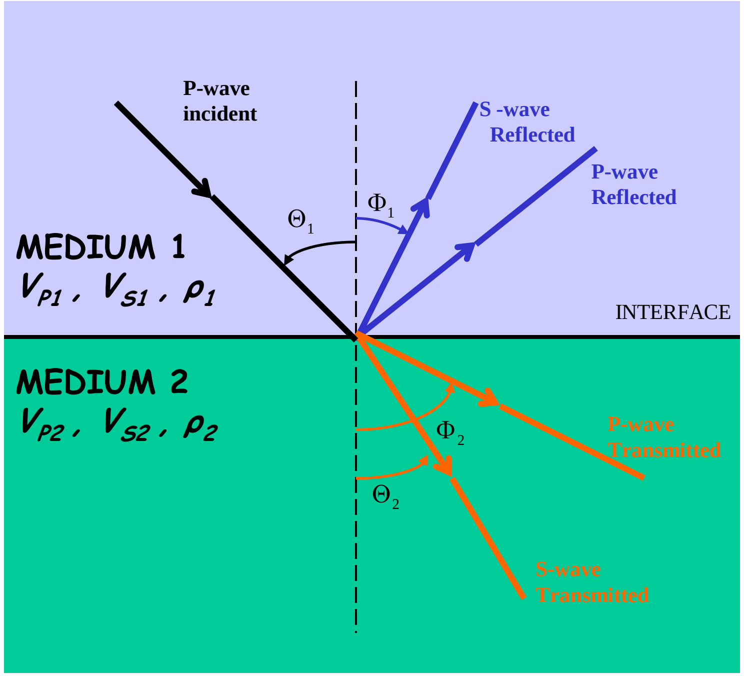
Typically, reflection amplitude decreases (falls) with offset due to geometrical spreading, attenuation and other factors.

Amplitude Versus Offset or **Amplitude Variation with Offset** – AVO is an ANALYSIS Technique to understand any anomalous behaviour of AMPLITUDE



Amplitude
Variation
with
Offset

REFLECTION SEISMIC: AVO



$$ray\ \ parameter = p = \frac{\sin\Theta_1}{V_{P1}} = \frac{\sin\Theta_2}{V_{P2}} = \frac{\sin\Phi_1}{V_{S1}} = \frac{\sin\Phi_2}{V_{S2}}$$

REFLECTION COEFFICIENT Rp

For a P-wave with vertical incidence the Rp can be calculated by:

$$R_P = \frac{V_{P2}\rho_2 + V_{P1}\rho_1}{V_{P2}\rho_2 - V_{P1}\rho_1} \qquad \text{i.e.} \qquad R_P = \frac{I_{P2} - I_{P1}}{I_{P2} + I_{P1}}$$

The general case (P and S waves) in much more complicated and in linear (matrix) form is:

$$Q = \begin{pmatrix} \grave{P}\acute{P} & \grave{S}\acute{P} & \acute{P}\acute{P} & \acute{S}\acute{P} \\ \grave{P}\acute{S} & \grave{S}\acute{S} & \acute{P}\acute{S} & \acute{S}\acute{S} \\ \grave{P}\grave{P} & \grave{S}\grave{P} & \acute{P}\grave{P} & \acute{S}\grave{P} \\ \grave{P}\grave{S} & \grave{S}\grave{S} & \acute{P}\grave{S} & \acute{S}\grave{S} \end{pmatrix} = P^{-1}R$$

Aki & Richards (1980)

Where:

$$P = \begin{pmatrix} -\sin\Theta_1 & -\cos\Phi_1 & \sin\Theta_2 & \cos\Phi_2 \\ \cos\Theta_1 & -\sin\Phi_1 & \cos\Theta_2 & -\sin\Phi_2 \\ 2\rho_1 V_{S1}\sin\Phi_1\cos\Theta_1 & \rho_1 V_{S1}(1-2\sin^2\Phi_1) & 2\rho_2 V_{S2}\sin\Phi_2\cos\Theta_2 & \rho_2 V_{S2}(1-2\sin^2\Phi_2) \\ -\rho_1 V_{P1}(1-2\sin^2\Phi_1) & \rho_1 V_{S1}\sin 2\Phi_1 & \rho_2 V_{P2}(1-2\sin^2\Phi_2) & -\rho_2 V_{S2}\sin 2\Phi_2 \end{pmatrix}$$

Propagation/Transmission

$$R = \begin{pmatrix} \sin\Theta_1 & \cos\Phi_1 & -\sin\Theta_2 & -\cos\Phi_2 \\ \cos\Theta_1 & -\sin\Phi_1 & \cos\Theta_2 & -\sin\Phi_2 \\ 2\rho_1 V_{S1}\sin\Phi_1\cos\Theta_1 & \rho_1 V_{S1}(1-2\sin^2\Phi_1) & 2\rho_2 V_{S2}\sin\Phi_2\cos\Theta_2 & \rho_2 V_{S2}(1-2\sin^2\Phi_2) \\ \rho_1 V_{P1}(1-2\sin^2\Phi_1) & -\rho_1 V_{S1}\sin 2\Phi_1 & -\rho_2 V_{P2}(1-2\sin^2\Phi_2) & \rho_2 V_{S2}\sin 2\Phi_2 \end{pmatrix}$$

Reflection

➔ Reflected (and transmitted) **AMPLITUDE f(Vp, Vs, ρ, angle)**

REFLECTION SEISMIC: AVO

There are several simplified eq. for specific angle ranges:

Reflection Amplitude:

$$R_R(\theta) \approx \frac{1}{2}\left(1-4\left(\sin\theta/\theta\right)^2 V_S^2\right)\left(\frac{\Delta\rho}{\rho}\right)+\frac{1}{2\cos^2(\theta)}\cdot\left(\frac{\Delta V_P}{V_P}\right)-4V_S^2\rho^2\frac{\Delta V_S}{V_S}$$

Aki & Richards (1980)

Moreover:

$$V_P = \sqrt{\frac{\lambda+2\mu}{\rho}}$$

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

⟷

Lithology
fluid types
fluid saturation
Porosity
Anisotropy
etc…

Velocities $\boldsymbol{V_P}$, $\boldsymbol{V_S}$ *are in turn dependent on elastic constants* $\boldsymbol{\lambda}$, $\boldsymbol{\mu}$, *and* ρ, *and inherent rock properties*

REFLECTION SEISMIC: AVO

The seismic response & rock properties

2D, 3-D seismic data
Borehole log data

↓

Observable parameters
Seismic amplitude *(Rc)*
V_P V_S Density *(ρ)*

↓

Elastic Constants
λ μ ρ κ

↓

Can indicate the differences between fluids, porosity, saturation,…

REFLECTION SEISMIC: AVO

There are many possible applications depending from the final objectives, the available data and the data quality

1) *AVO ANALYSIS* *Study the Amplitude behaviour on multi-offset (multi-fold) 2D or 3D registered data*
2) *AVO MODELING* *1D, 2D and 3D synthetic offset/angle gathers calculations (also from well log data). Modeling can be performed first, in order to determine what type of AVO anomaly may be anticipated.*
3) *AVO INVERSION* *extract lithologic and pore fluid information, removing the effects of the seismic wavelet and optimising thin-layer resolution*

REFLECTION SEISMIC: AVO ANALYSIS

Many analysis techniques:

A simplified equation for the reflection amplitude is:

$$R_{PP}(\Theta_1) = R_P + B\sin^2\Theta_1$$

Shuey's eq. ➔ linear relation between A(r) and incidence angle $\sin^2\Theta$

Intercept (A) & Gradient (B)

R_P = A = "AVO Intercept parameter" ➔ f(porosity)

B = "AVO gradient" $B = A_0 R_P + \frac{\Delta\sigma}{(1-\sigma)^2}$ B= AVO gradient ➔ f(σ=Poisson) ➔ Physical rock/fluid parameter ➔ liquid saturation ➔

Scaled Poisson's Ratio

$\Delta\sigma = \frac{4}{9}(A+B)$ ➔ hydrocarbon indicator

Shear wave reflectivity

Rs=shear wave reflectivity ➔ $R_S = \frac{1}{2}(R_P - B)$ ➔ Fluid saturation

Fluid factor

Δf=fluid factor ➔ $\Delta F = \frac{\Delta V_P}{V_P} - c_1 \frac{V_S}{V_P}\frac{\Delta V_S}{V_S}$

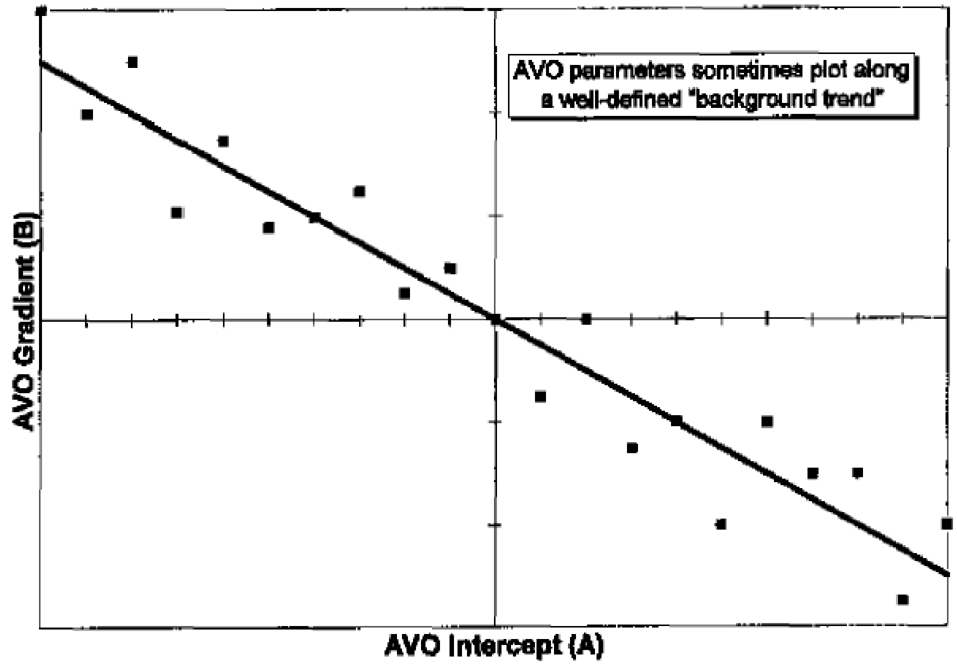
- $\Delta F \cong 0$ water saturated rocks
- $\Delta F < 0$ possible top of oil reservoir
- $\Delta F > 0$ below a gas (or oil) reservoir

(Smith e Gidlow, 1987)

REFLECTION SEISMIC: AVO ANALYSIS

AVO Crossplot

AVO Crossplot ➔ A graph showing amplitudes value as a function of:
AVO intercept attribute (A)
AVO gradient attribute (B)

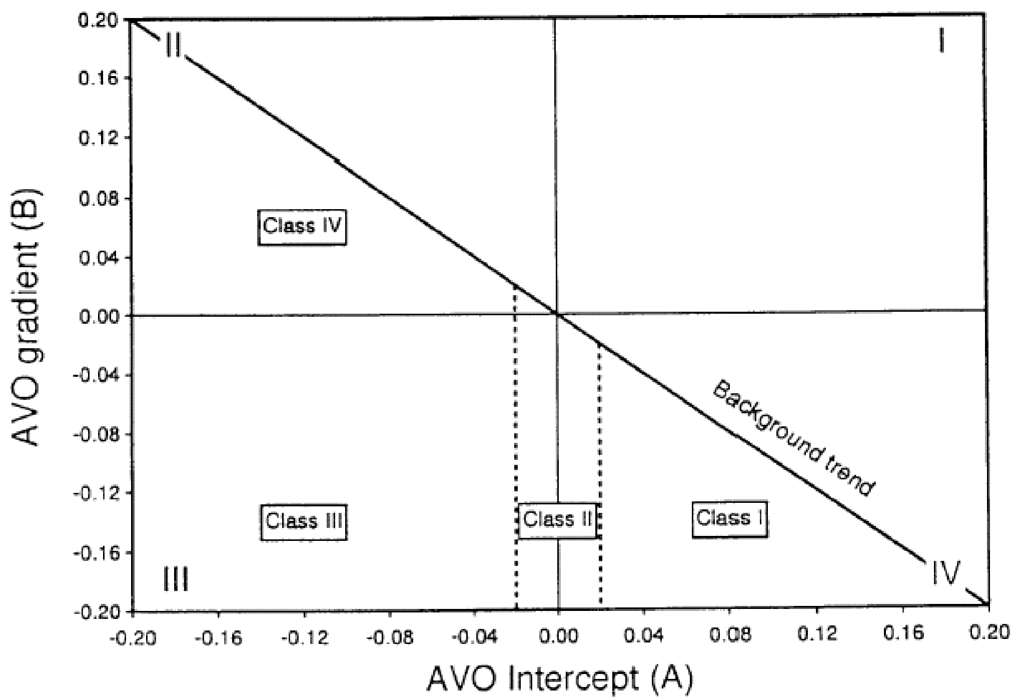


For brine-saturated (clastic) rocks in a particular site, there may be a well-defined relationship between the AVO intercept (A) and the AVO gradient (B).

Thus, in a given time window, non hydrocarbon-bearing clastic rocks often exhibit a well-defined background trend; **deviations from** this **background** are indicative of hydrocarbons or unusual lithologies.

REFLECTION SEISMIC: AVO ANALYSIS

AVO Crossplot - CLASSIFICATION



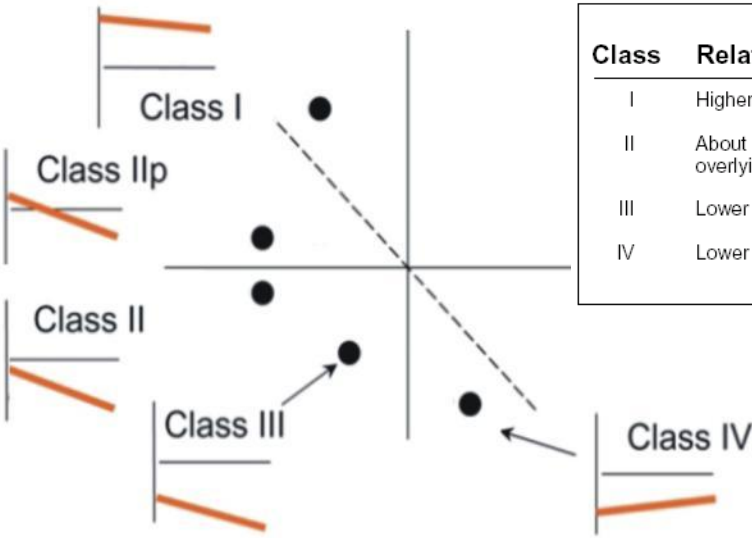
The classification of AVO responses should be based on position of the reflection of interest on an A versus B crossplot. First, the background trend within a given time and space window must be defined. This can be done with well control if the seismic data are correctly amplitude calibrated, or with the seismic data itself if care is taken to exclude prospective hidden hydrocarbon-bearing zones.

Top of gas sand reflections then should plot below the background trend and bottom of gas sand reflections should plot above the trend.

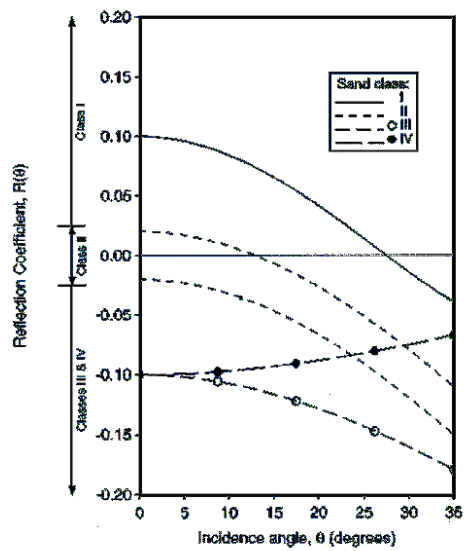
We can classify the gas sand response according to position in the A-B plane of the top of gas sand reflections.

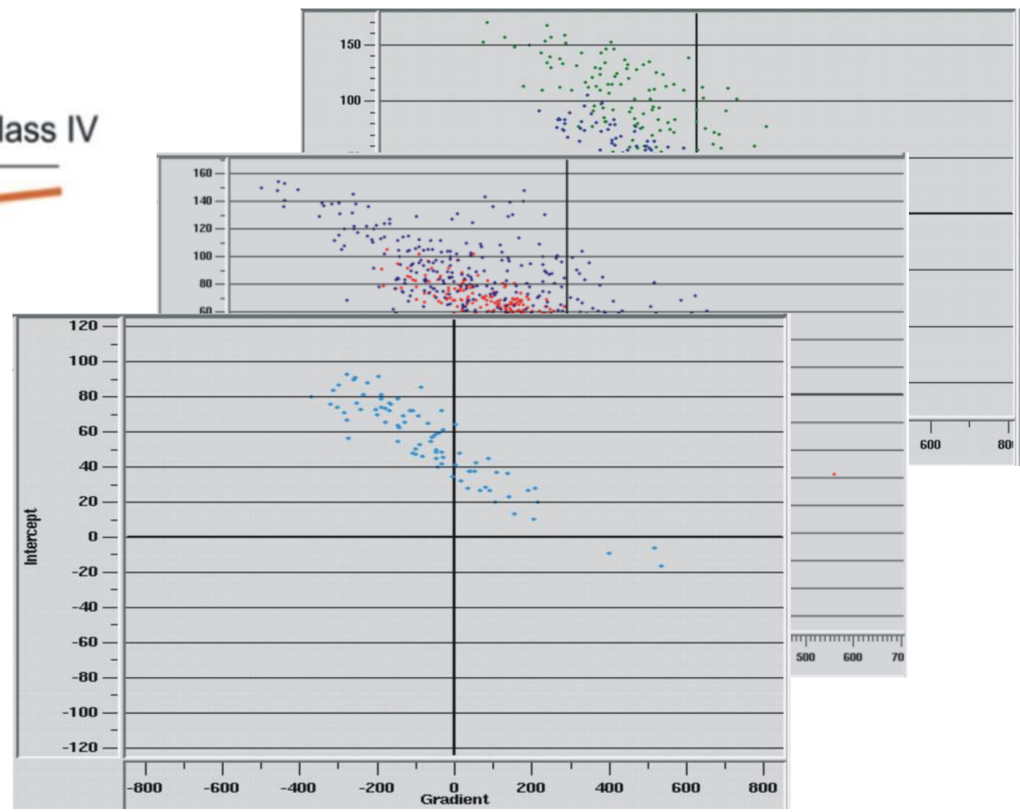
REFLECTION SEISMIC: AVO ANALYSIS

AVO Crossplot - CLASSIFICATION



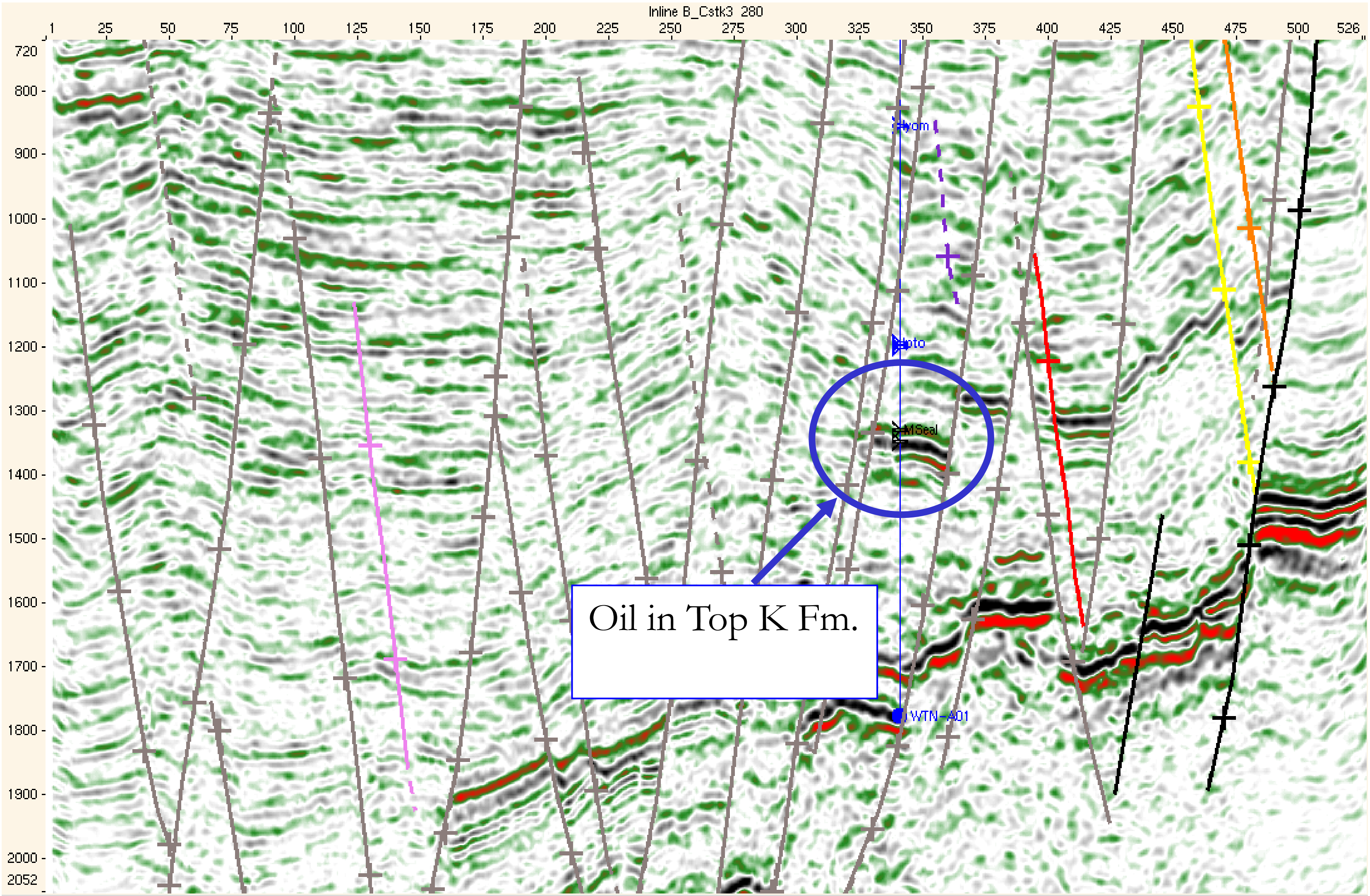
Class	Relative Impedance	Quadrant	A	B	Amplitude vs. Offset
I	Higher than overlying unit	IV	+	-	Decreases
II	About the same as the overlying unit	II, III, or IV	+ or -	-	Increase or decrease; may change sign
III	Lower than overlying unit	III	-	-	Increases
IV	Lower than overlying unit	II	-	+	Decreases





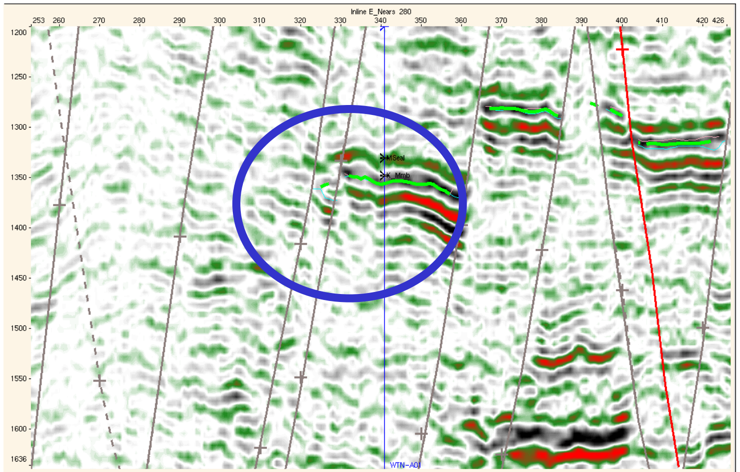
REAL EXAMPLES

REFLECTION SEISMIC: AVO ANALYSIS
REAL EXAMPLES

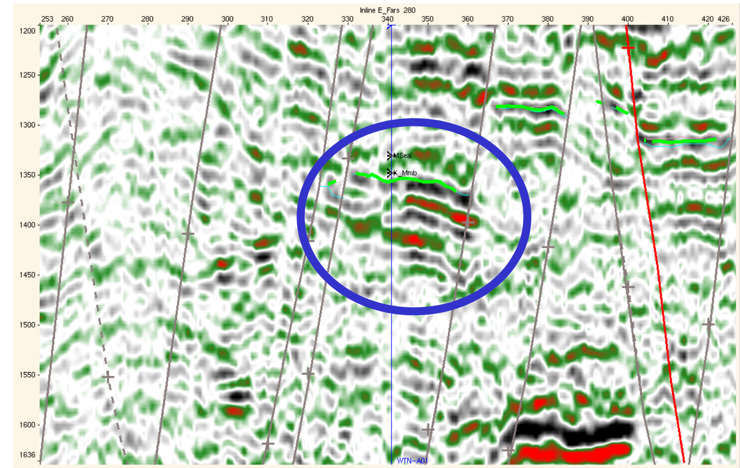


REFLECTION SEISMIC: AVO ANALYSIS

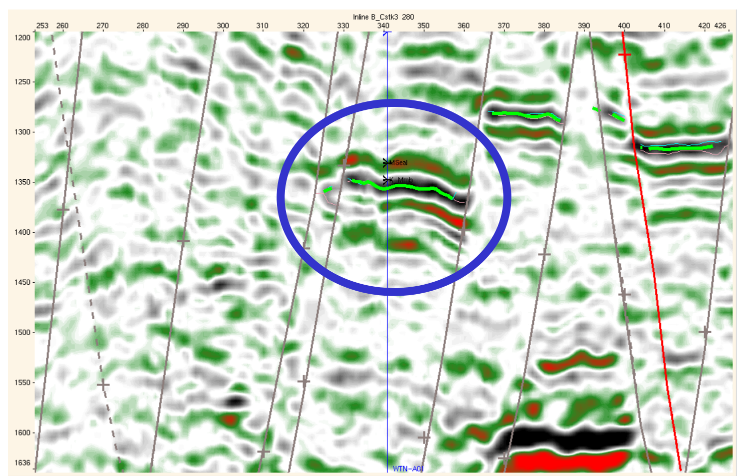
REAL EXAMPLES



Near Offset Stack



Far Offset Stack



Normal Stack

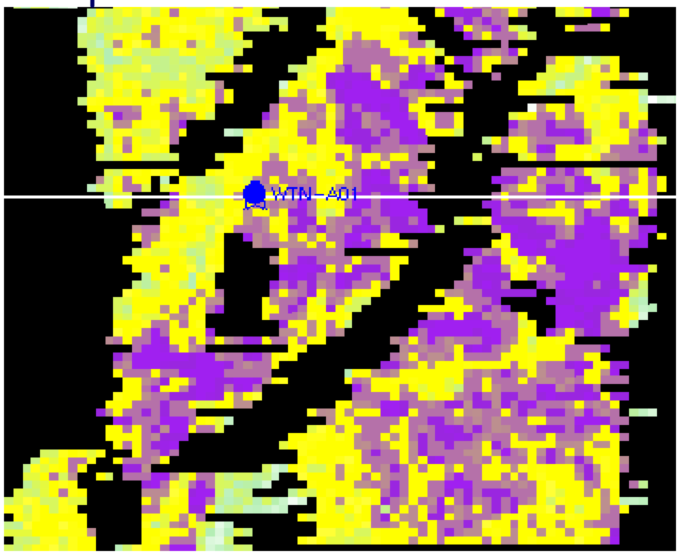
RC +


RC -

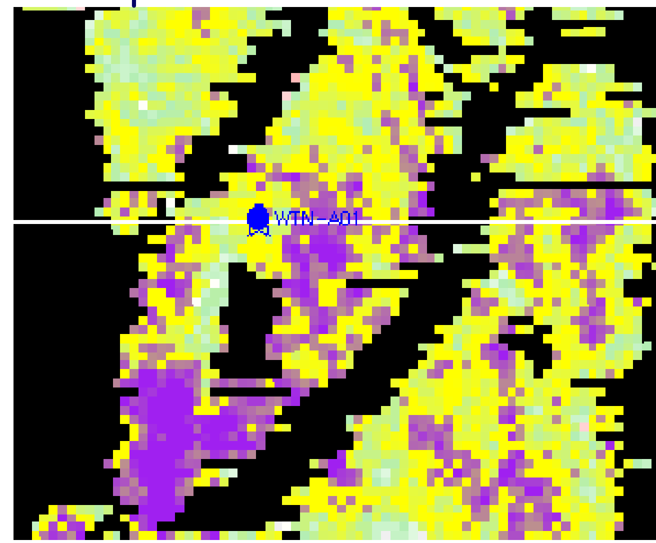
REFLECTION SEISMIC: AVO ANALYSIS

REAL EXAMPLES

Ampl. extraction - near stack

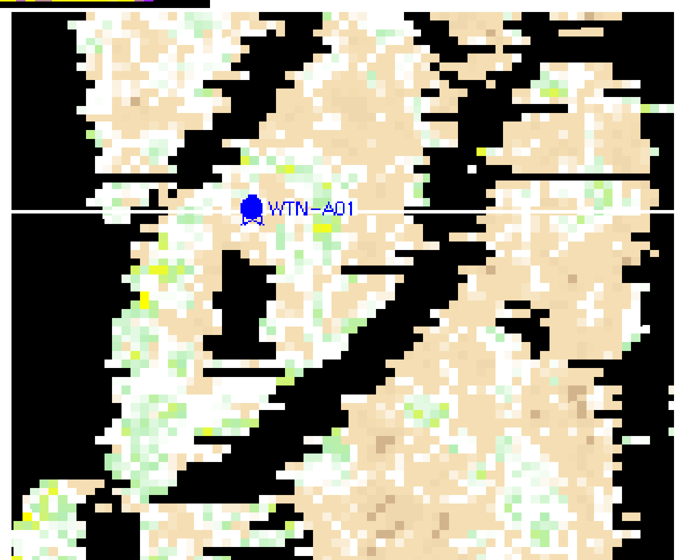


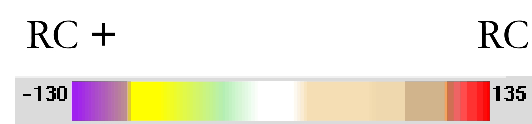
Ampl. extraction - far stack



Amplitude extraction

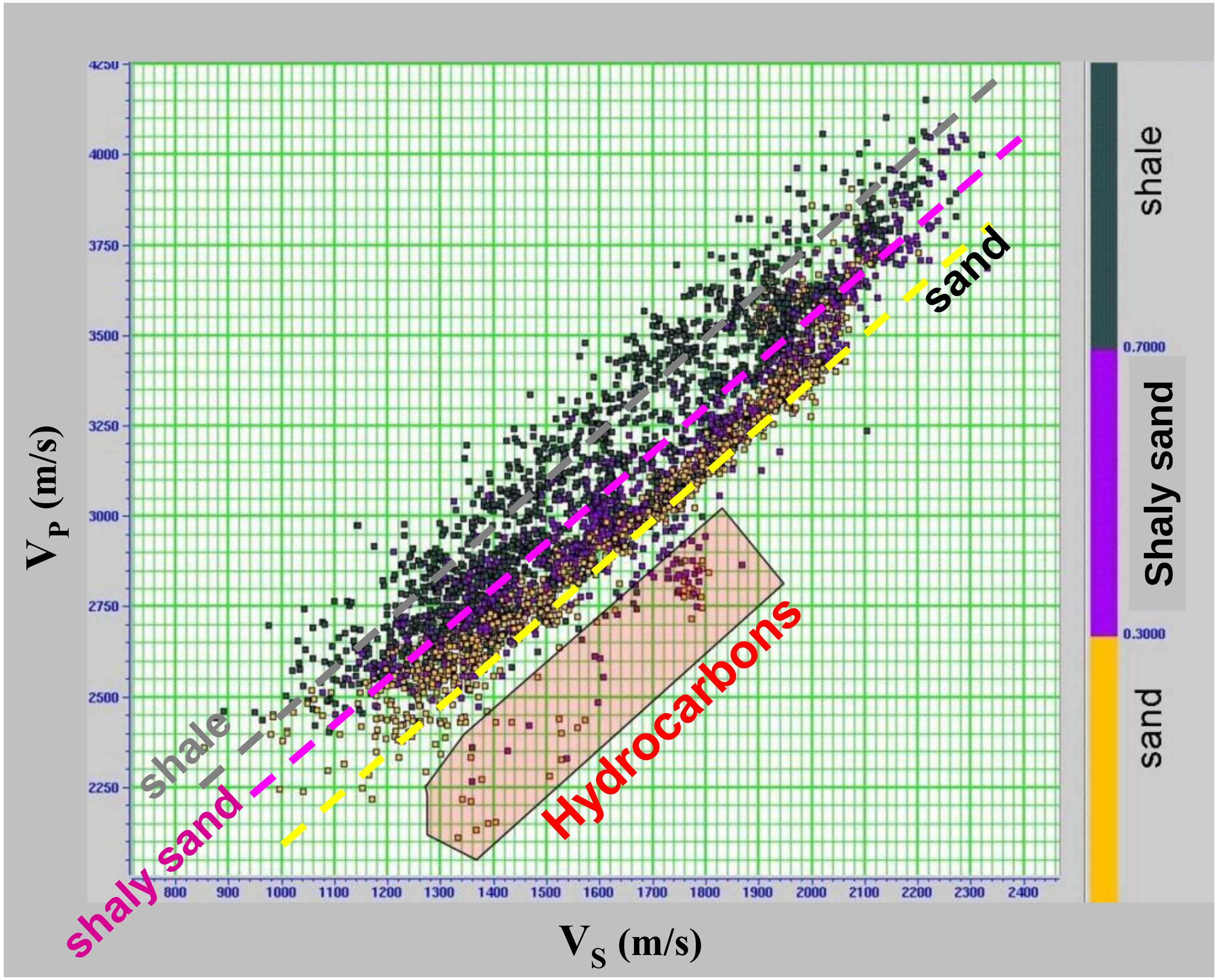
far-near difference





REFLECTION SEISMIC: AVO ANALYSIS
REAL EXAMPLES

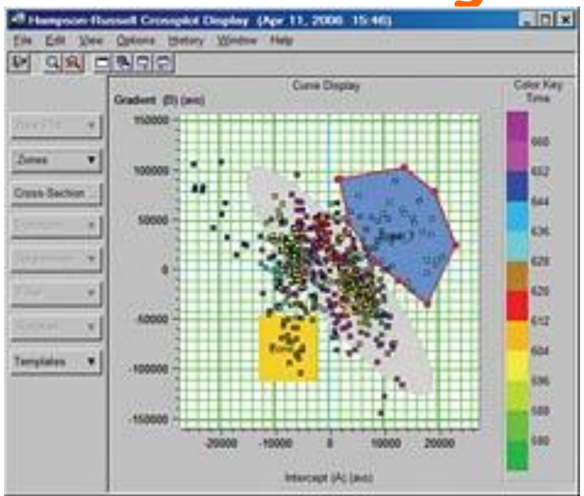
Crossplot of V_P vs. V_S from Seismic + log data

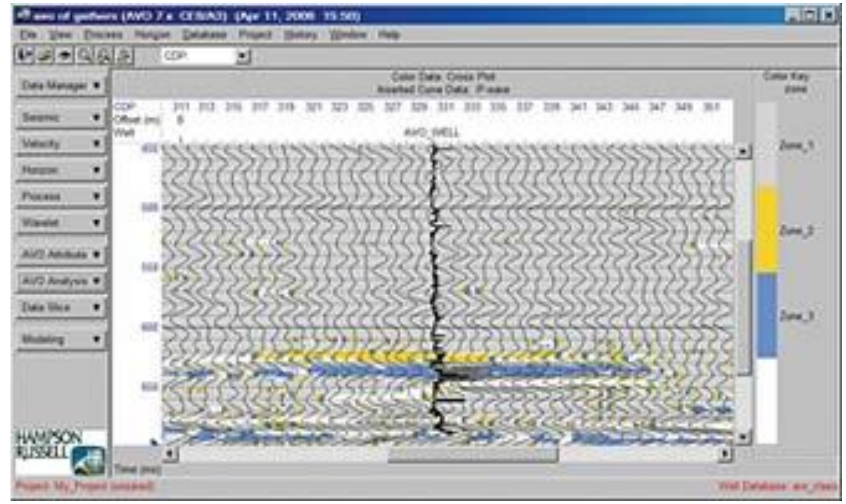


REFLECTION SEISMIC: AVO ANALYSIS

REAL EXAMPLES

AVO Integration and Calibration with LOGs





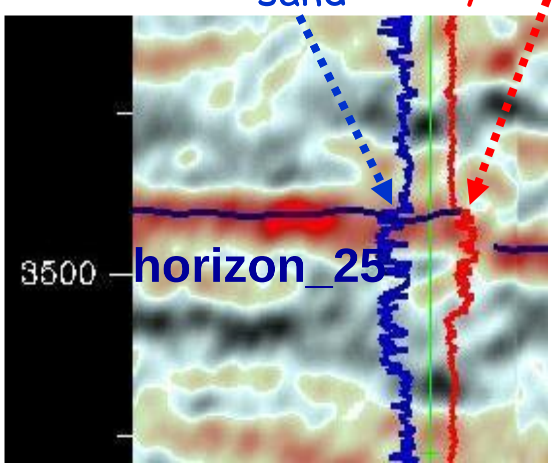
C1

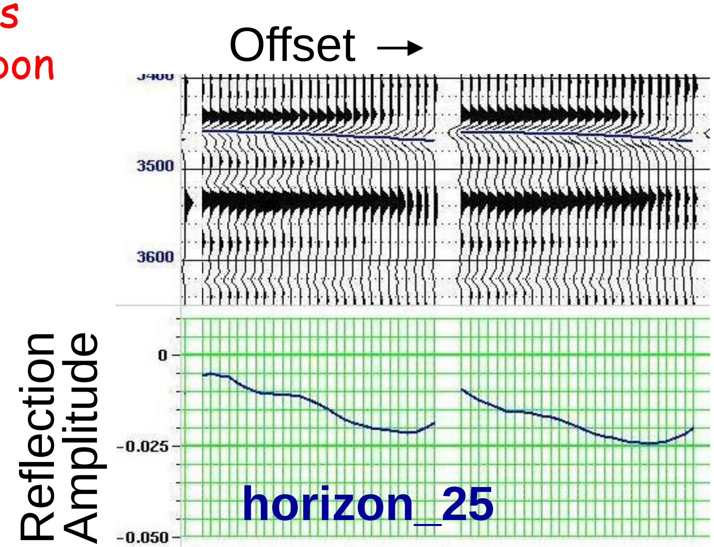
C2

C3

GR indicates sand

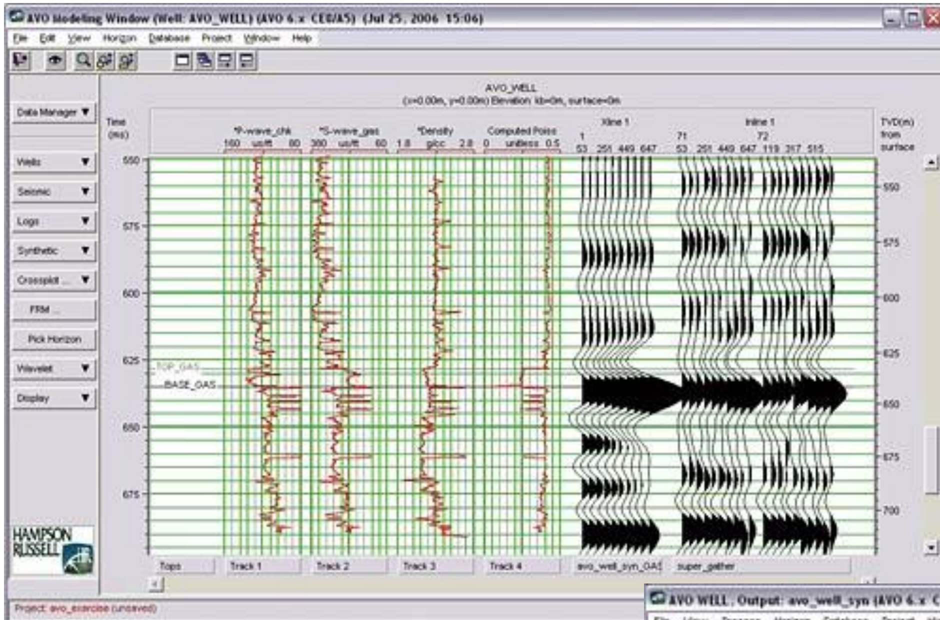
Resistivity indicates hydrocarbon



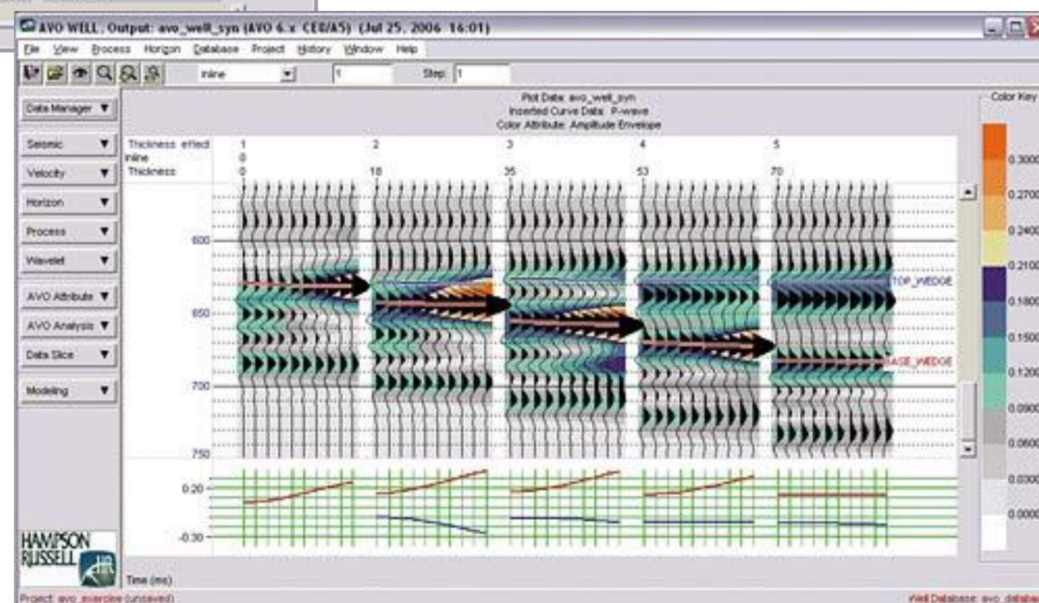


AVO indicates Class III

REFLECTION SEISMIC: AVO MODELING



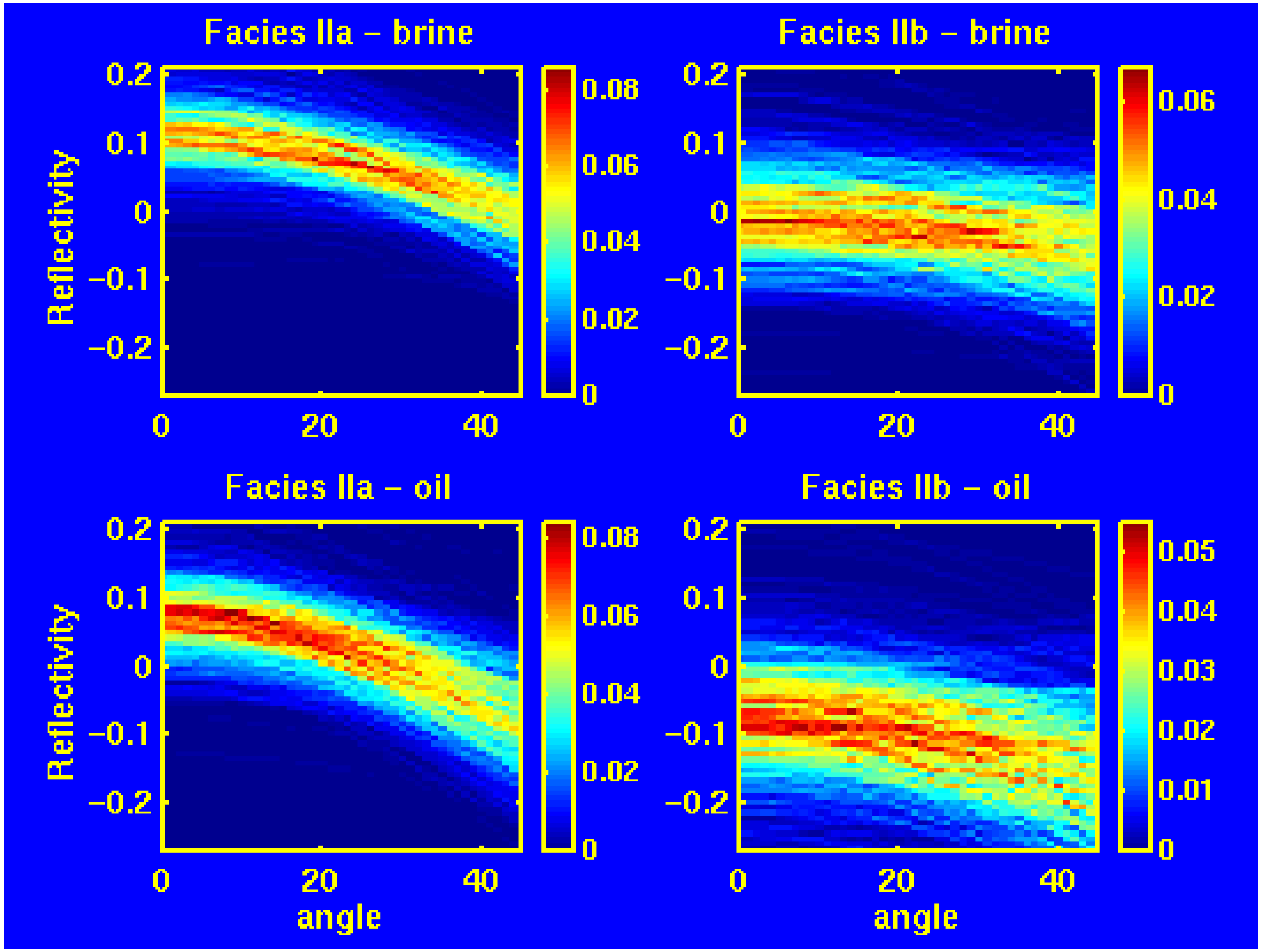
LOG data ➔ Modeling of a "virtual" acquisition :
➔ AVO applicability
➔ AVO validation



Classically, changes in reservoir fluid type and saturation, as well as changes in porosity, are modeled

REFLECTION SEISMIC: AVO MODELING

Improved (quantitative) interpretation of AVO analyses



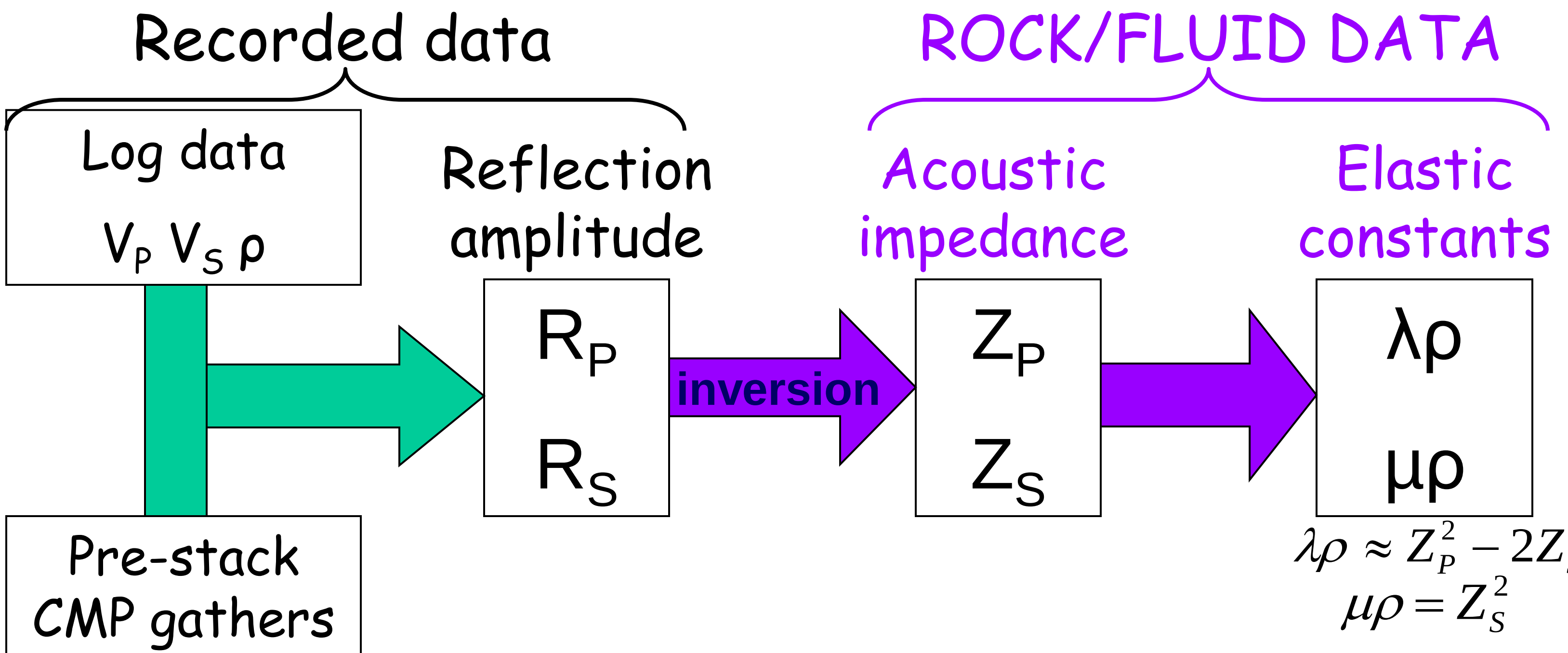
REFLECTION SEISMIC: AVO INVERSION

What is Inversion?

Seismic (AVO) inversion is the process of determining what physical characteristics of rocks and fluids could have produced the seismic record you are viewing

*i.e. ➔ it's a procedure trying to determine the **INPUT** by looking at the output of an experiment*

- Elastic Impedance (EI) inversion *(Connolly, 1999)*
- Lambda-Mu-Rho (LMR) inversion *(Goodway, 1997)*



$$\lambda\rho \approx Z_P^2 - 2Z_S^2$$
$$\mu\rho = Z_S^2$$

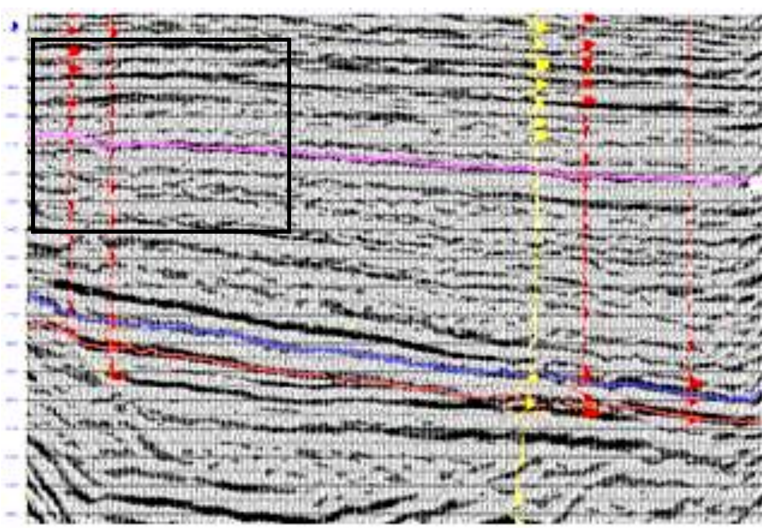
REFLECTION SEISMIC: AVO INVERSION

EI inversion: Generalization of acoustic impedance for variable angle of incidence *Connolly, 1999*

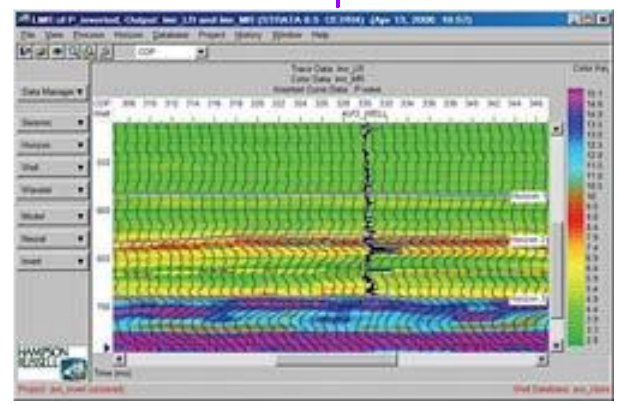
$$EI(\theta) = V_P^{(1+\tan^2\theta)} V_S^{(-8K\sin^2\theta)} \rho^{(1-4K\sin^2\theta)}$$

where $K = \left(V_P / V_S \right)$

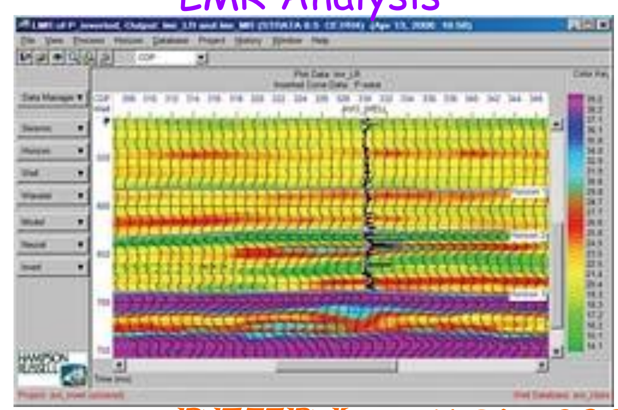
2D interpreted seismic section



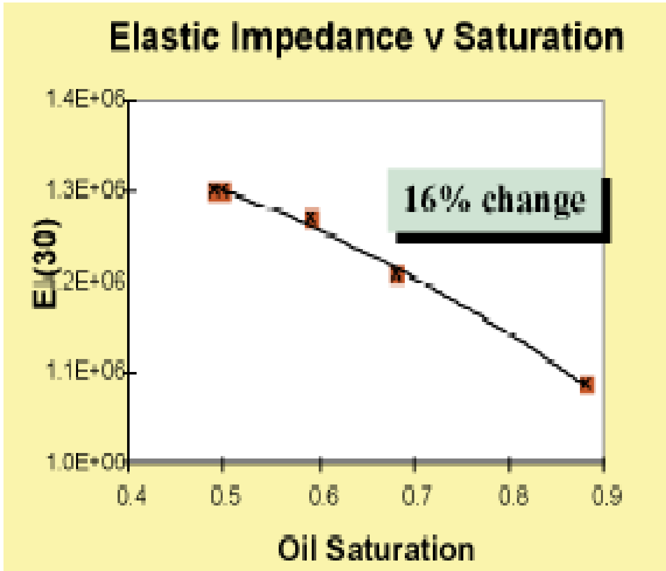
Elastic Impedance

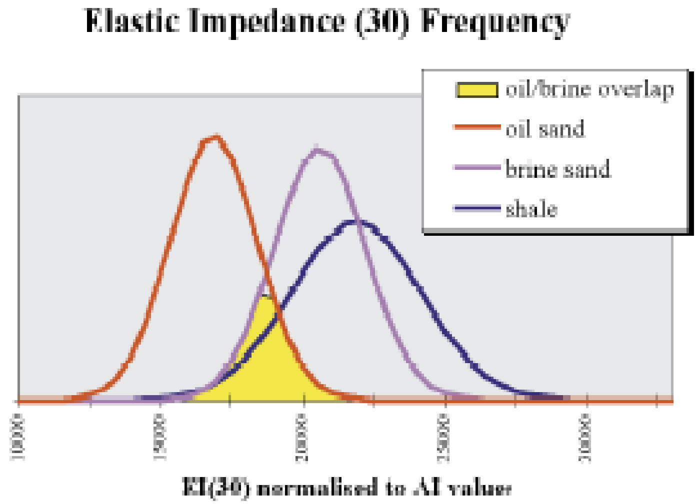


LMR Analysis

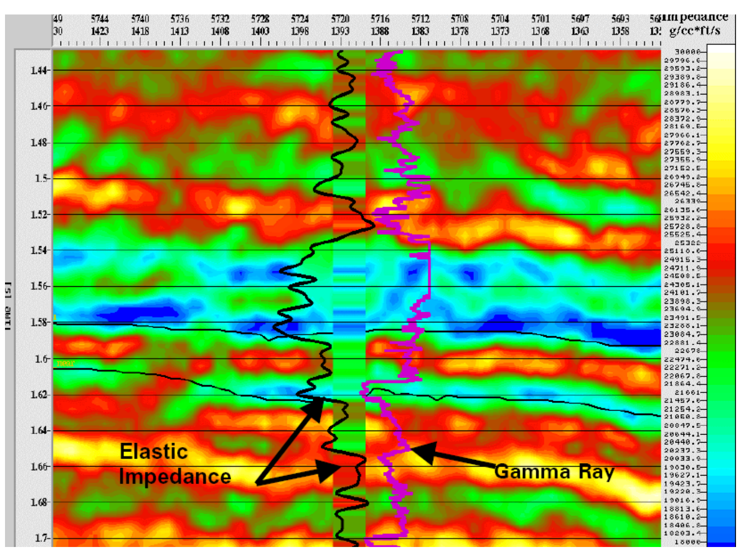


REFLECTION SEISMIC: AVO INVERSION





Connolly, 1999



Savic et al, 2000

Very Low values of Elastic Impedance → Gas saturation

REFLECTION SEISMIC: AVO INVERSION

Lambda-Mu-Rho (LMR) inversion

λ & μ are elastic constants

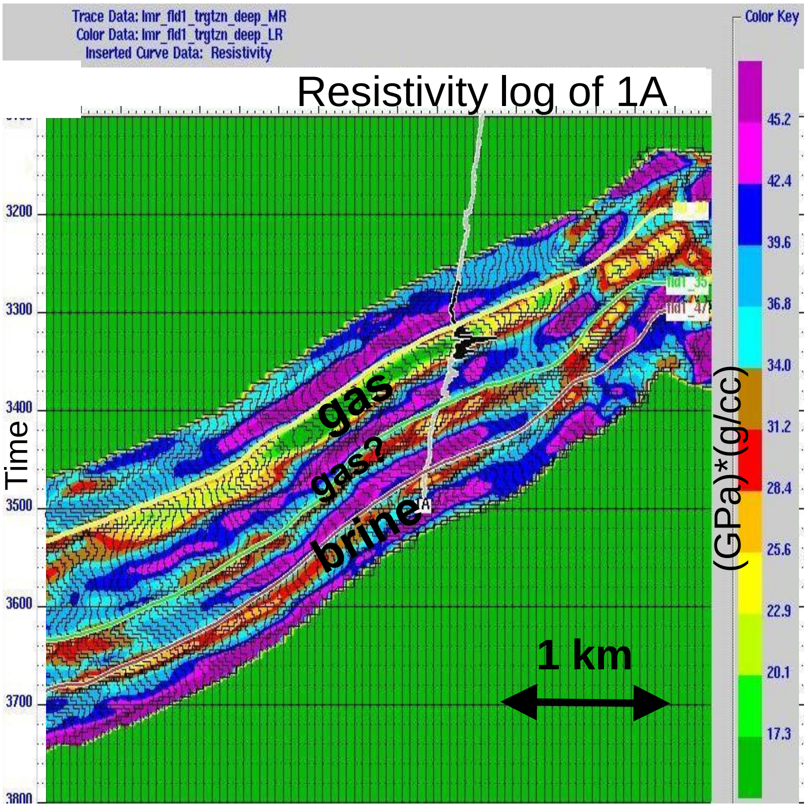
λ = fluid incompressibility is in theory affected only by the type of fluid in the pore space ➔ **Low λ suggests gas saturation**

μ = rigidity is in theory affected only by the type of matrix ➔ **High μ suggests hard compact materials**

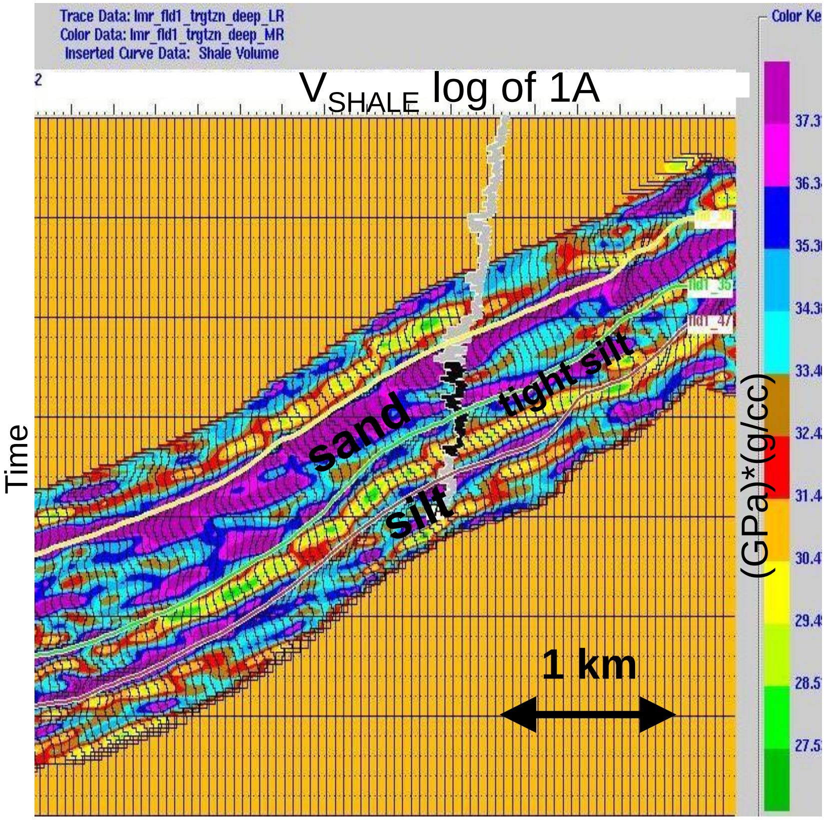
Low λ + High μ ➔ Gas Sand

REFLECTION SEISMIC: AVO INVERSION

$\lambda\rho$
fluid indicator
(LR)



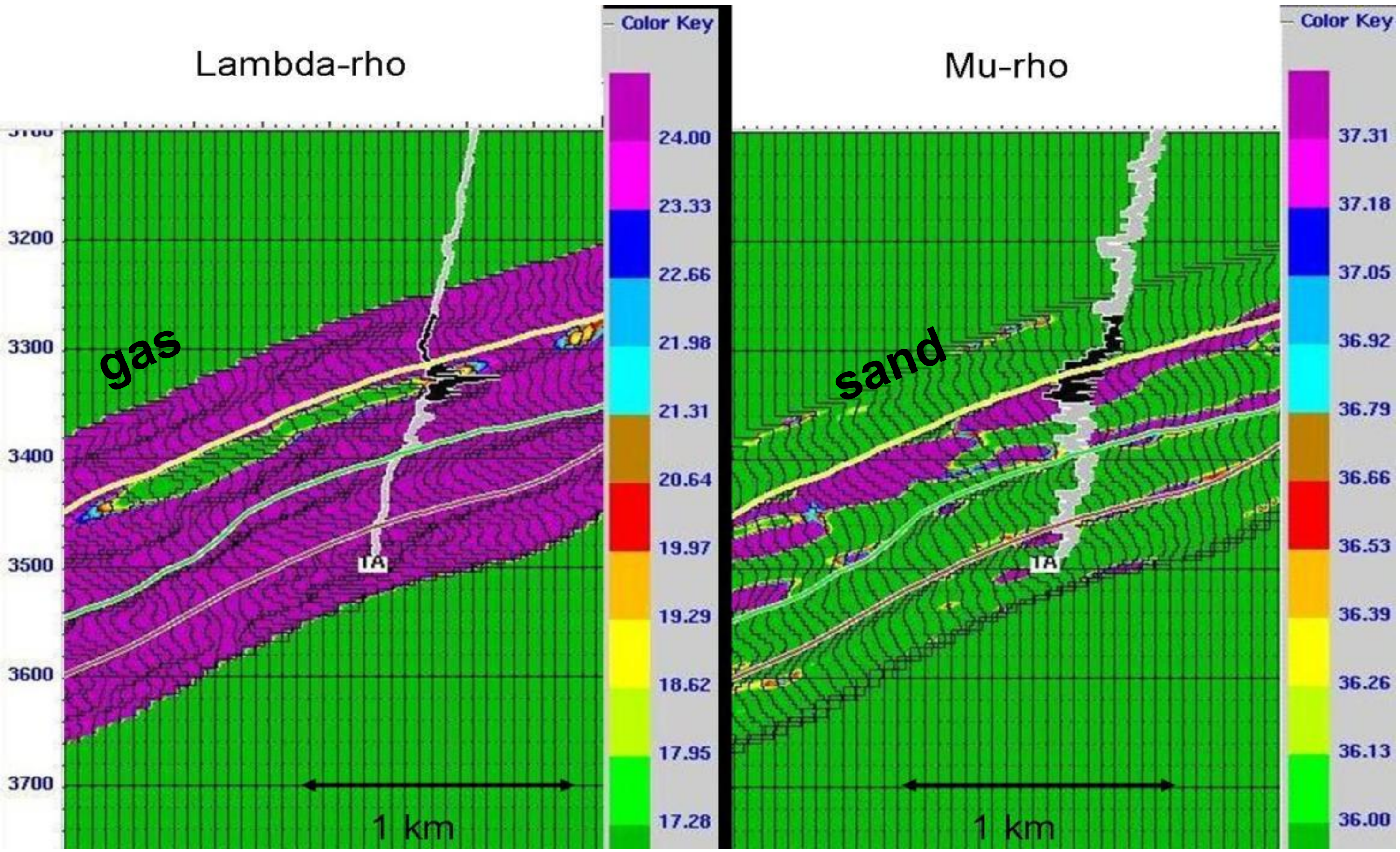
$\mu\rho$
matrix indicator
(MR)



REFLECTION SEISMIC: AVO INVERSION

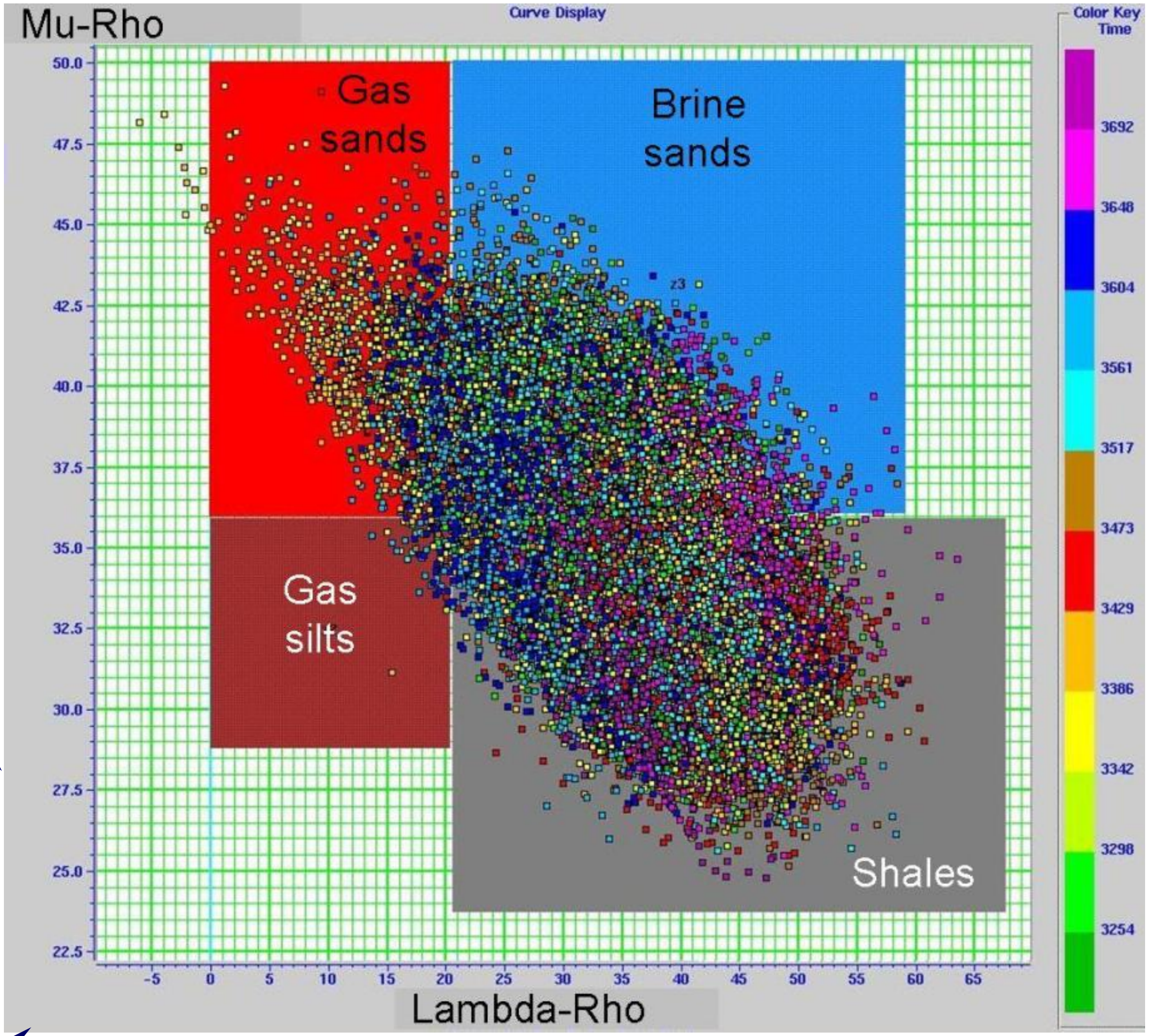
λρ
fluid indicator
(LR)

μρ
matrix indicator
(MR)



REFLECTION SEISMIC: AVO INVERSION

LMR crossplot

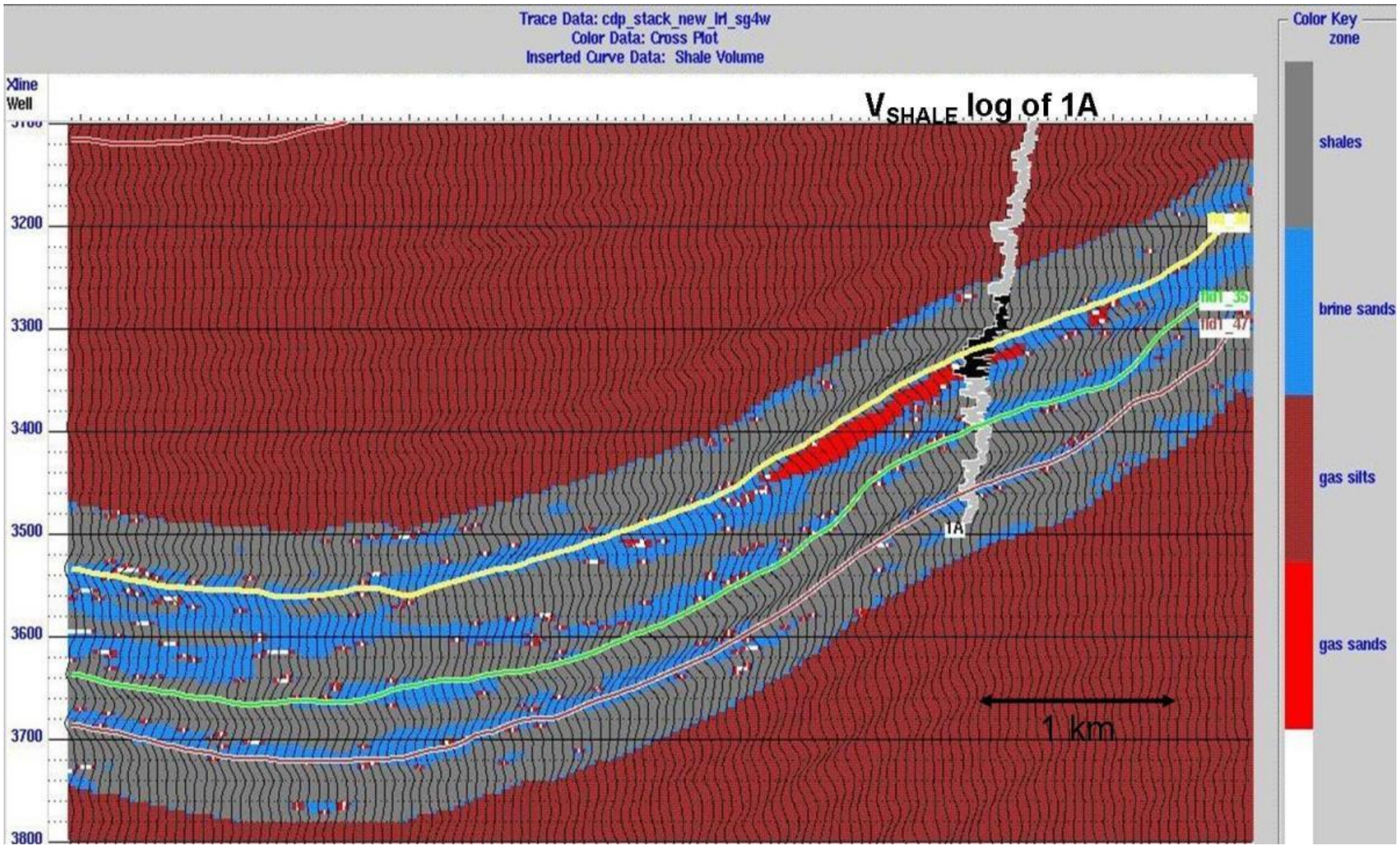


Sand will have high rigidity

Gas will have low fluid incompressibility

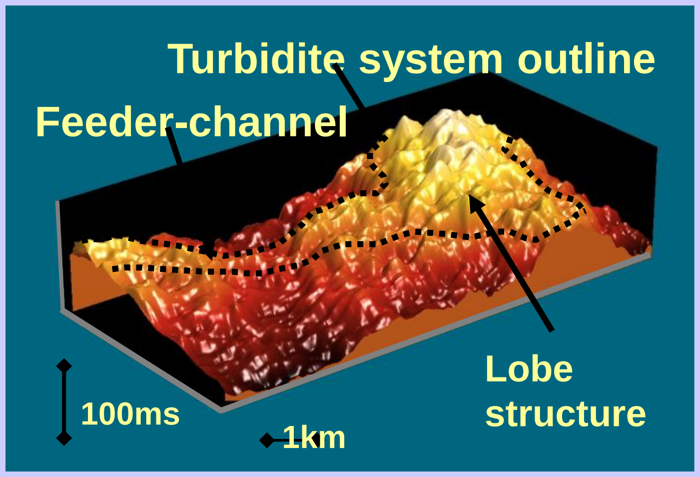
REFLECTION SEISMIC: AVO INVERSION

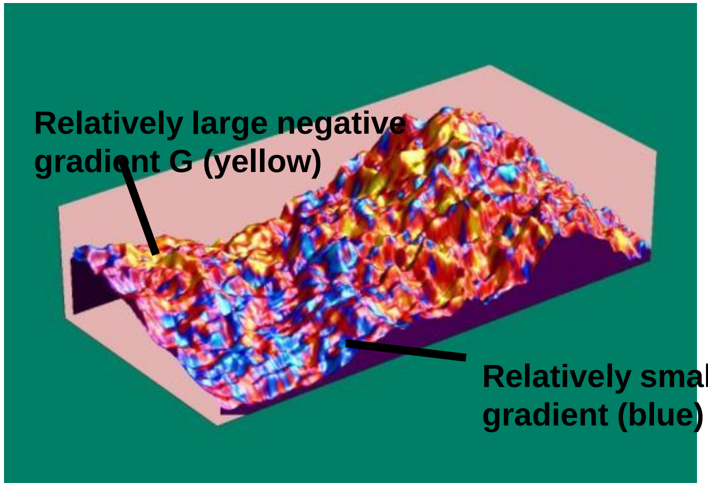
Rock and Fluid probability

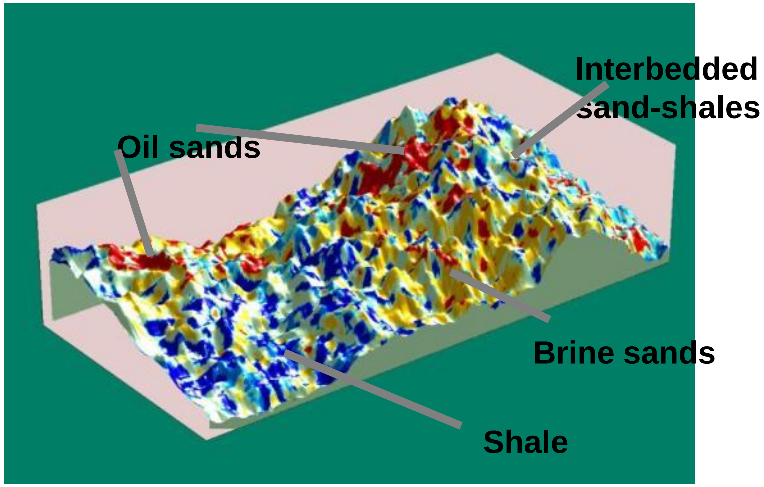


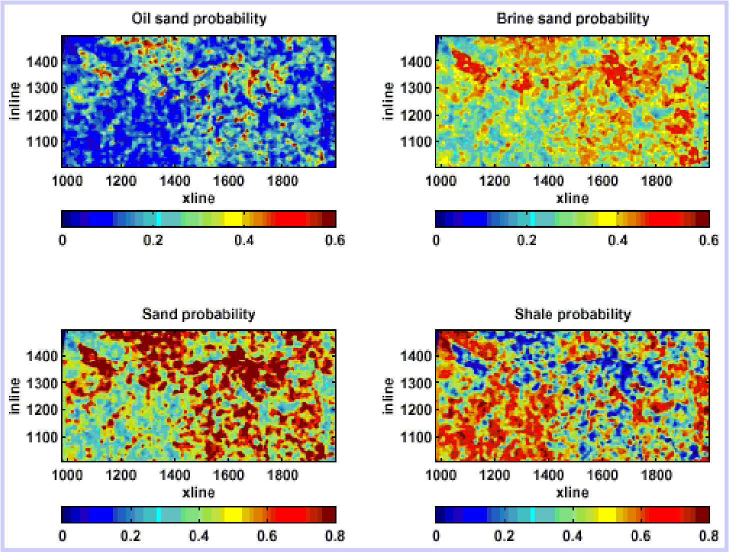
REFLECTION SEISMIC: AVO INVERSION

3-D seismic Facies and Fluid probability







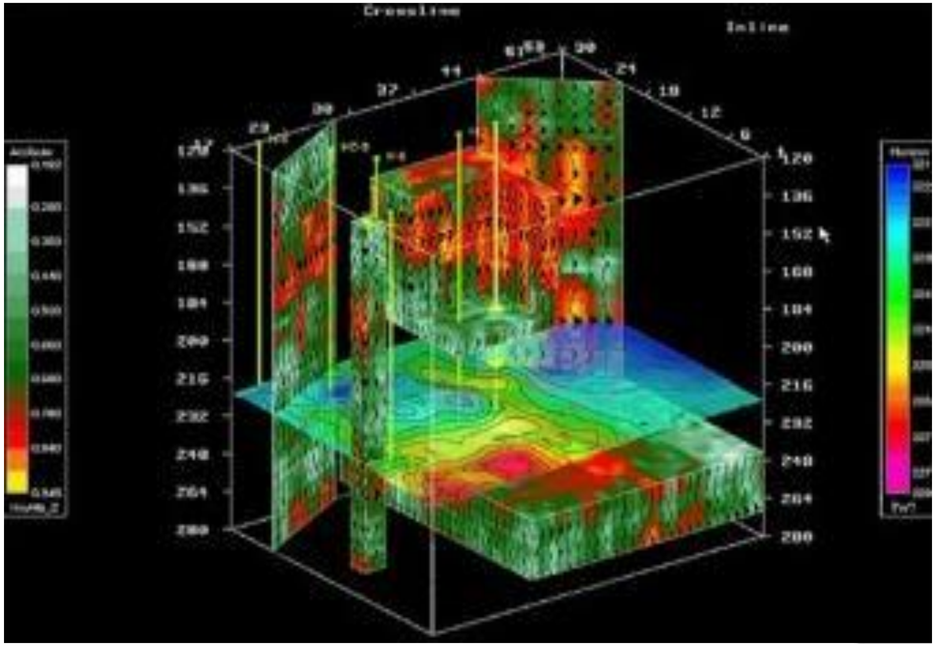


REFLECTION SEISMIC: AVA

Amplitude Vs. Azimuth

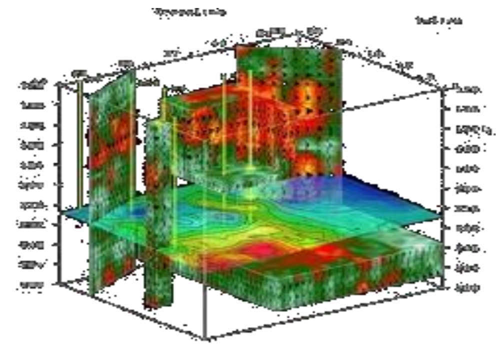
In general AMPLITUDE VARIATIONS (anisotropy)
+ local velocity variations (heterogeneity)
+ Discontinuity trend
+ Density variations
+ Anisotropy of secondary porosity/permeability ➔ Unhomogeneous fluid distribution/saturation

Similar techniques as for the AVO analysis, but MORE UNCERTAINTIES And 3D dense data are required

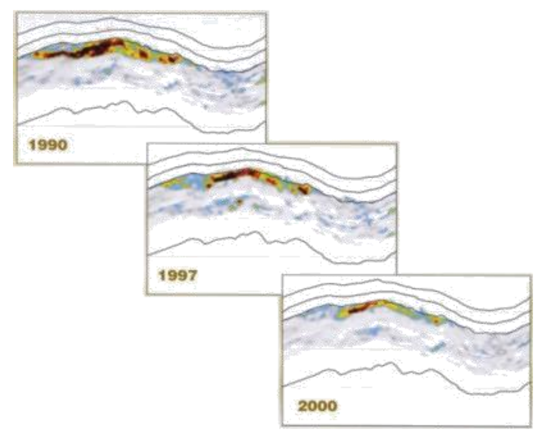


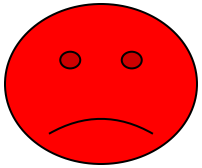
AVO: PROS

- Qualitative AND QUANTITATIVE data



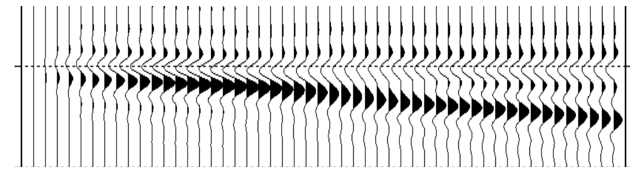
- Volumetric info (extrapolation of log data)
- No needs for new data acquisition, reprocessing of old datasets
- Specific rock (matrix) and Fluid indicators
- Possible 4D analyses



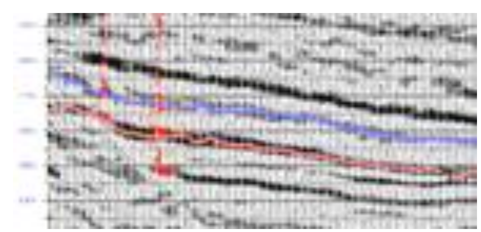


AVO: LIMITS

- ✓ Tuning and thin-bed effects



- ✓ Noise and processing effects
- ✓ Lateral velocity trends in overburden
- ✓ Needs for validation (logs, wells, …)
- ✓ Site dependent results
- ✓ Representative statistics?
- ✓ Supervised seismic interpretation



DOMANDE?