Velocity modeling to determine pore aspect ratios of the Haynesville Shale

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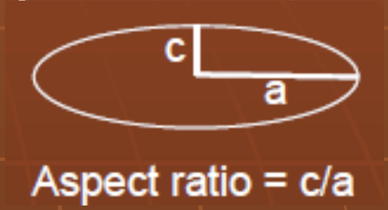
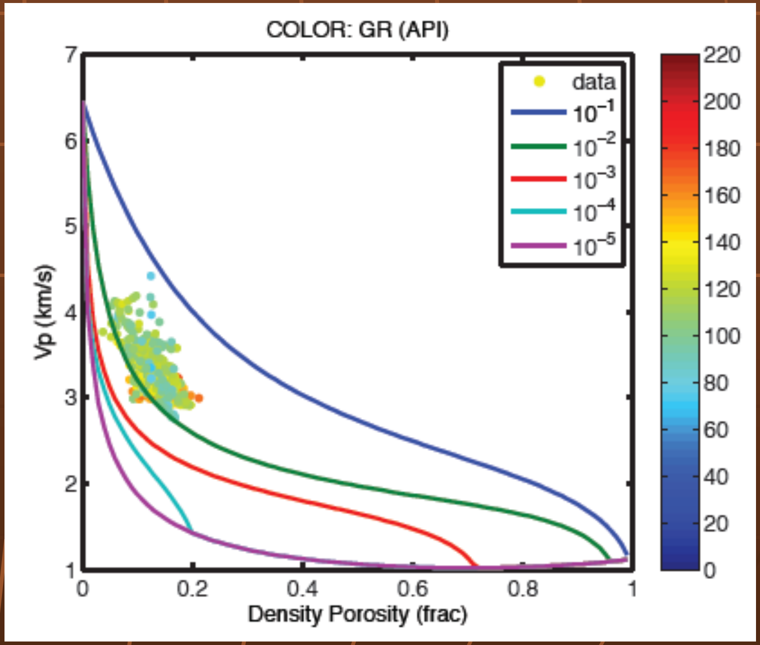
Motivation

The Haynesville Shale have penny-shaped pores (Low aspect ratio)(Curtis et al., 2010).



The pore shape of the formation
- closely related to pore stiffness and rock stiffness

Purpose of modeling :
- determine pore aspect ratios by comparing the modeled velocities to the upscaled velocities (P-wave)



(Jiang and Spikes, 2011)

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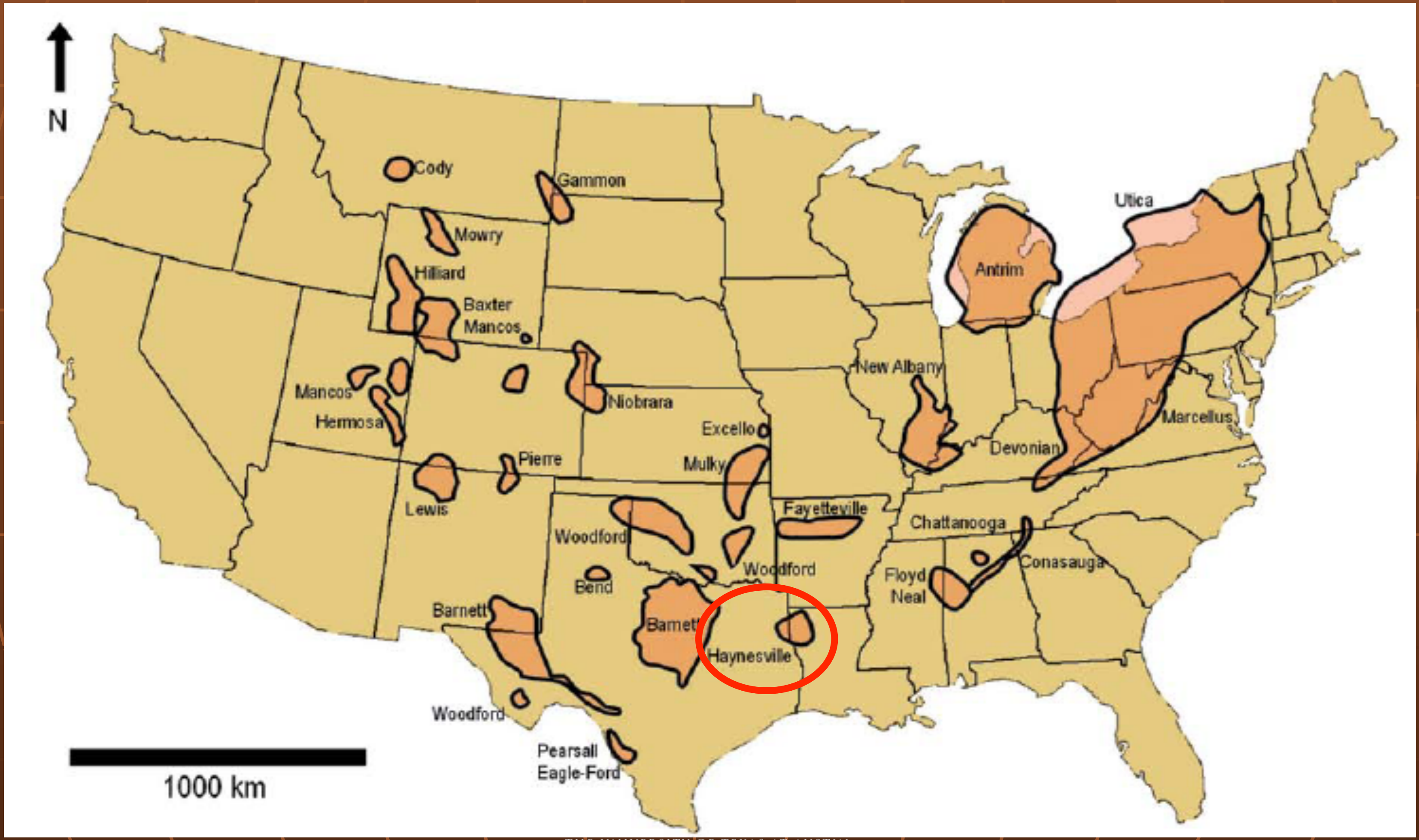
1. Introduction

USA gas shale plays



(Horne et al., 2012)

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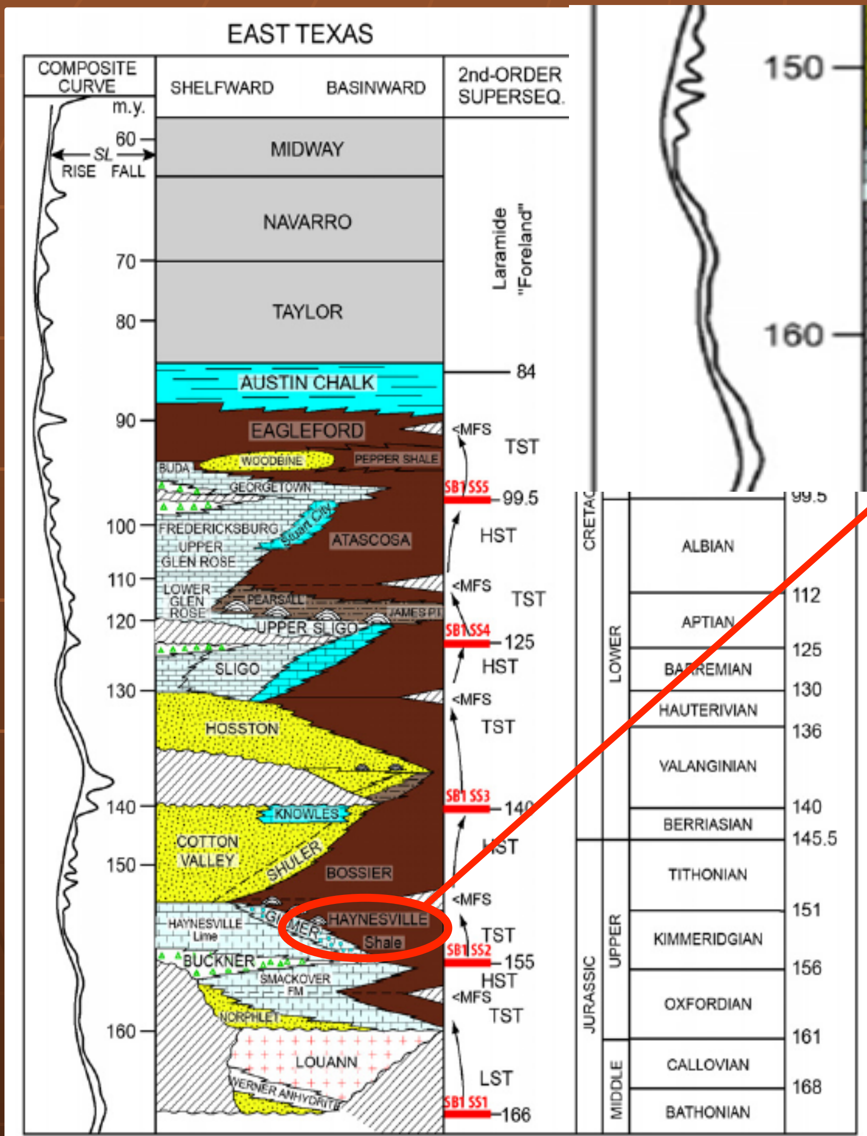
- Located in northwest Louisiana and East Texas

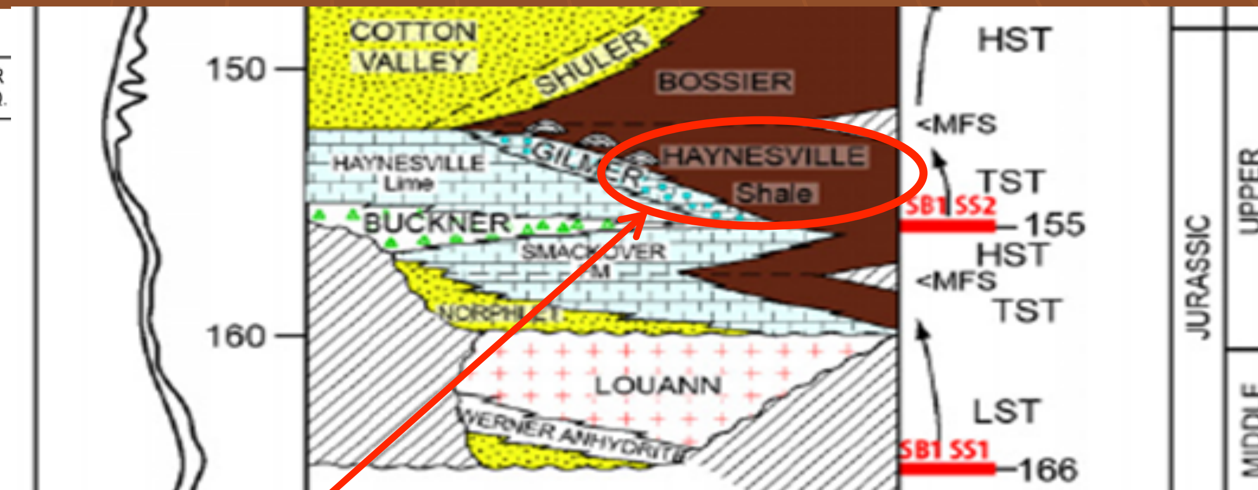
- Lying approximately 10,000 to 13,000 feet sub-surface

- A rock formation containing oil and gas and an important shale-gas resource play

- Total reserves : 100 Tcf
- Production : about 2 Bcf/d (Hammes et al. 2011)

Sequence Stratigraphy





- Deposited about 150 million years ago in a shallow offshore environment.

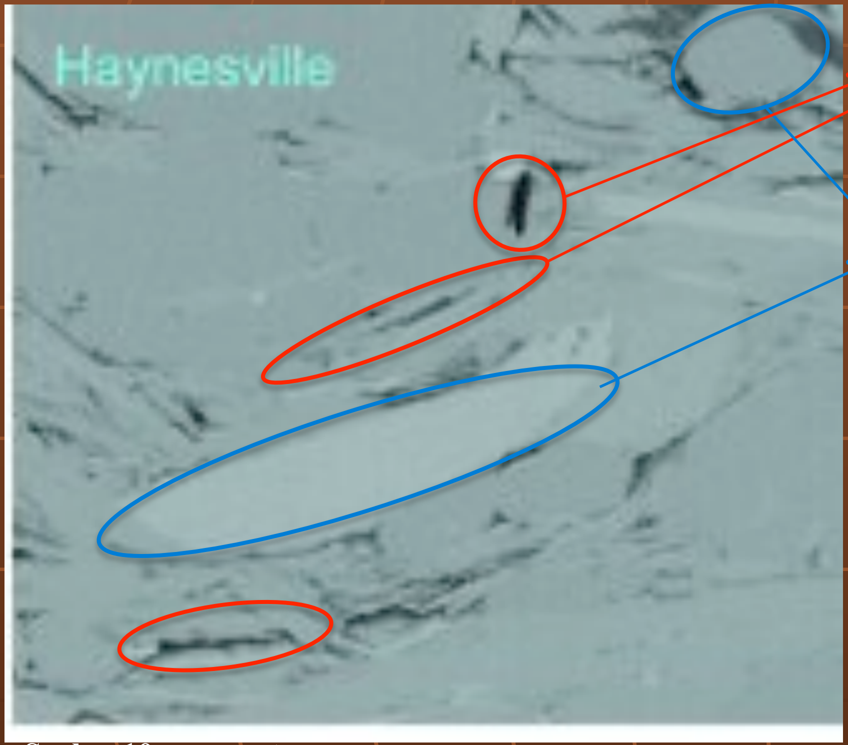
- Black, organic-rich shale of Upper Jurassic

- Marine transgressive to highstand mudrocks within mixed carbonate-clastic depositional systems

(Goldhammer and Johnson, 2001)

A Micro-structural Image

Nano-scale image



Scale : 10 nanometer

(Modified from Curtis et al, 2010)

- Dark is organic material (solid) inside pore.

- Light gray is matrix or grain.

- Most pore shapes are flat (crack-like) : (low aspect ratio).

- Variable grain shapes

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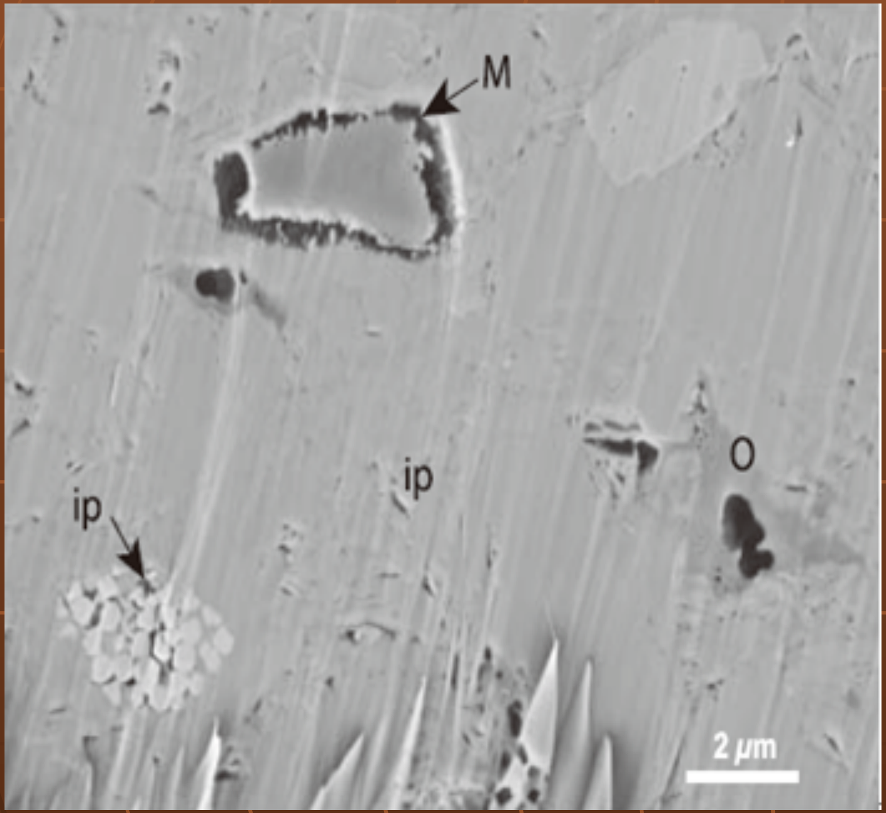
SEM image



(Hammes et al., 2011)

On the middle right (O)
- Numerous nano-scale pores and one μm-scale pore including organic material .

At the lower left (ip)
- Inter-crystalline pores between pyrite framboid crystals.

In the top center (M)
- Moldic pores between organic matter and mineral grain.

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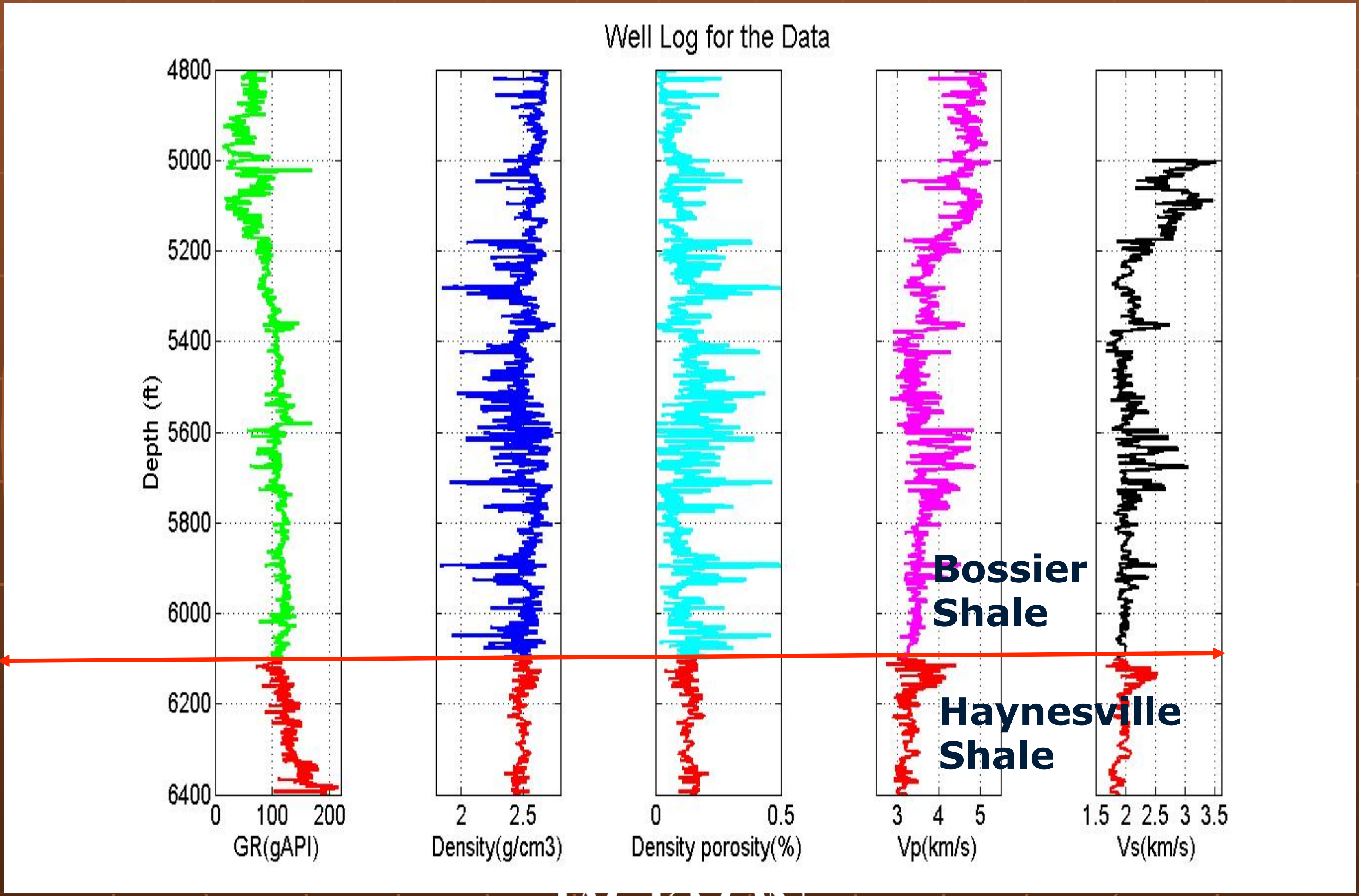
Well Log Data



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2. Theory

1)Effective media theory - Backus Average

λ : the wavelength, d : the layer thickness

When $\lambda / d >> 1$, the wave velocity is given by an average of the individual layers (Backus, 1962).

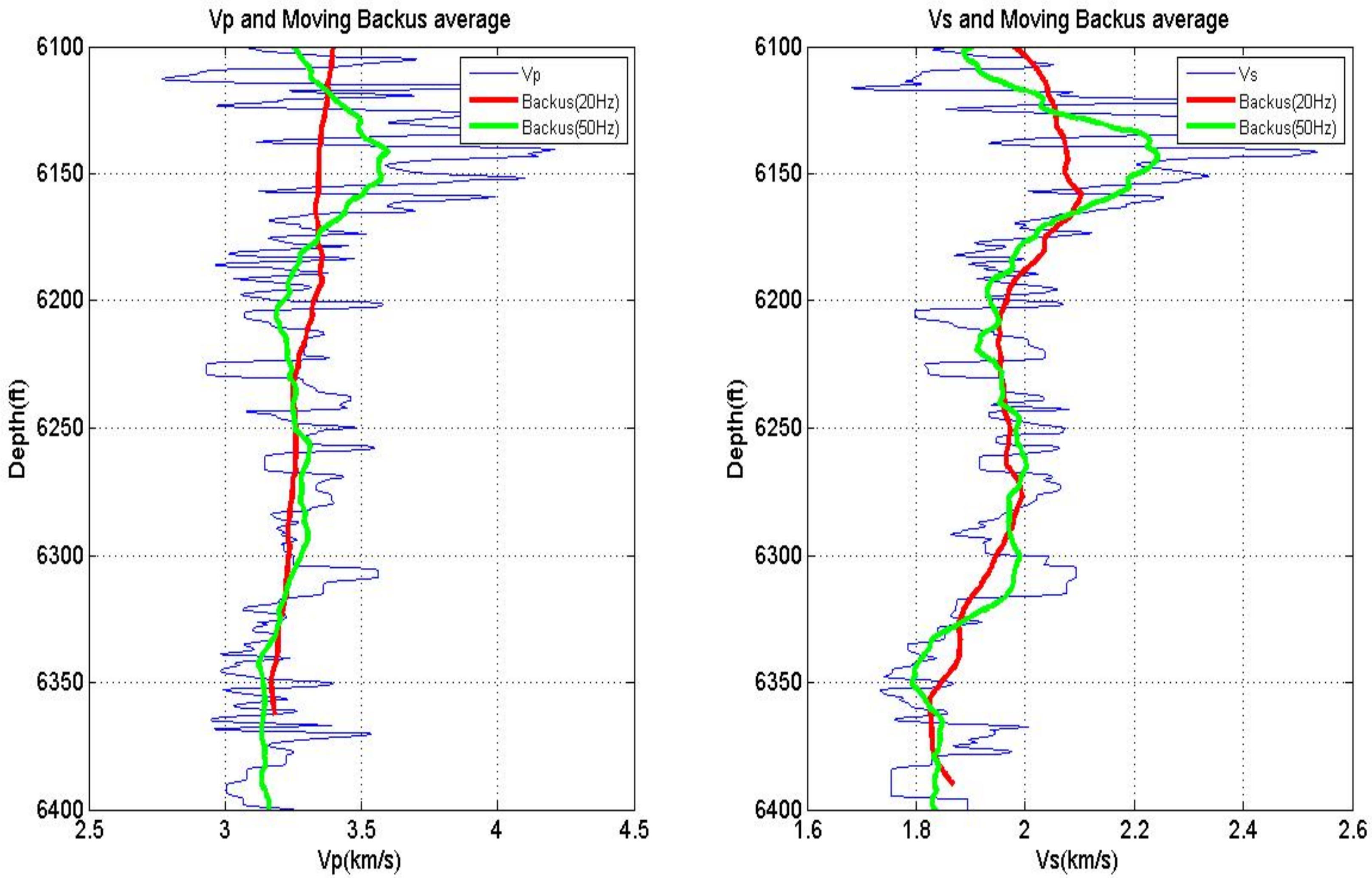
For normal incidence propagation

$$V_{EMT} = (M_{EMT}/\rho_{ave})^{1/2} \quad (V_{EMT}\text{: Backus average velocity})$$

$$M_{EMT} = \left[\sum_{k} f_k / M_k\right]^{-1} \quad \text{or} \quad 1/\rho_{ave} V_{EMT}^{2} = \sum_{k} f_k$$

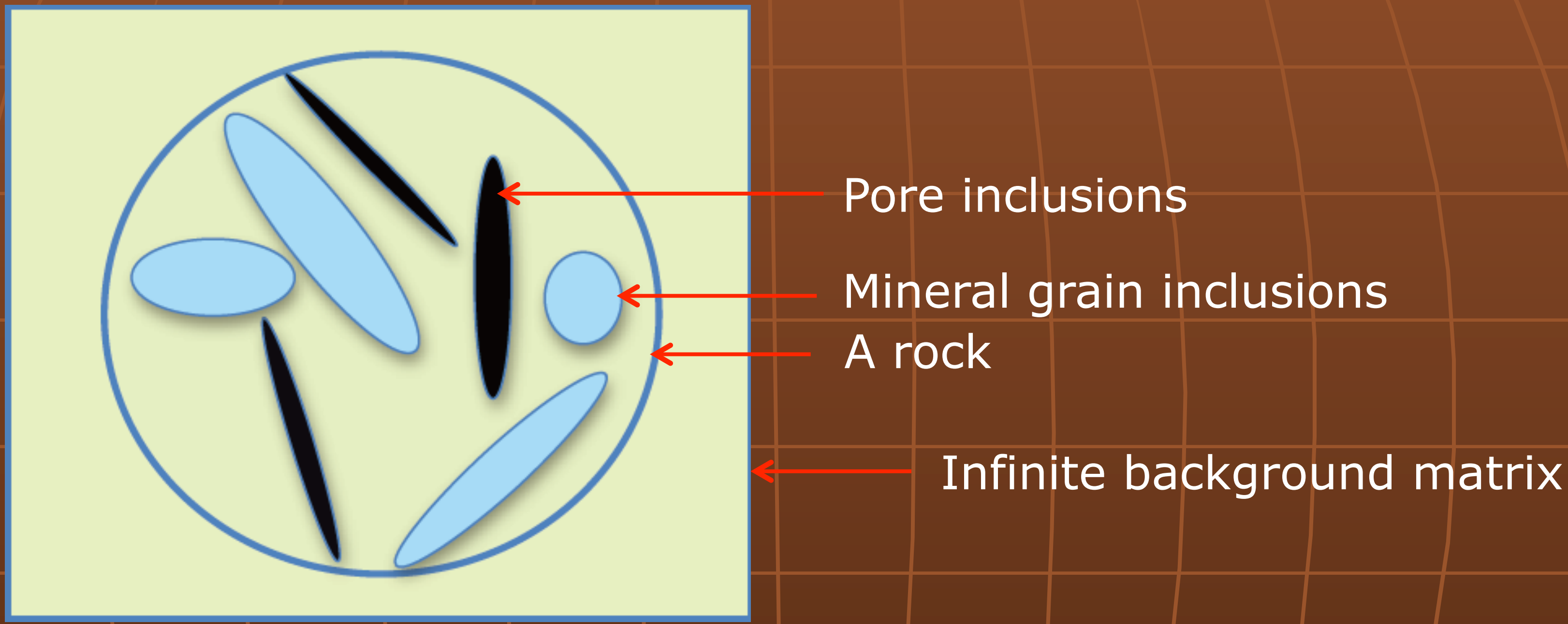
$$\rho_{ave} = \sum_{k} f_k \rho_k$$

Backus Average(Vp, Vs)



2) Self-Consistent Model

Schematic diagram of the self-consistent model



(Jiang and Spikes, 2011)

The elastic moduli of the rock depend on the elastic properties of the grain inclusions and pore inclusions.

Berryman (1980b, 1995) gives a general form of the self-consistent approximations for N-phase composites:

$$\sum_{i=1}^{N} x_i \left(K_i - K_{SC}^{*}\right) P^{*i} = 0$$

$$\sum_{i=1}^{N} x_i \left(\mu_i - \mu_{SC}^{*}\right) Q^{*i} = 0$$

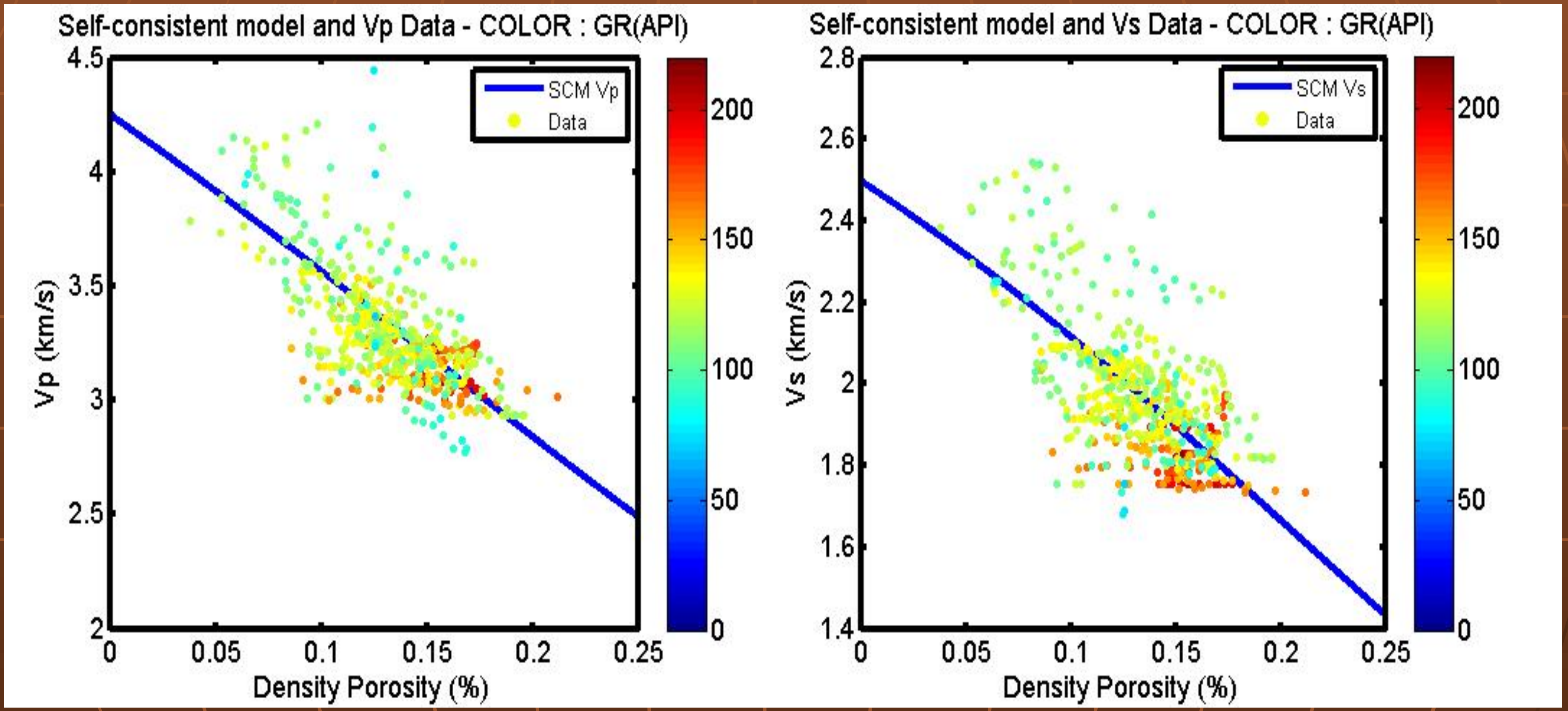
(Mavko et al., 2009)

Where i : i^{th} material, x_i : its volume fraction, P and Q : geometric factors. K^*_{SC} and u^*_{SC} : self-consistent effective moduli.

Advantages

Not limited to specific compositions and are able to model multiple mineralogical phases, as well as their shapes

Self-consistent modeling results



Aspect ratio: $N(0.145, 0.01^2)$
Average composition (XRD)

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3) Gassmann fluid substitution

Gassmann fluid substitution allows us to obtain the bulk and shear moduli of the fluid-saturated rock from the dry rock mineral moduli, porosity, and fluid moduli.

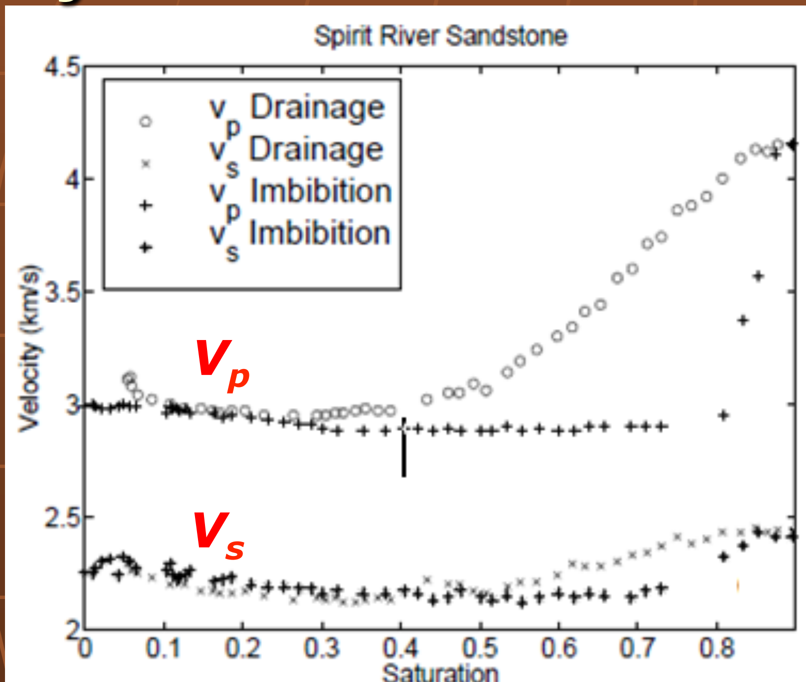
Gassmann (1951) provided this general relation between the dry rock and saturated-rock moduli.

$$\frac{K_2}{K_{min}-K_2} - \frac{K_{fl2}}{\varphi(K_{min}-K_{fl2})} = \frac{K_1}{K_{min}-K_1} - \frac{K_{fl1}}{\varphi(K_{min}-K_{fl1})}$$

$$\frac{K_{sat}}{K_{min}-K_{sat}} = \frac{K_{dry}}{K_{min}-K_{dry}} + \frac{K_{fluid}}{\varphi(K_{min}-K_{fluid})}, \quad \frac{1}{\mu_{sat}} = \frac{1}{\mu_{dry}}$$

4) Partial saturation

hysteresis effect



(Berryman et al., 1999)

Elastic velocities can be significantly affected by the pore-scale mixing of fluids.

Patchy saturation : Drainage

$$K_{fl}=\sum S_i K_i$$

(upper bounds)

Uniform saturation : Imbibition

$$1/K_{fl}=\sum (S_i/K_i)$$

(lower bounds)

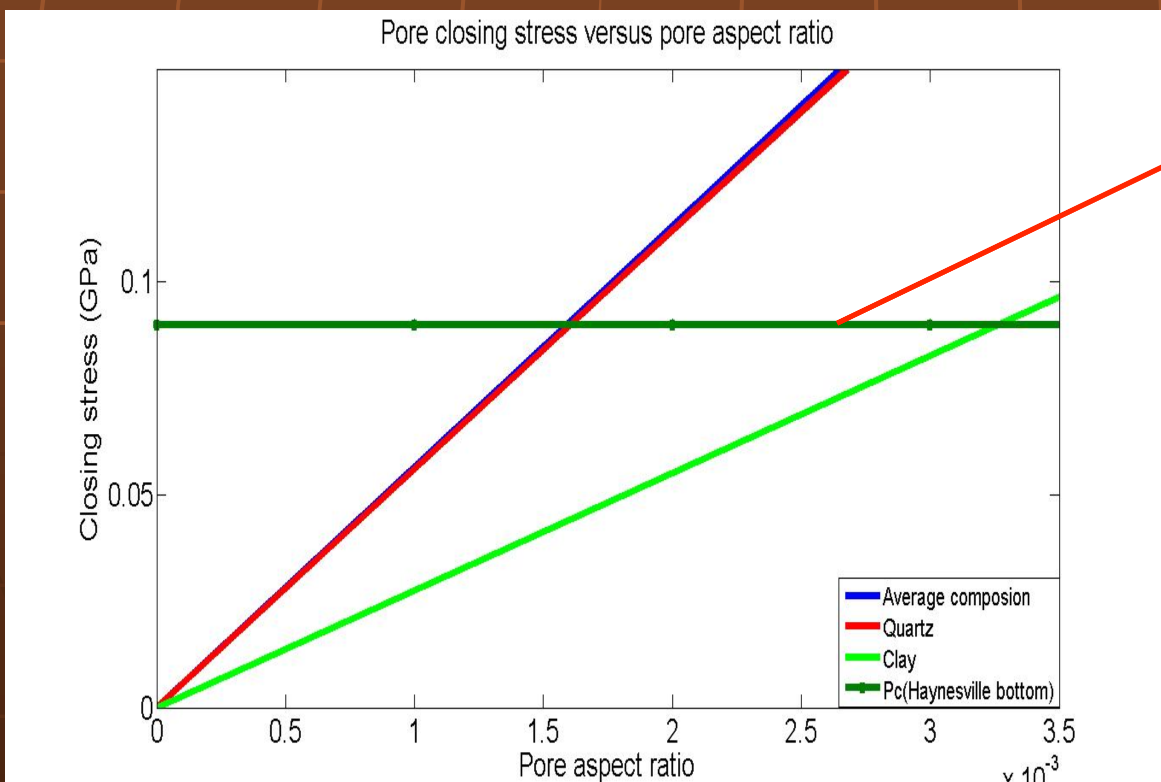
Patchy saturation is always higher velocities than Uniform saturation. (Mavko and Mukerji, 1998)

5) Closing stress

The closing stress of the pores (Mavko et al., 2009).

$$\sigma_{close} = \frac{3\pi(1-2\nu_0)}{4(1-\nu_0^2)}\alpha K_0$$

ν_0 : Poisson's ratio of the matrix
K_0 : bulk modulus of the matrix
α : pore aspect ratio



P_c : 85 - 90 MPa

Pore aspect ratio (α) which closes the pore

- Average composition & Quartz (0.0015 to 0.0016)

- Clay (0.0035)

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3. Modeling methodology (20Hz, 50 Hz)

Self-consistent model

Input(1) : composition data

Input(2) : fluid property

Estimate : *a(aspect ratio)*

Output : K^*_{SC} μ^*_{SC} V_{p_scm} V_{s_scm}

Difference < 0.5% V_{p_scm} - V_{p_BA}

No — Iteration

Yes

Determine : a K^*_{SC} μ^*_{SC} V_{p_scm} V_{s_scm}

Backus Average

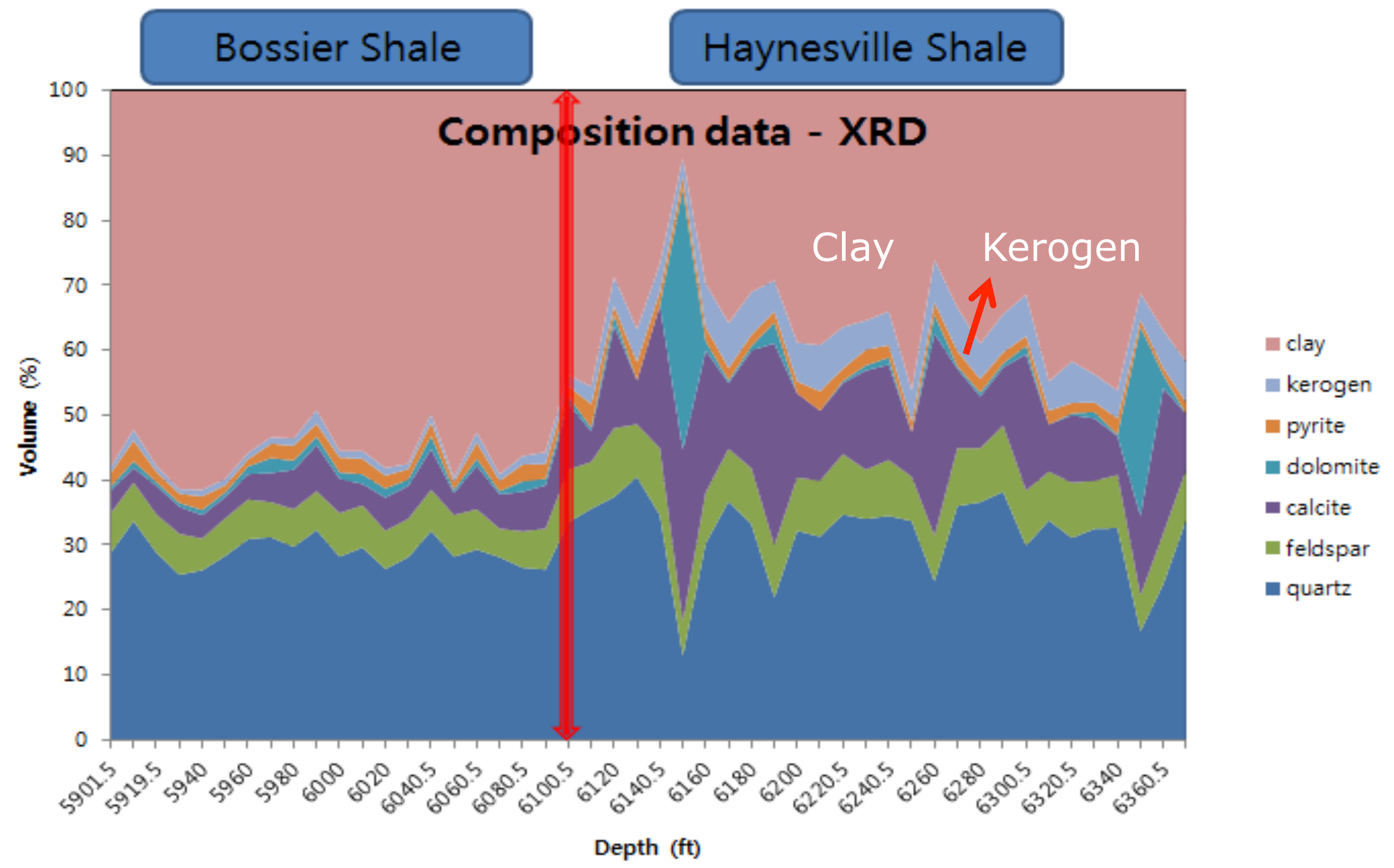
Well log data

Upscaling : **Moving Backus Average**

Output : V_{p_BA} V_{s_BA} ρ_{MA}

- Input(1) : Composition data
  - XRD data
  - Interpolated data
- Input(2) : Fluid property
  - Fixed (K:1 GPa, ρ: 0.8 g/cc)
  - Dry pores
  - Patchy saturation
  - Uniform saturation

Composition data



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4. Results of velocity modeling

1) Pore aspect ratios for fixed fluid properties
2) Effect of fluid property changes to velocities
3) Pore aspect ratios for various fluid properties

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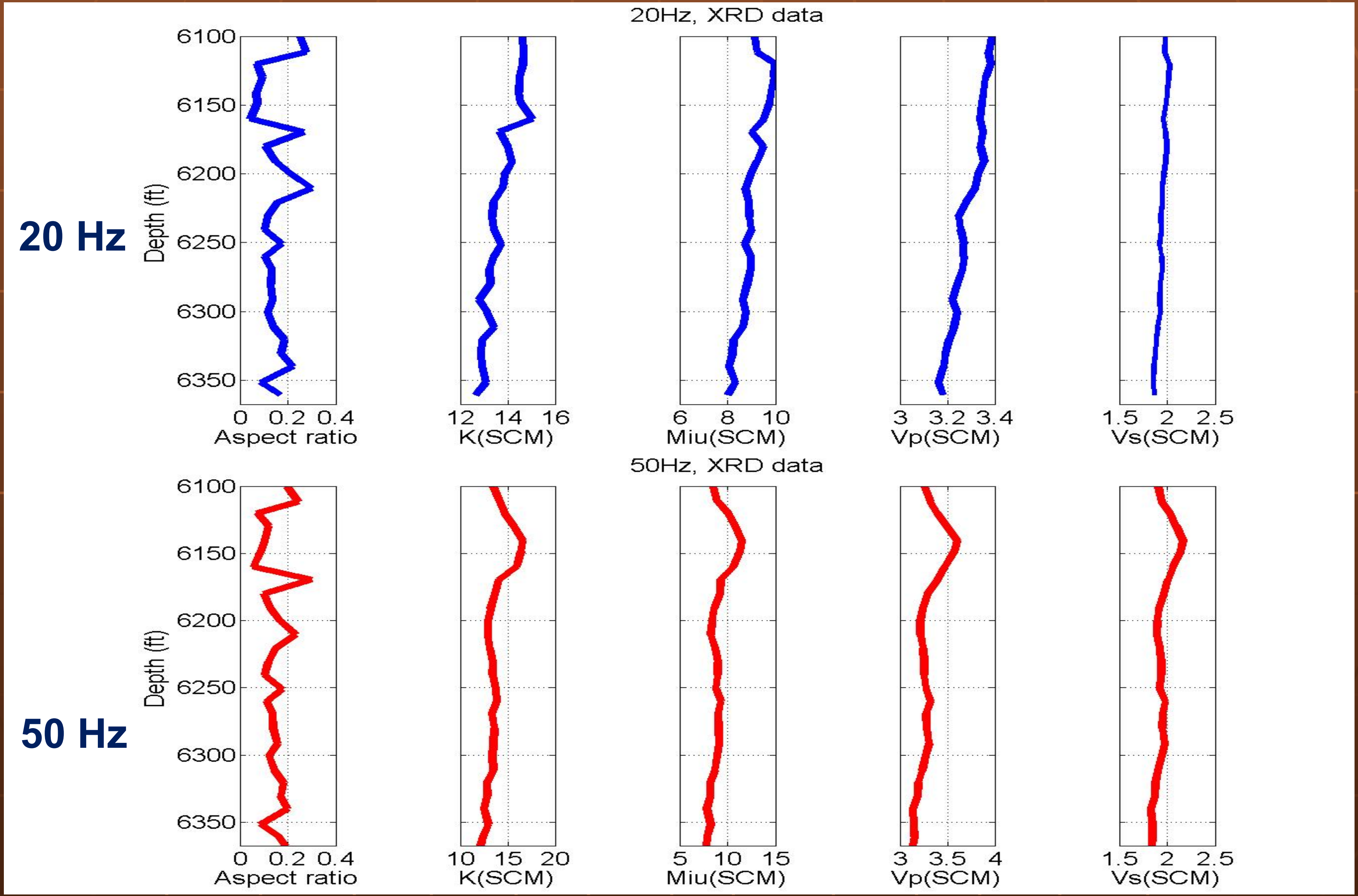
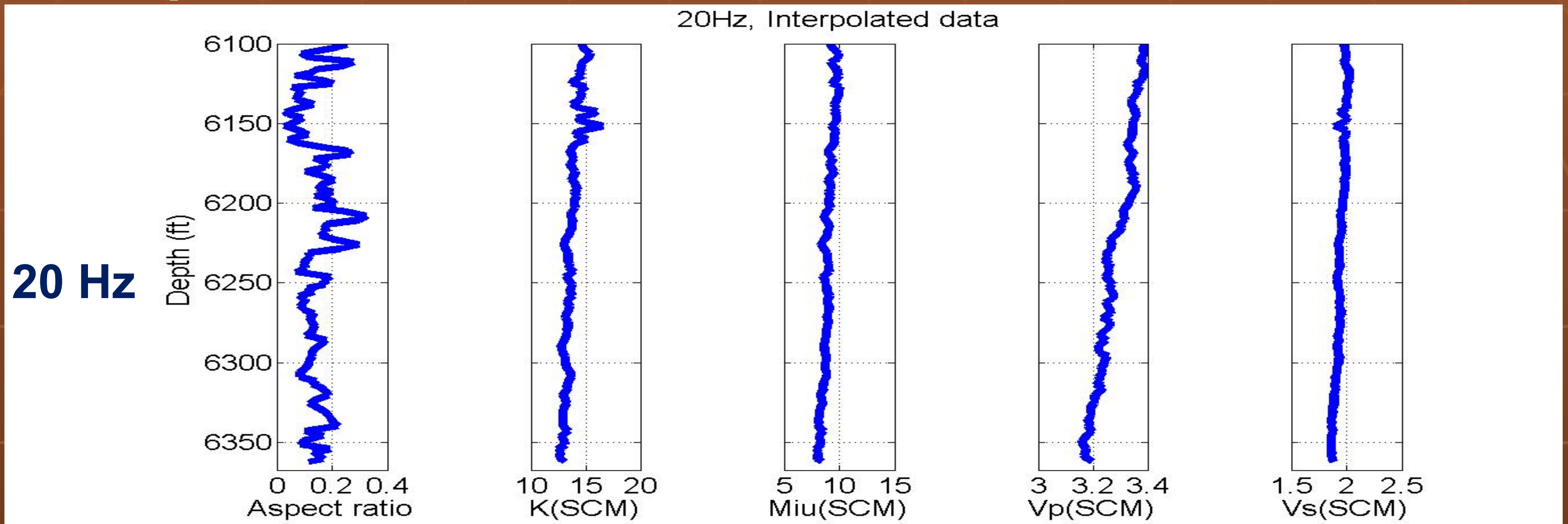
1) Pore aspect ratios for fixed fluid properties

- XRD data (Fluid properties - *K:1 GPa, ρ: 0.8 g/cc)*



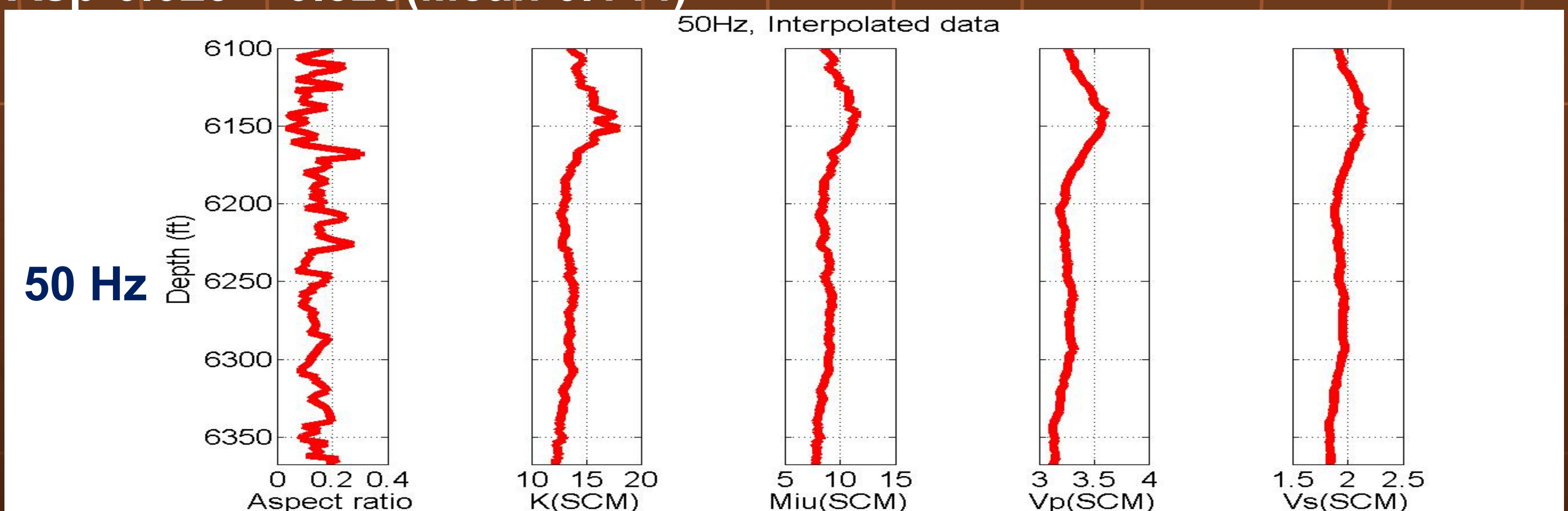
- Interpolated data (Fluid properties - *K:1 GPa, ρ: 0.8 g/cc)*

20 Hz



Asp 0.029 – 0.320(Mean 0.144)

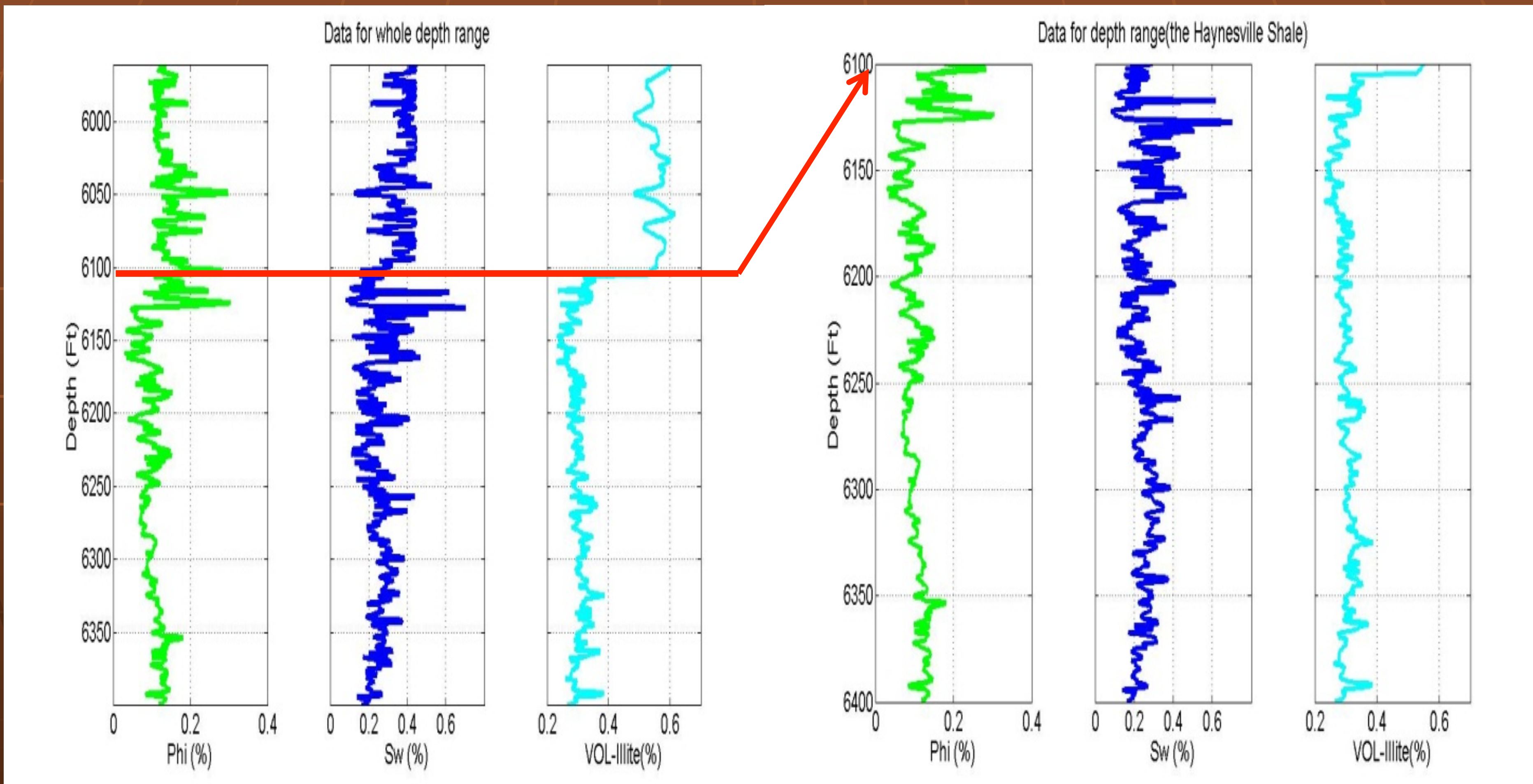
50 Hz



Asp 0.035 – 0.298(Mean 0.143)

2) Effect of fluid property changes to velocities

(Well-log data for porosity, S_w, V_{illite})



Sw: 0.082 to 0.702
(Mean 0.246)

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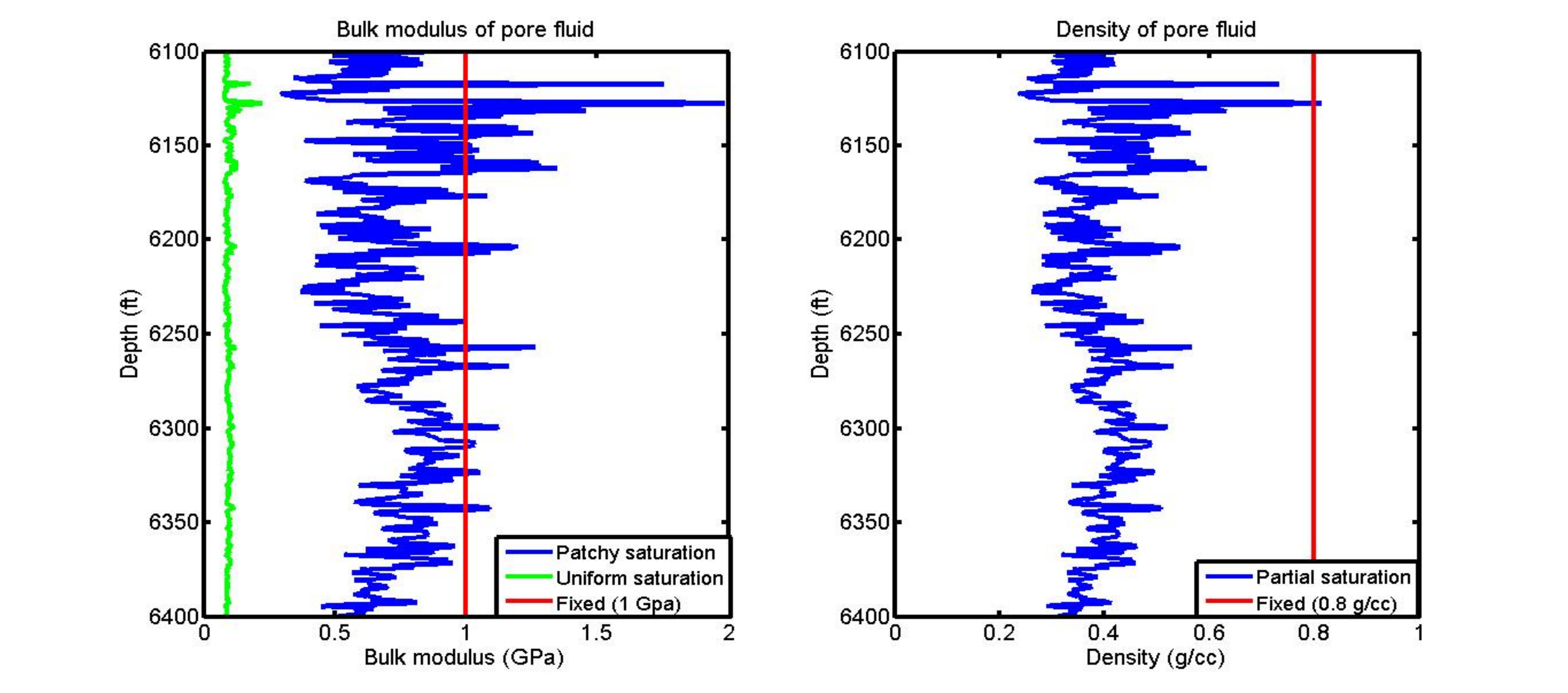
1) Patchy saturation and uniform saturation



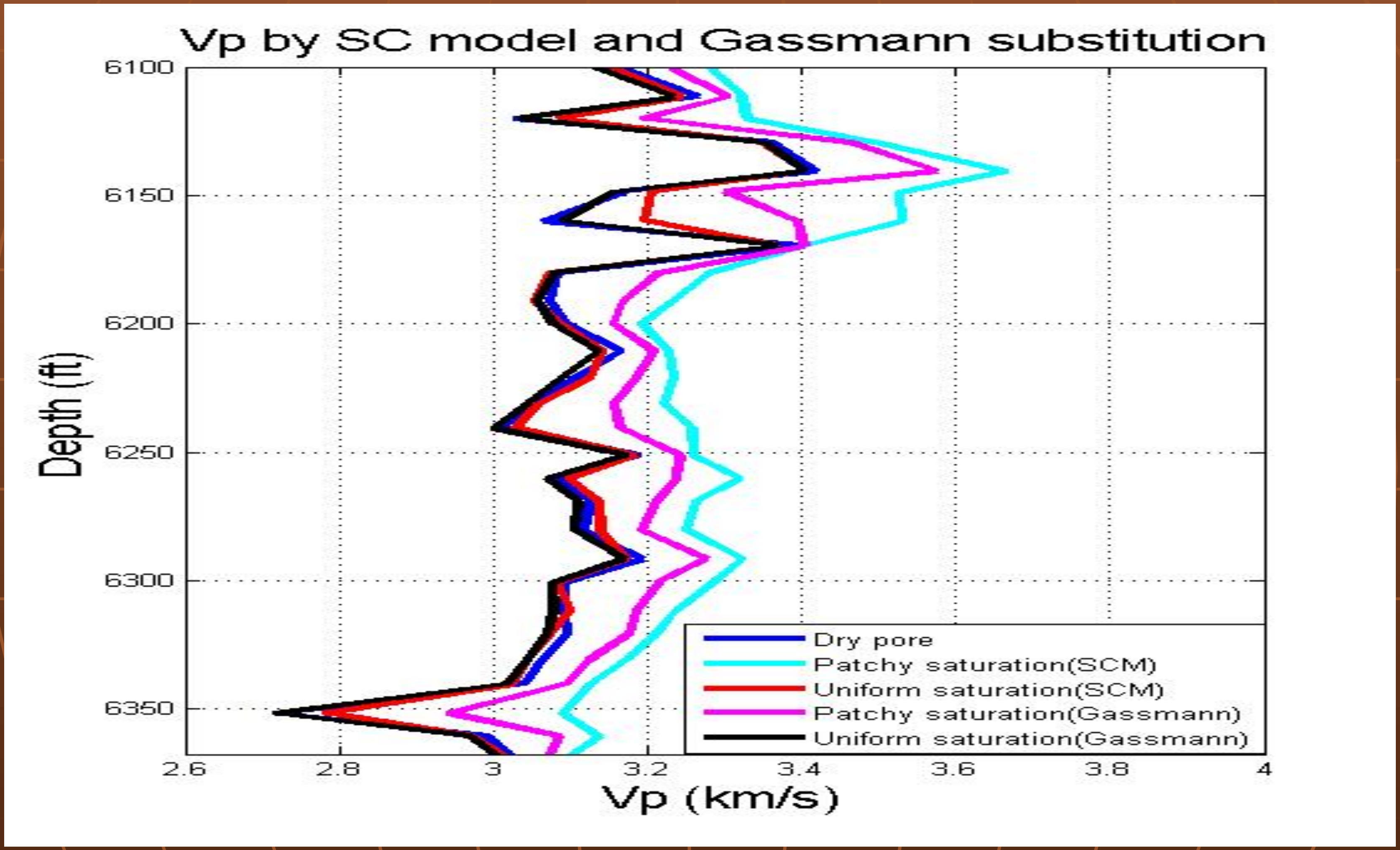
Pore fluid	Fixed	Patchy saturation			Uniform saturation		
		Max	Mean	Min	Max	Mean	Min
Bulk modulus (Gpa)	1	1.9866	0.7421	0.2936	0.2219	0.0932	0.0761
Density (g/cc)	0.8	0.8129	0.3889	0.2362	0.8129	0.3889	0.2362

2) Cases to be considered

The effect of pore fluid properties were analyzed by comparing calculated Vp.

- self-consistent model
  - dry pores
  - patchy saturation
  - uniform saturation cases
- Gassmann fluid substitution
  - patchy saturation
  - uniform saturation cases

3) Velocity comparison (P-wave)



$V_{p\_patchy\_SCM} > V_{p\_patchy\_Gassmann} > V_{p\_uniform\_SCM} > V_{p\_dry} > V_{p\_Uniform\_Gassmann}$

3) Pore aspect ratios for various fluid properties

The effect of pore fluid properties to determine pore aspect ratios by velocity modeling were analyzed.

- self-consistent model
  - dry pores
  - patchy saturation
  - uniform saturation cases
- Gassmann fluid substitution
  - patchy saturation
  - uniform saturation cases

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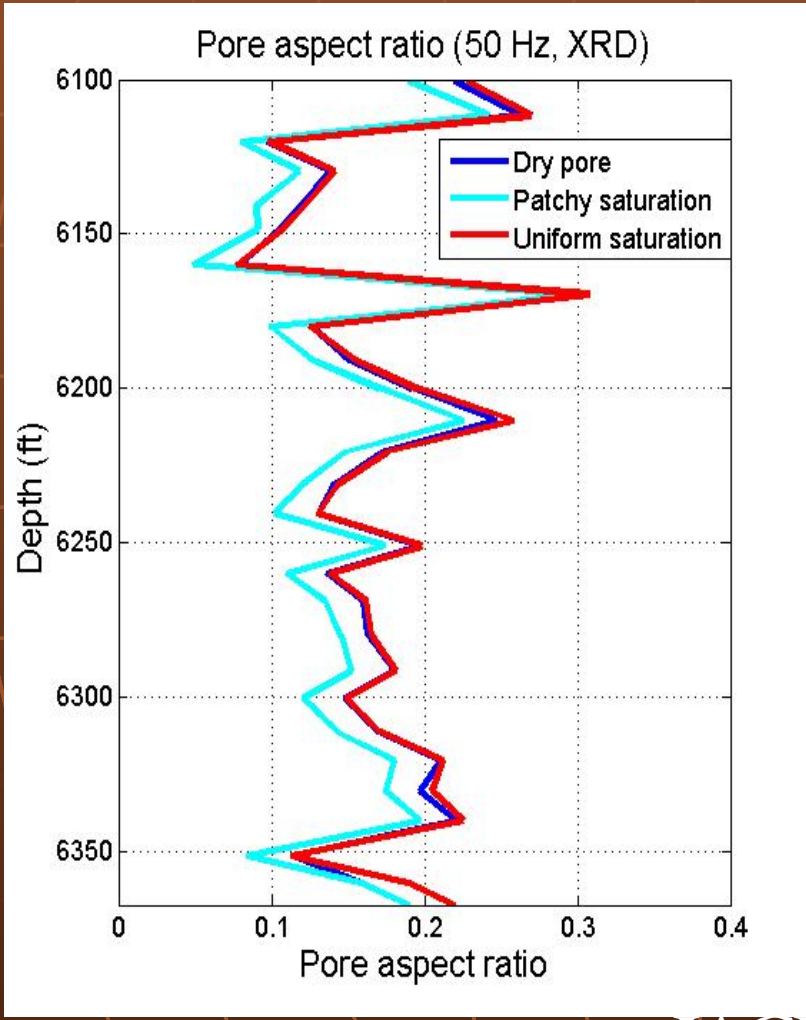
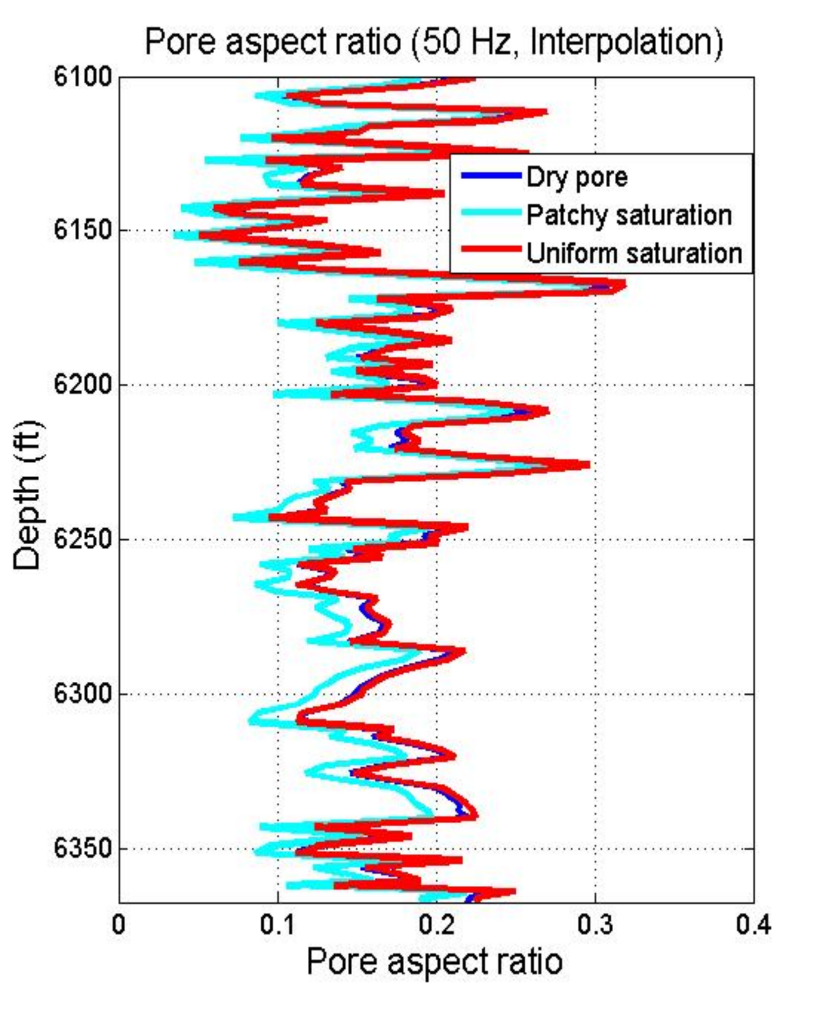
1) Comparison of results for SCM





XRD data **Interpolated data**

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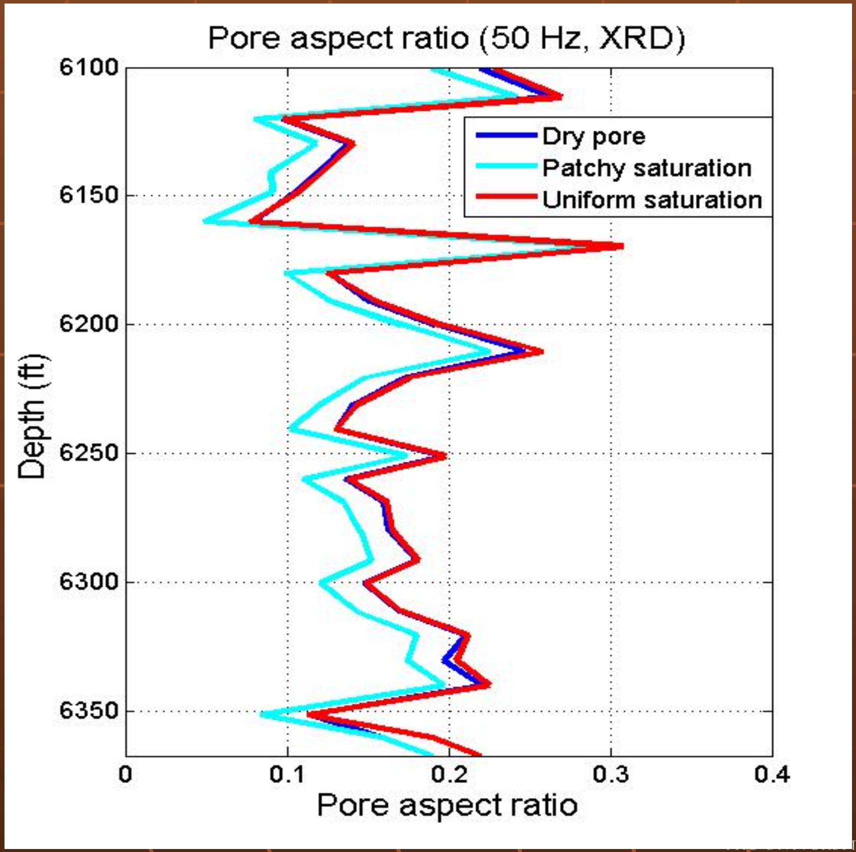
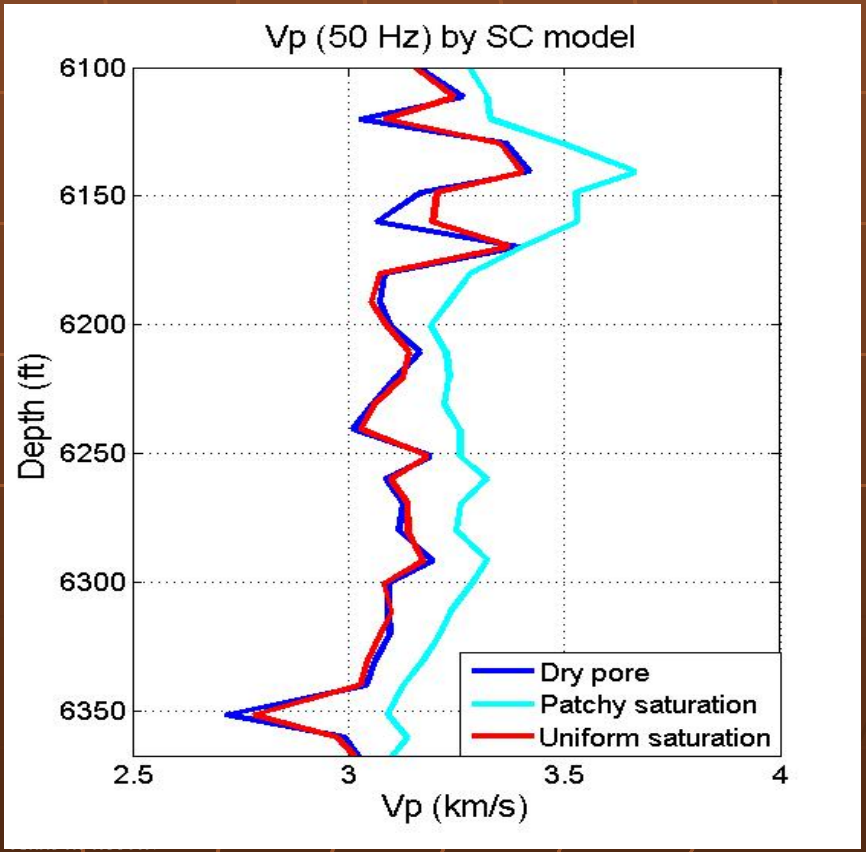
Difference b/w aspect ratio and V_p from SCM

Aspect ratio



P-wave velocity



Uni>Dry>Pat

Pat>Uni>Dry

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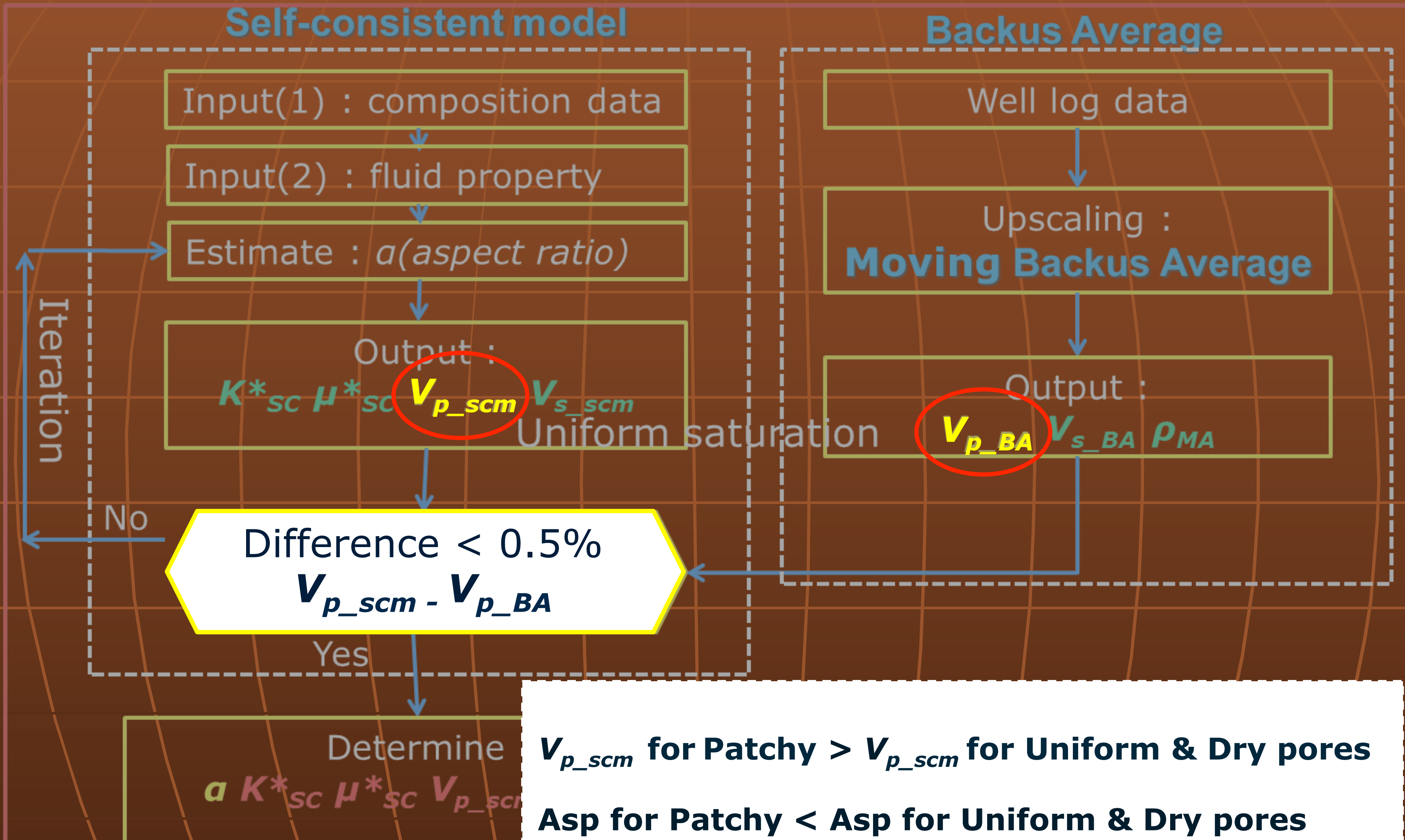
Relation b/w aspect ratio and V_p calculation from SCM

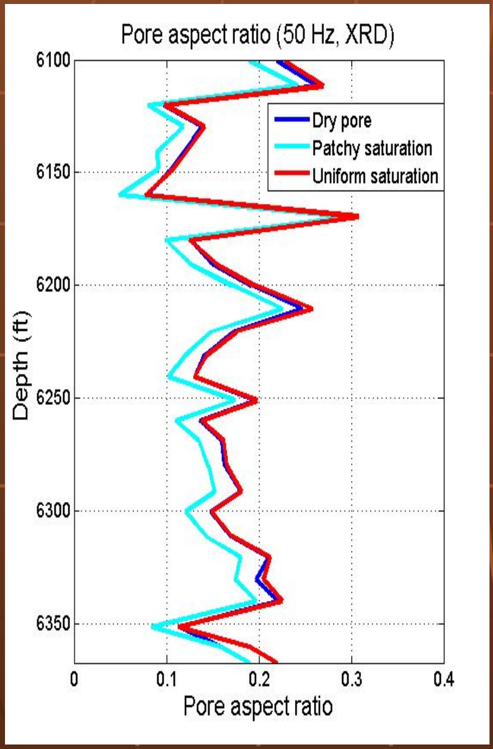


V_{p_scm} for Patchy > V_{p_scm} for Uniform & Dry pores

Asp for Patchy < Asp for Uniform & Dry pores

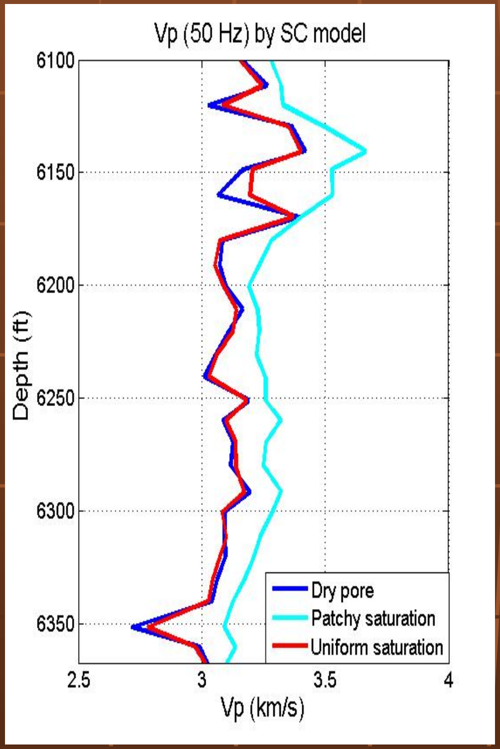
Relation b/w aspect ratio and V_p calculation from SCM

Aspect ratio



Uni>Dry>Pat

P-wave velocity



Pat>Uni>Dry

Vp or Bulk moduli increase

Pore aspect ratio decrease

Inverse relationship in SCM

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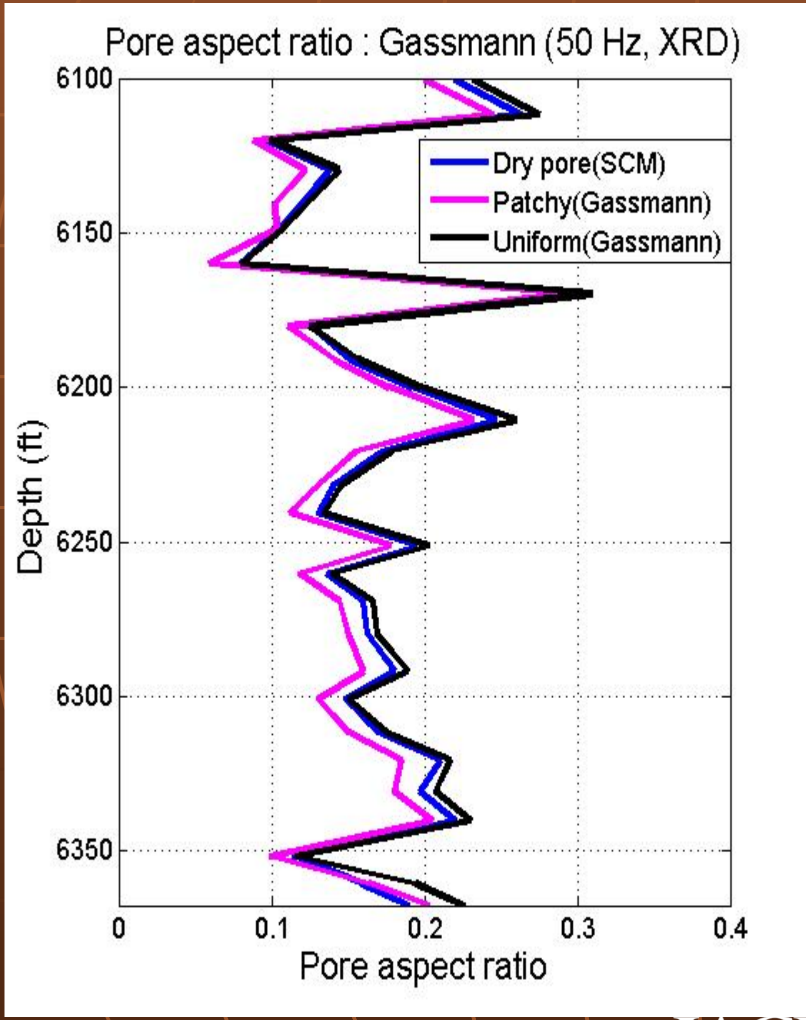
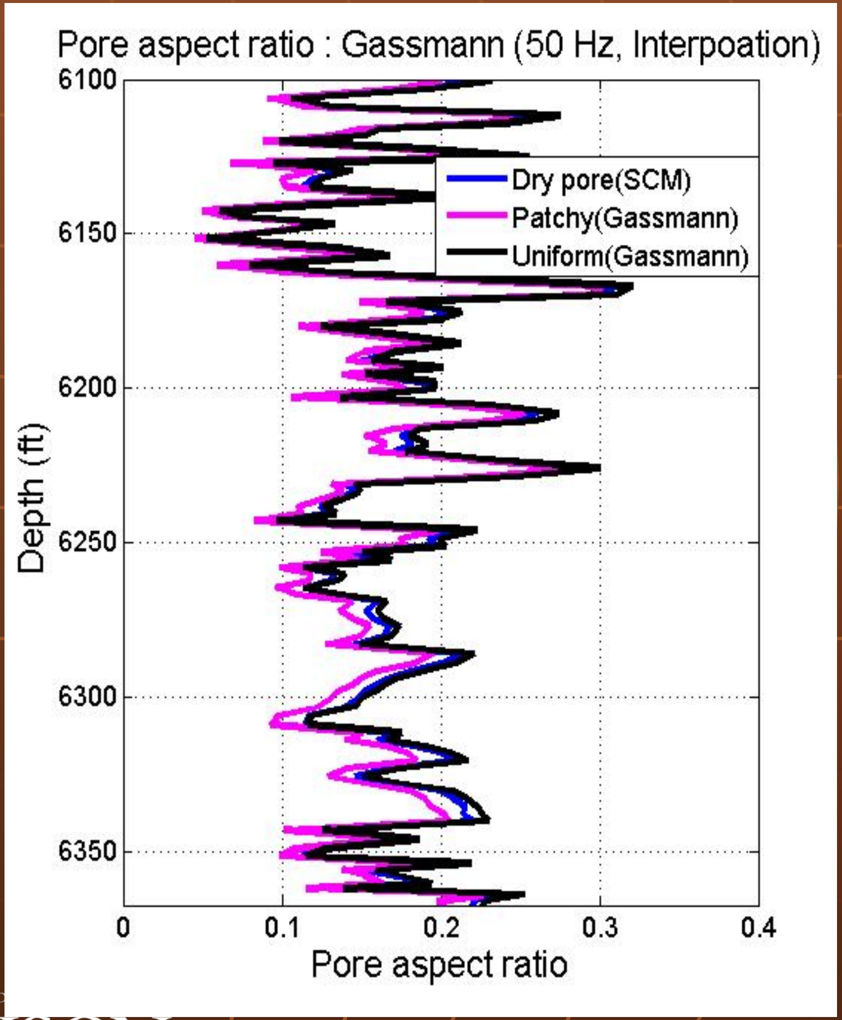
2) Comparison of results for Gassmann





XRD data **Interpolated data**

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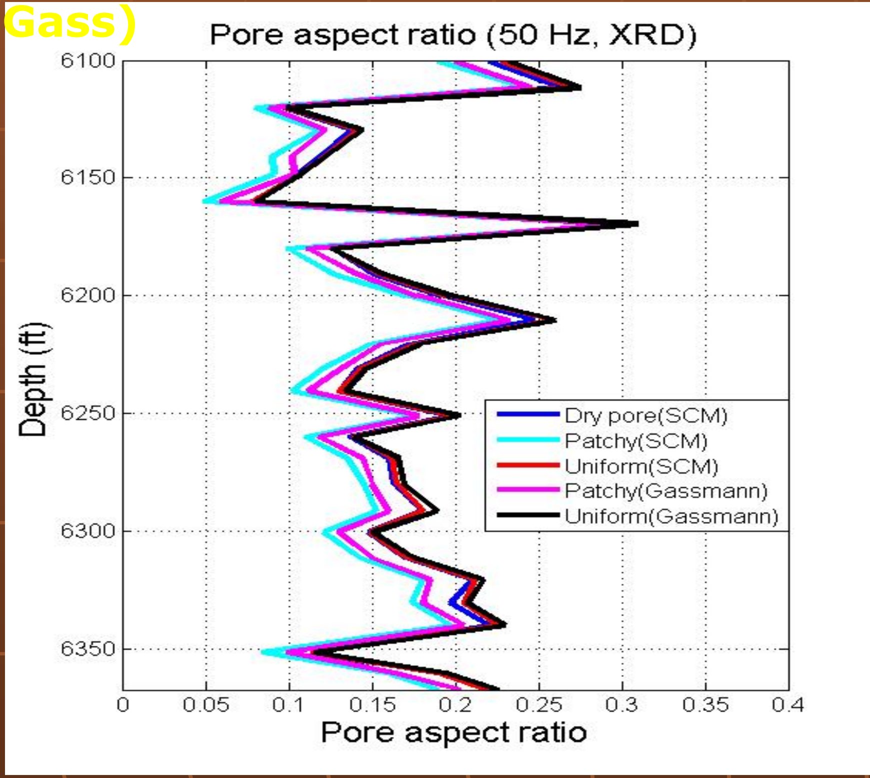
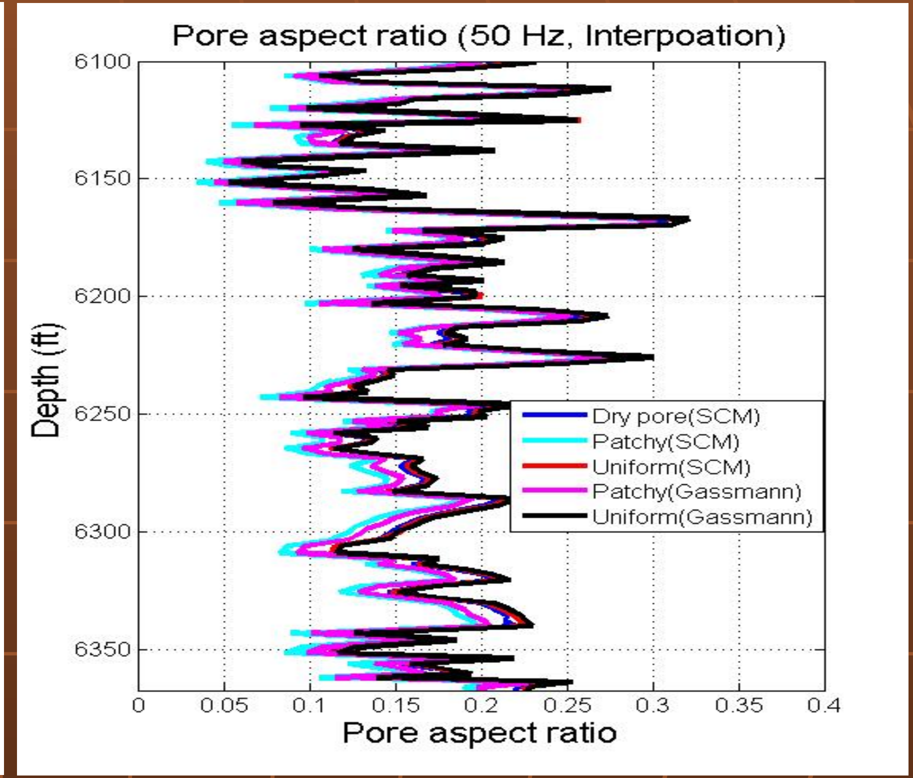
3) Comparison between SCM and Gassmann

Patchy(SCM) < Patchy(Gass) < Dry pores < Uniform(SCM)< Uniform (Gass)





Determined aspect ratios are strongly affected by the pore fluid mixing.

Mixing saturation in the Haynesville would be patchy saturation case. (air/water interface) Pore aspect ratio : 0.035 - 0.296 (Mean : 0.145)

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7. Conclusion

- Determining pore aspect ratios
  : reservoir characteristics at the seismic scale.

- V_p and S_w in water/gas reservoir
  : heterogeneous (patchy) or homogeneous (uniform).
  → Pore aspect ratio determination

- Fluid mixing types affect differently the calculations for pore aspect ratios and P-wave velocities.

- Help to find optimal locations for fracturing for the shale gas production.

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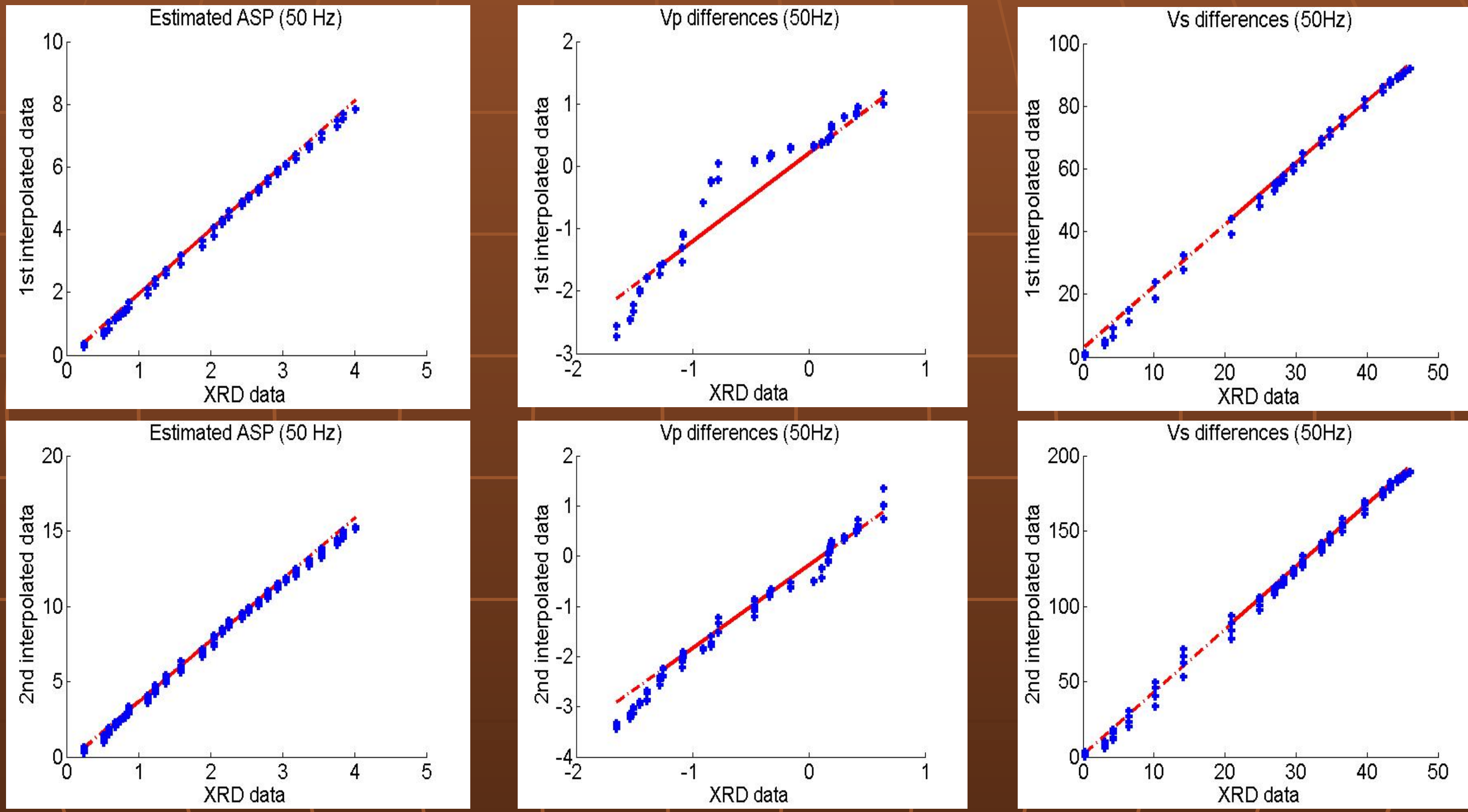
Appendix

Q-Q plot for 50 Hz : Comparing two distributions

Aspect ratios | Vp diffrences | Vs differences

1st Interpolation

2nd Interpolation



Original data

Correlation coefficients - 0.9987 **0.9545** **0.9985**

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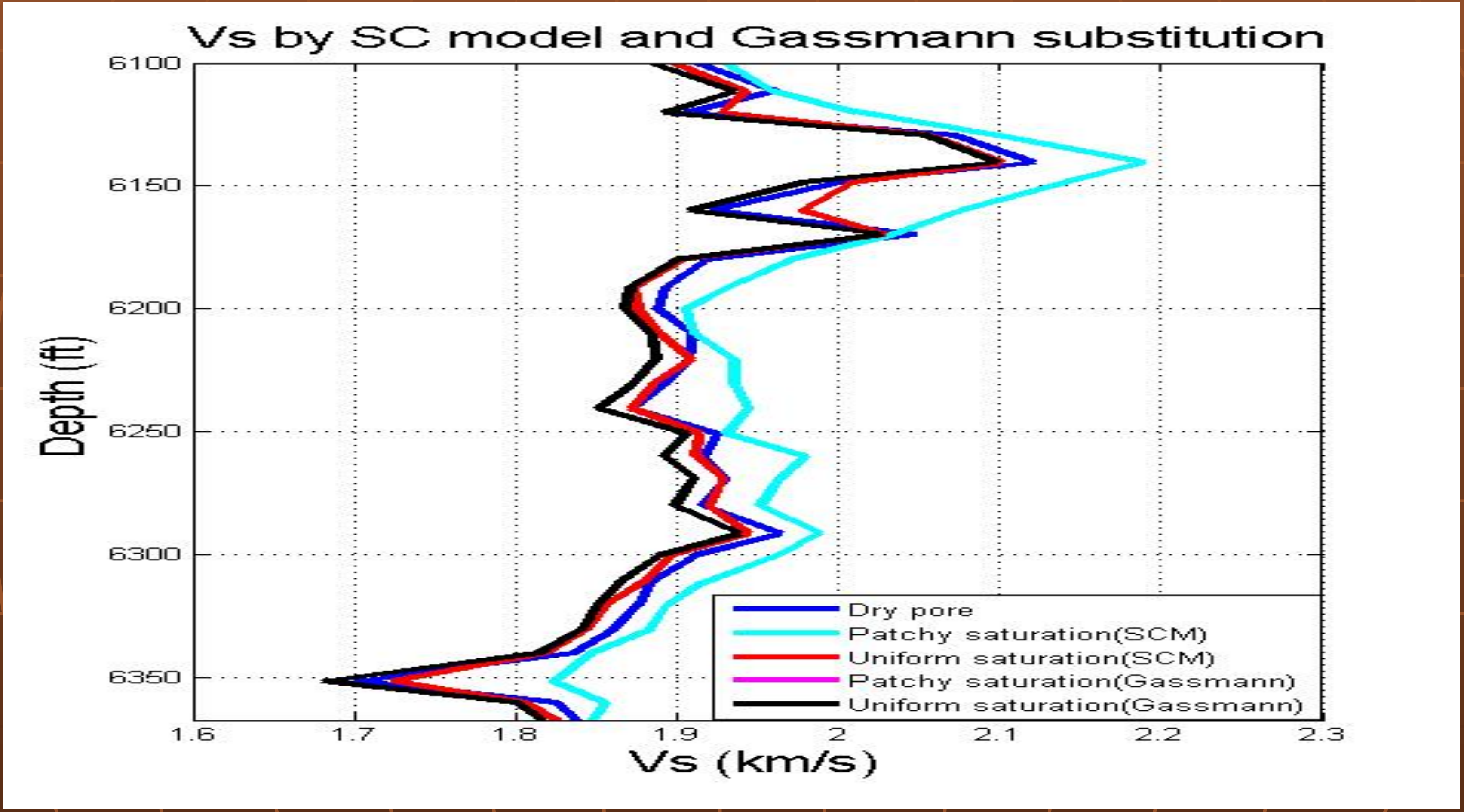
Velocity comparison (S-wave) by SCM



$V{\downarrow}s_{\text{patchy\_SCM}} > V{\downarrow}s_{\text{dry}} > V{\downarrow}s_{\text{uniform\_SCM}} > V{\downarrow}s_{\text{patchy\_Gassmann}} = V{\downarrow}s_{\text{uniform\_Gassmann}}$

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