Stochastic Inversion of Seismic PP and PS Data for Reservoir Parameter Estimation

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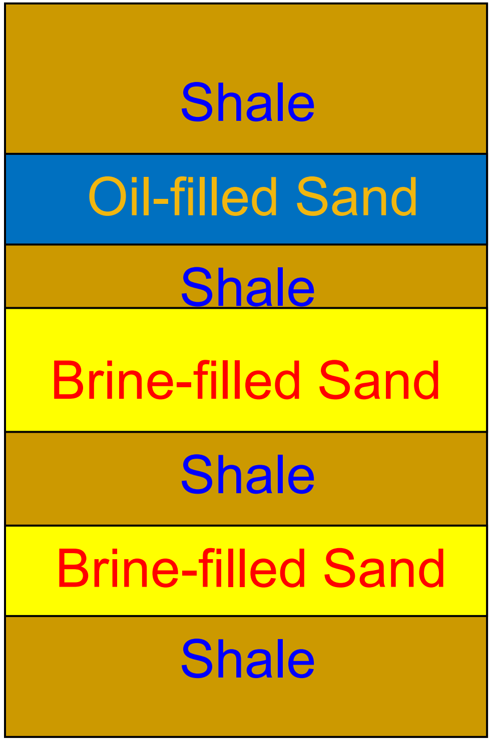
Outline

- ❑ Background
- ❑ Hierarchical Bayesian model for joint inversion
- ❑ Synthetic case study based on field data
- ❑ Summary and conclusions

Delivery: Open-source Java software for inversion of seismic PP data



(Gunning and Glinsky, 2004)

- ❑ Each layer is modeled as a mixture of permeable (sand or carbonate) and impermeable rock (shale or mudstone).
- ❑ The ratio of permeable to impermeable rock is determined by net-to-gross (NG).
- ❑ Each permeable rock may include one of four fluid types (oil, gas, brine, or low-saturation gas).

Delivery: Data and unknown variables

- Data
  - PP traces as functions of incident angles (S_{pp})
  - PP time registration with uncertainty (T_{pp})

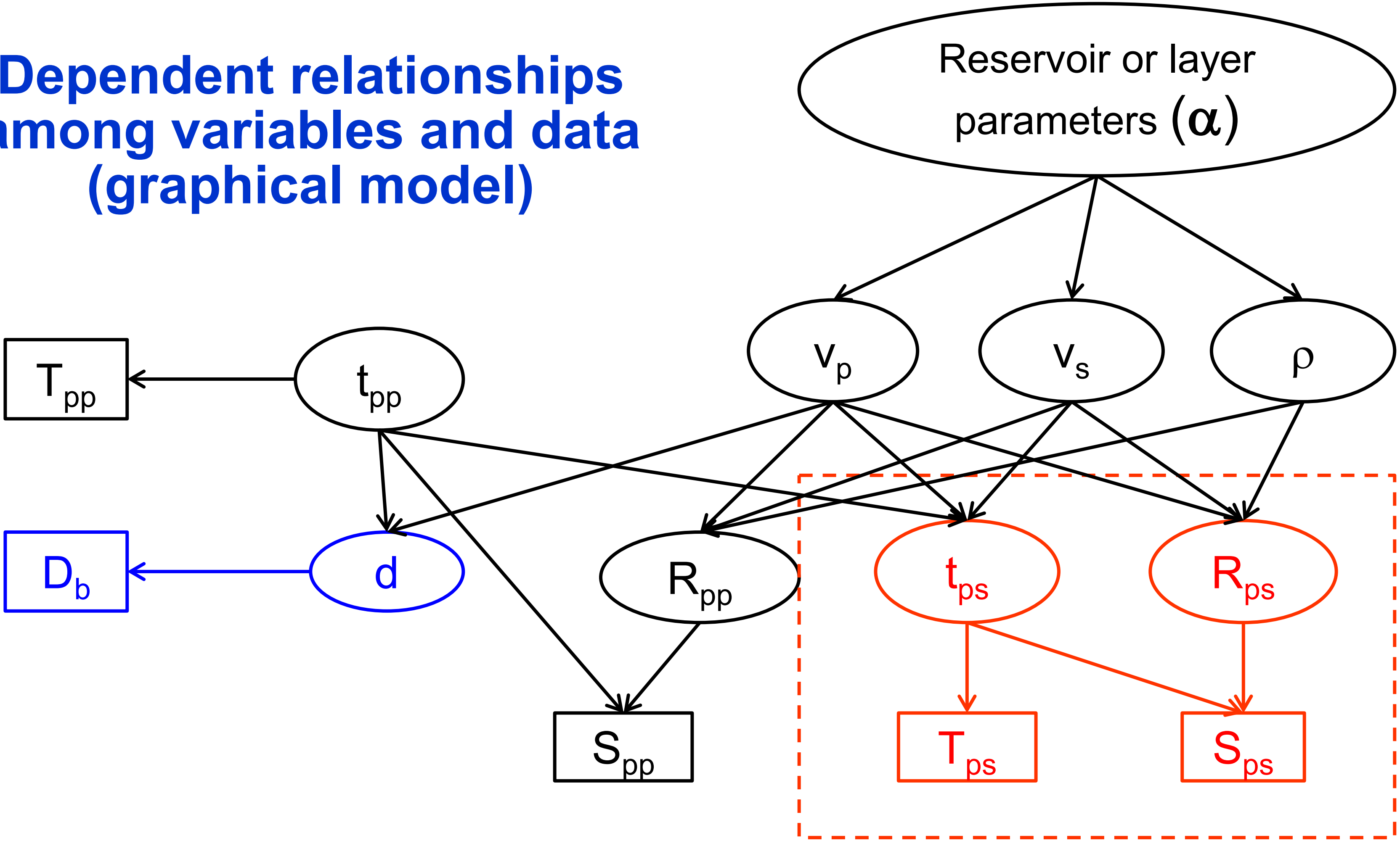
- Unknown variables
  - PP travel time to each interface (t_1, t_2, …, t_n)
  - Permeable rock: Porosity, P-wave and S-wave velocity.
  - Impermeable rock: Density, P-wave and S-wave velocity.
  - Fluid: fluid density and P-wave velocity, fluid saturation.
  - Other unknowns: net-to-gross, layer thickness, etc.

Extension of Delivery for inversion of PP and PS data

- Add two types of seismic data:
  - PS traces in the PS time domain (S_{ps})
  - PS time registration (T_{ps})

- Add two types of unknown variables:
  - PS travel time (t_{ps})
  - PS reflectivity (R_{ps})

Dependent relationships among variables and data (graphical model)



Hierarchical Bayesian model

$$f(\alpha, \mathbf{t}_{pp}, \mathbf{t}_{ps}, \mathbf{d}, \mathbf{v}_p, \mathbf{v}_s, \rho, \mathbf{R}_{pp}, \mathbf{R}_{ps} \mid \mathbf{S}_{pp}, \mathbf{S}_{ps}, \mathbf{T}_{pp}, \mathbf{T}_{ps}, \mathbf{D}_b)$$

$\propto f(\mathbf{S}_{pp} \mid \mathbf{t}_{pp}, \mathbf{R}_{pp})$	Likelihood of PP data
$\times f(\mathbf{S}_{ps} \mid \mathbf{t}_{ps}, \mathbf{R}_{ps})$	Likelihood of PS data
$\times f(\mathbf{T}_{pp} \mid \mathbf{t}_{pp})$	Likelihood of PP time registration
$\times f(\mathbf{T}_{ps} \mid \mathbf{t}_{ps})$	Likelihood of PS time registration
$\times f(\mathbf{D}_b \mid \mathbf{d})$	Likelihood of depth data
$\times f(\mathbf{d} \mid \mathbf{t}_{pp}, \mathbf{v}_p)$	Linkage between PP time and depth
$\times f(\mathbf{R}_{pp}, \mathbf{R}_{ps} \mid \mathbf{v}_p, \mathbf{v}_s, \rho)$	Linearized Zoeppritz equations
$\times f(\mathbf{t}_{ps} \mid \mathbf{t}_{pp}, \mathbf{v}_p, \mathbf{v}_s)$	Linkage between PS and PP time
$\times f(\mathbf{v}_p, \mathbf{v}_s, \rho \mid \alpha)$	Rockphysics models
$\times f(\alpha) f(\mathbf{t}_{pp})$.	Priors on parameters and PP time

PP and PS reflectivities using linearized Zoeppritz equations

$$R_{pp}(\theta) = \frac{1}{2}\left(\frac{\Delta v_p}{v_p} + \frac{\Delta \rho}{\rho}\right) + \frac{1}{2}\left[\frac{\Delta v_p}{v_p} - 4\left(\frac{v_s}{v_p}\right)^2\left(\frac{\Delta \rho}{\rho} + 2\frac{\Delta v_s}{v_s}\right)\right]\theta^2 + O(\theta^4),$$

$$R_{ps}(\theta) = -\frac{1}{2}\left[\frac{\Delta \rho}{\rho} + 2\left(\frac{v_s}{v_p}\right)\left(\frac{\Delta \rho}{\rho} + 2\frac{\Delta v_s}{v_s}\right)\right]\theta + O(\theta^3).$$

Where $v_p = (v_{p1} + v_{p2})/2$, $v_s = (v_{p1} + v_{p2})/2$, $\rho=(\rho_1+\rho_2)/2$,

$\Delta v_p = v_{p2} - v_{p1}$, $\Delta v_s = v_{s2} - v_{s1}$, and $\Delta \rho = \rho_2 - \rho_1$.

Linkage between PP and PS travel time

- Find an interface on which both PP and PS have strong reflection.
- Use the PS time on the interface as the reference to calculate PS time for other interfaces.
- Relative PP and PS time for a given layer is calculated by

$$\Delta t_{ps} = \frac{1}{2}\left(1 + \frac{v_p}{v_s}\right)\Delta t_{pp}$$

Floating-grain rockphysics model by Gunning and Glinsky (2007)

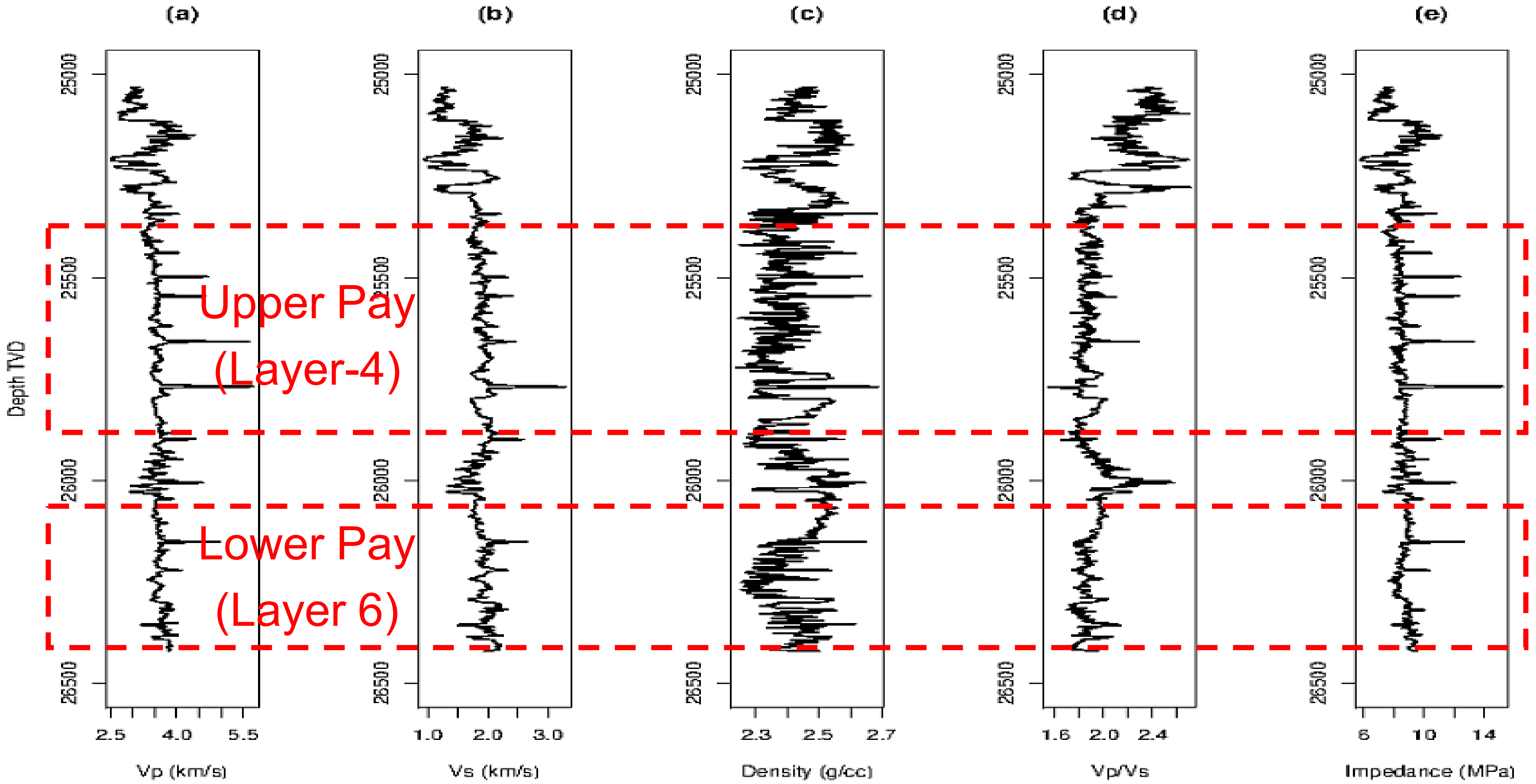
$$v_p = a_{vp} + b_{vp} Z + c_{vp} X + \varepsilon_{vp}, \qquad \varepsilon_p \sim N(0, \sigma_{vp}^2)$$

$$v_s = a_{vs} + b_{vs} v_{vp} + \varepsilon_{vs}, \qquad \varepsilon_s \sim N(0, \sigma_{vs}^2)$$

$$\rho = a_\rho + b_\rho v_p + c_\rho X + \varepsilon_\rho, \qquad \varepsilon_\rho \sim N(0, \sigma_\rho^2)$$

where Z is the loading depth or other variable representing the effect of pressure, and X is floating grain fraction. All the coefficients and variance are obtained from fitting of borehole logs.

Borehole logs from Gunning and Glinsky (2007)

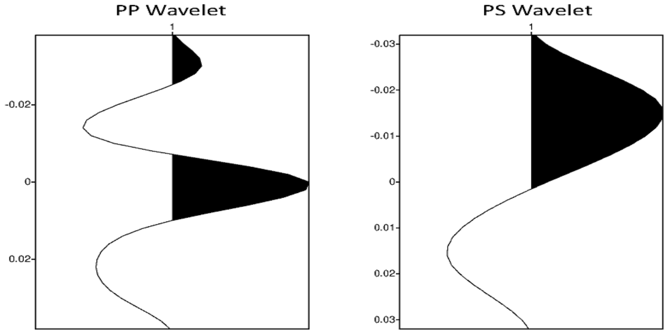


Summary of parameters in the six-layer model

	Geology	Vp (km/s)	Vs (km/s)	Rho (g/cc)	Vp/Vs	NG	Porosity	Floating Fraction
1	Marl	3.67	1.75	2.54	2.10	0.00		
2	Silt Marl Mix	2.85	1.17	2.38	2.44	0.00		
3	Bounding Shale	3.32	1.63	2.50	2.04	0.00		
4	Sand / Mixing Shale	3.49	1.89	2.39	1.84	0.65	0.187	0.035
5	Bounding Shale	3.48	1.76	2.52	1.98	0.00		
6	Sand / Mixing Shale	3.58	1.97	2.41	1.81	0.65	0.181	0.035

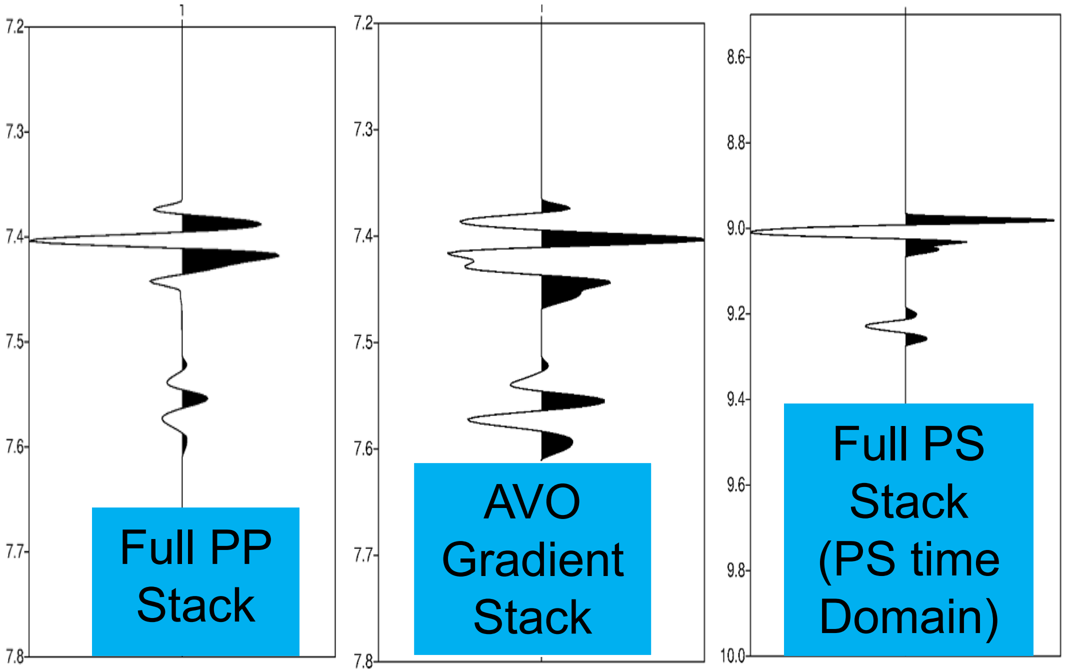
PP and PS reflectivities and seismic data

	Full PP Stack ($\theta=0^0$)	Full PS Stack ($\theta=45^0$)	AVO Gradient Stack ($\theta=45^0$)
1			
2	-0.1586	0.1347	0.3282
3	0.1001	-0.1334	-0.2721
4	0.0040	-0.0697	-0.0882
5	0.0245	0.0313	0.0187
6	-0.0096	-0.0542	-0.0571



PP Wavelet PS Wavelet

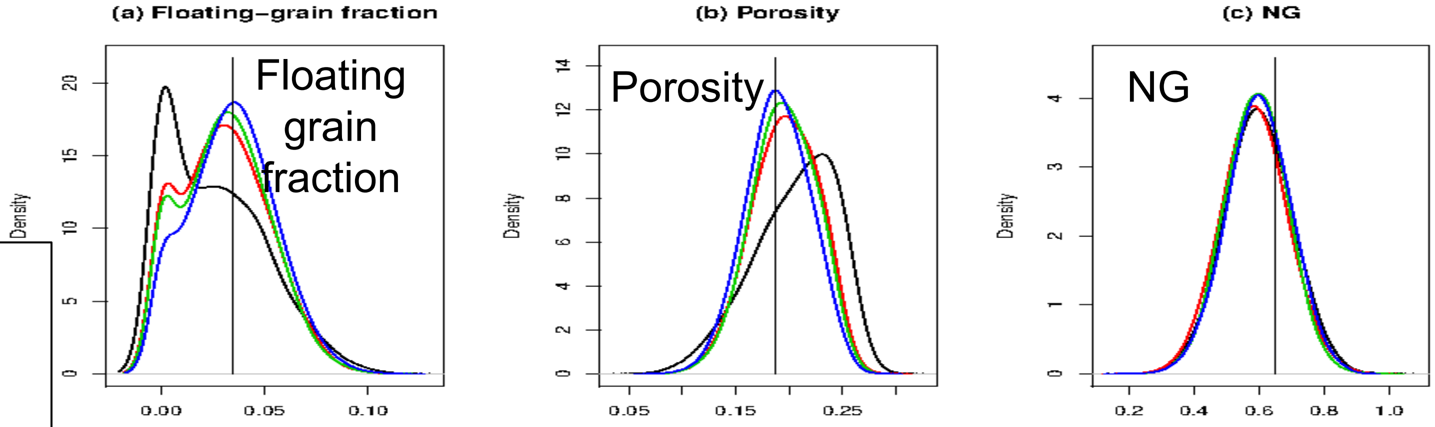
(Sassen & Glinsky, 2013)



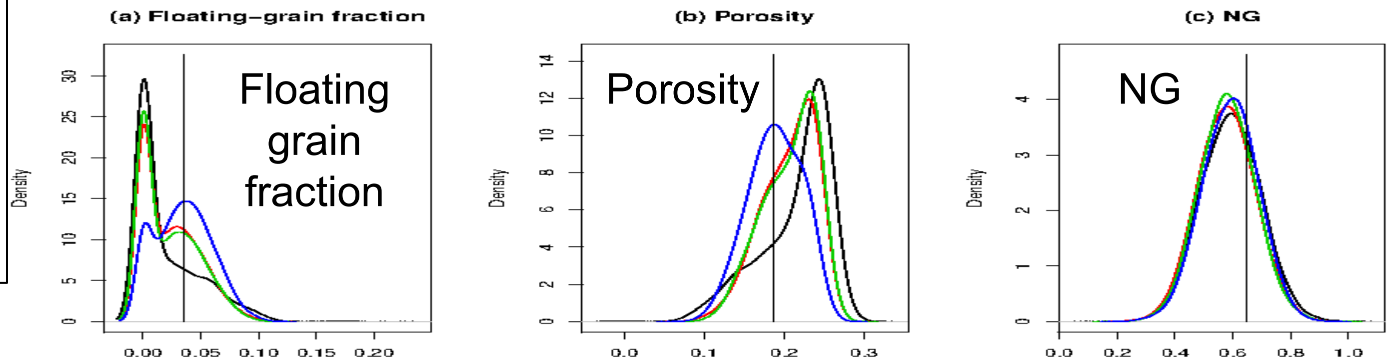
Priors about floating-grain fraction

- Black: Priors
- Red: Full PP
- Green: Full PP plus AVO gradient
- Blue: Full PP plus full PS

Strong prior: X~N(0.02, 0.03^2), True X=0.035



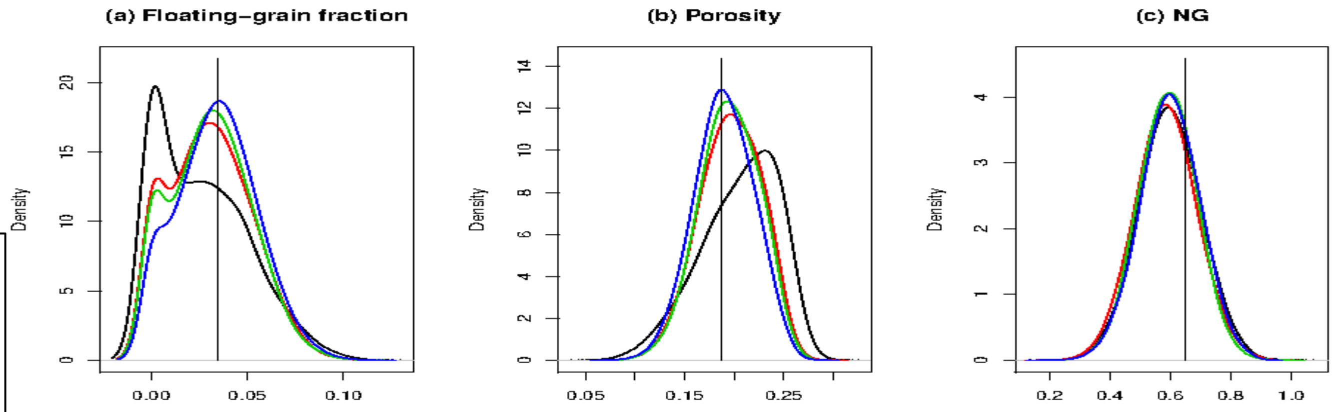
Weak prior: X~N(0.0, 0.05^2), True X=0.035



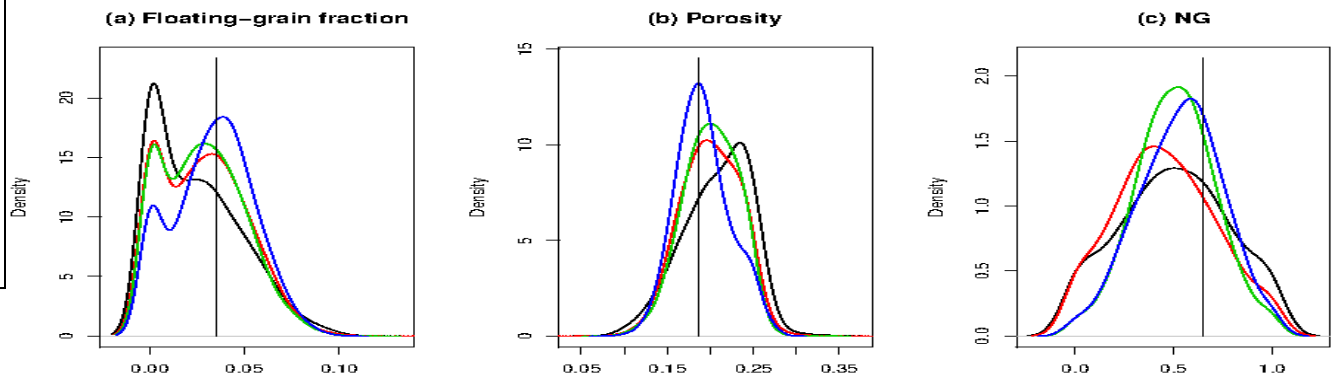
Priors about net-to-gross

- Black: Priors
- Red: Full PP
- Green: Full PP plus AVO gradient
- Blue: Full PP plus full PS

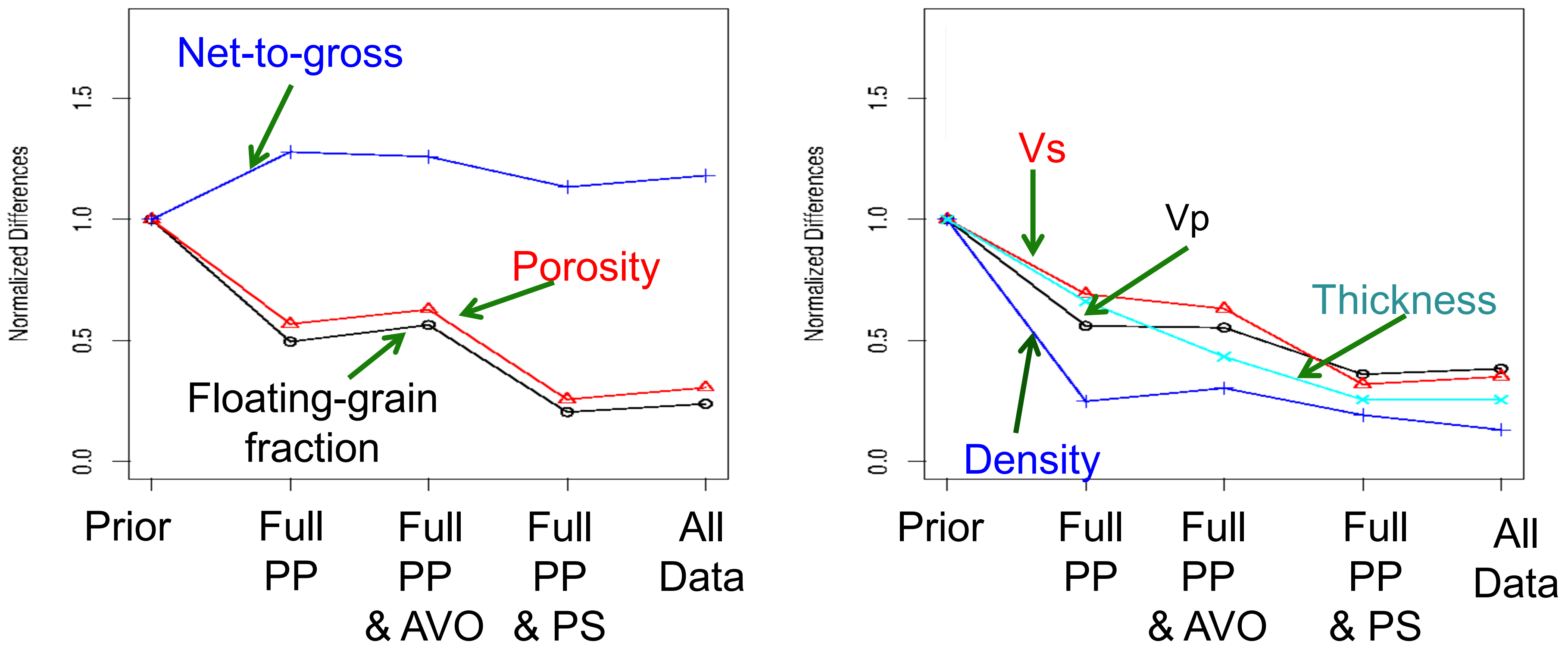
Strong prior: NG~N(0.6, 0.1^2), True NG=0.65



Weak prior: NG~N(0.5, 0.3^2), True NG=0.65

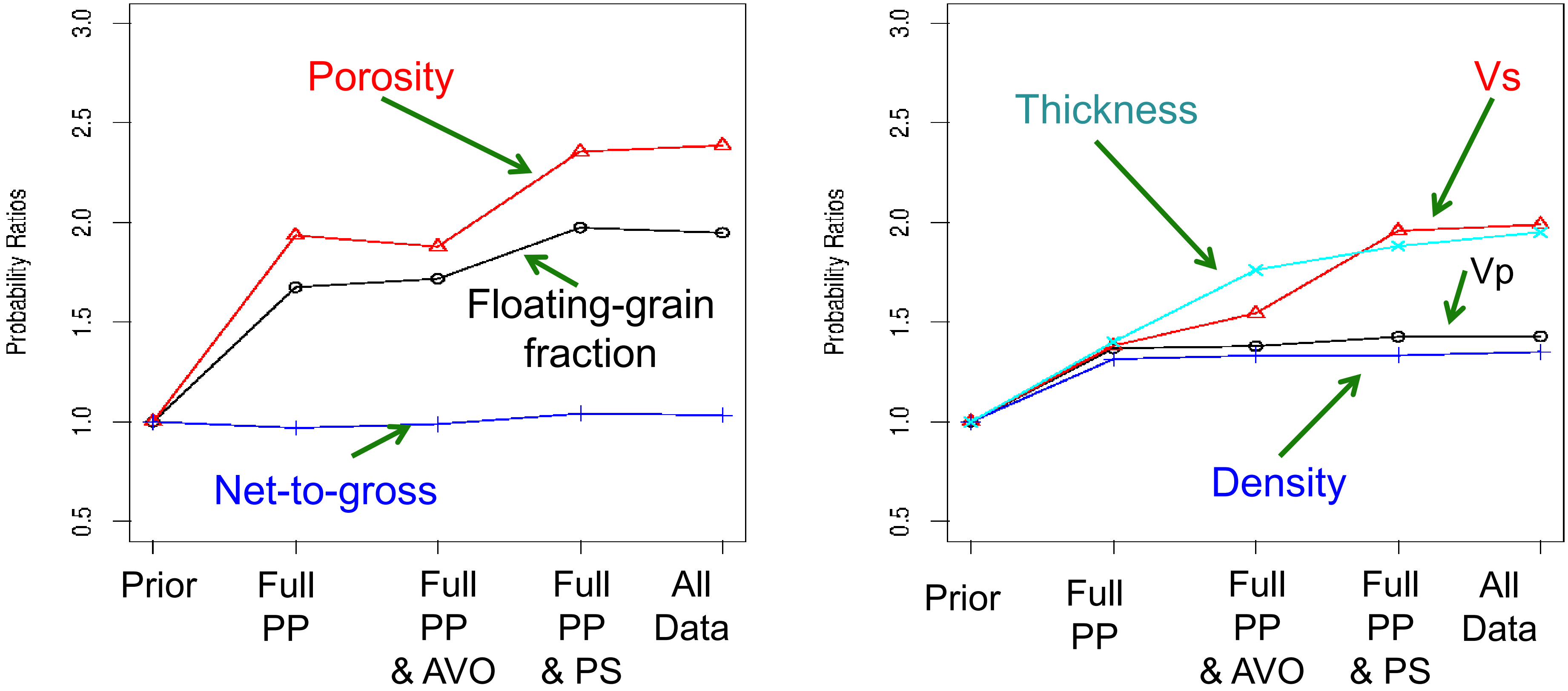


Differences between the true values and estimated medians



Probability of small regions around the true values

$$\text{Prob}(\theta \in [0.95\theta^{True},\ 1.05\theta^{True}] \mid \text{Data})$$



Summary and conclusions

- ❑ We developed a tool to combine PP and PS data by extending 'Delivery' to include PS responses and time registration as data.

- ❑ The revised codes take full advantage of Delivery in model specification, Markov chain Monte Carlo (MCMC) sampling, and post analysis.

- ❑ We applied the codes to a synthetic model based on actual borehole logs. We used a floating-grain rockphysics model to link reservoir parameters to seismic attributes.

- ❑ The case study results show that full PS data provide more information than AVO gradient data. Specifically, PS data significantly improve the estimates of floating-grain fraction and porosity.

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