Discrimination between Pressure-Saturation Changes in Compacting Reservoirs Using Time-Lapse Amplitudes and Travel Times

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Outline

- Background Studies
- Objective
- Review of methods
- Rock Physics Model
- Results
- Results with random noise
- Discussions and conclusions

Background studies

Several researchers introduce various 4D seismic inversion methods to estimate changes in pressure and saturation

- Estimation based on P and S –wave impedance (Tura and Lumley, 1999)
- Estimation based on time lapse PP- AVO data (Landrø; 1999, 2001)
- Estimation based on time lapse PP and PS information (Landrø et al., 2003; Stovas et al.; 2003)
- Røste et al. (2007) develop method for compacting reservoir using time-lapse PP-AVO data
- Trani et al. (2011) use PP and PS travel time information

Objective

- To test how well changes in effective stress, saturation and porosity can be estimated using various combinations of seismic attributes compared to time-lapse PP AVO only

Review of methods

- Changes in PP-reflectivity (ΔR^{PP}) (Landrø ; 1999, 2001)

$$\Delta R^{PP}(\Theta) = \frac{1}{2}\left(\frac{\Delta\rho_2}{\rho_2} + \frac{\Delta\alpha_2}{\alpha_2}\right) - 2Y^2\left(\frac{\Delta\rho_2}{\rho_2} + \frac{2\Delta\beta_2}{\beta_2}\right)\sin^2\Theta + \frac{\Delta\alpha_2}{2\alpha_2}\tan^2\Theta$$

where, $\alpha_2, \beta_2, \rho_2$ are Vp, Vs and density of reservoir layers

and $\Delta\alpha_2, \Delta\beta_2, \Delta\rho_2$ are changes in $\alpha_2, \beta_2, \rho_2$, due to saturation, pressure or porosity changes. Y is the velocity ratio (Vs/Vp)

- If we consider conventional AVO intercept and gradient formula

$$\Delta R_0^{PP} = \frac{1}{2}\left(\frac{\Delta\rho_2}{\rho_2} + \frac{\Delta\alpha_2}{\alpha_2}\right)$$

$$\Delta G^{PP} = -2Y^2\left(\frac{\Delta\rho_2}{\rho_2} + \frac{2\Delta\beta_2}{\beta_2}\right) + \frac{\Delta\alpha_2}{2\alpha_2}$$

Review of methods

- Changes in PS-reflectivity (ΔR^{PS}) (Landrø, 2003)

$$\Delta R^{PS}(\Theta) = -\frac{1}{2}((1+2Y)\frac{\Delta\rho_2}{\rho_2} + 4Y\frac{\Delta\beta_2}{\beta_2})\sin\Theta + 2Y\left[(Y+\frac{1}{2})(\frac{\Delta\rho_2}{\rho_2} + \frac{2\Delta\beta_2}{\beta_2}) - \frac{Y}{4}\frac{\Delta\rho_2}{\rho_2}\right]\sin^3\Theta$$

- The relative change in zero-offset PP-travel time (Landrø and Stammeijer, 2004; Hatchell and Bourne, 2005)

$$\frac{\Delta T_0^{PP}}{T_0^{PP}} = \frac{\Delta z_2}{z_2} - \frac{\Delta\alpha_2}{\alpha_2}$$

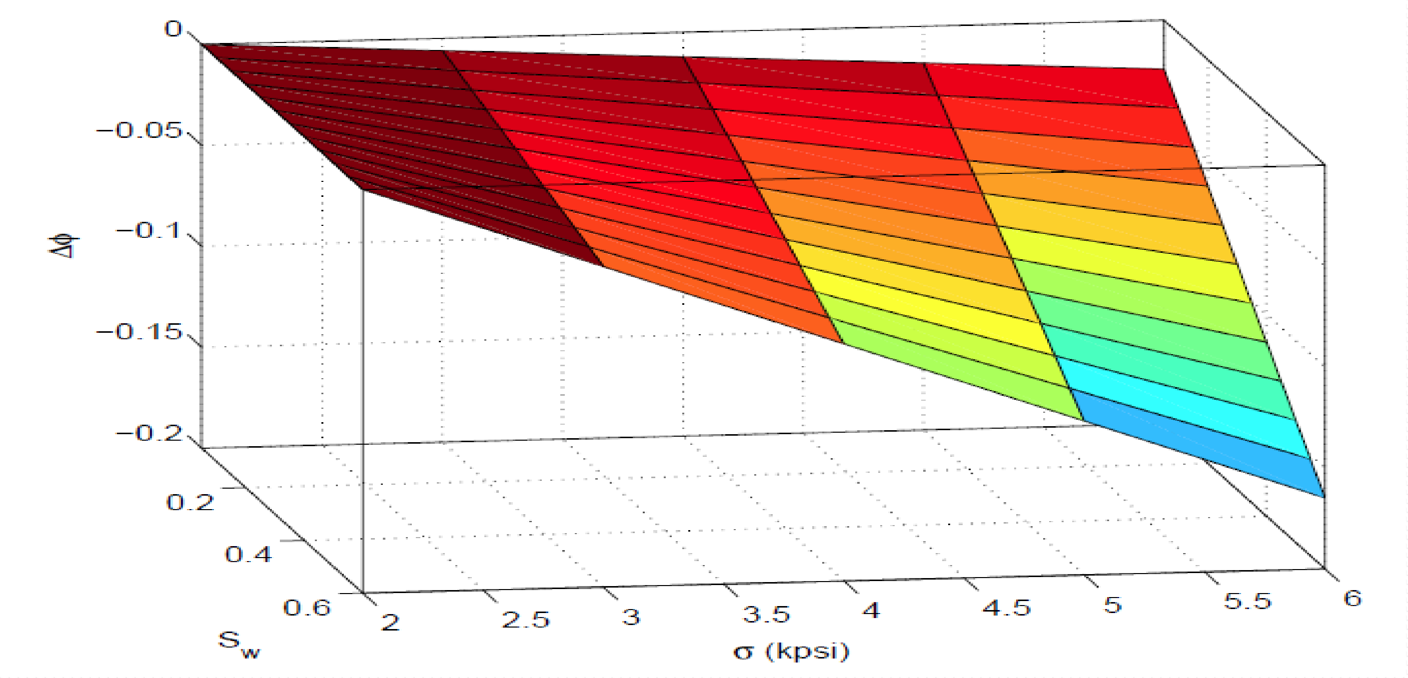
- Assuming uniaxial strain changes (Guilbot and Smith, 2002)

$$\Delta z_2 = z_2\frac{\Delta\phi_2}{1-\phi_2}$$

Rock Physics Model

- For compacting reservoir : ΔS_w , $\Delta\sigma$ and $\Delta\phi_2$
- From laboratory measurements (Sylte et al., 1999)

$$\Delta\phi_2 = \frac{\partial\phi_2}{\partial S_w}\Delta S_w + \frac{\partial\phi_2}{\partial\sigma}\Delta\sigma$$



for 42% porosity chalk

(after Røste et al., 2007)

Rock Physics Model

Changes in seismic parameters are due to the combine effects of

- porosity changes ($\Delta\phi$)
- fluid-pressure changes ($\Delta S_w, \Delta\sigma$) ,which is independent of porosity changes (ϕ_c)

$$\frac{\Delta\alpha_2}{\alpha_2} = \left[M_\alpha \Delta\phi_2\right]_{\Delta\phi} + \left[K_\alpha \Delta S_w + L_\alpha \Delta\sigma\right]_{\phi_C}$$

$$\frac{\Delta\beta_2}{\beta_2} = \left[M_\beta \Delta\phi_2\right]_{\Delta\phi} + \left[K_\beta \Delta S_w + L_\beta \Delta\sigma\right]_{\phi_C}$$

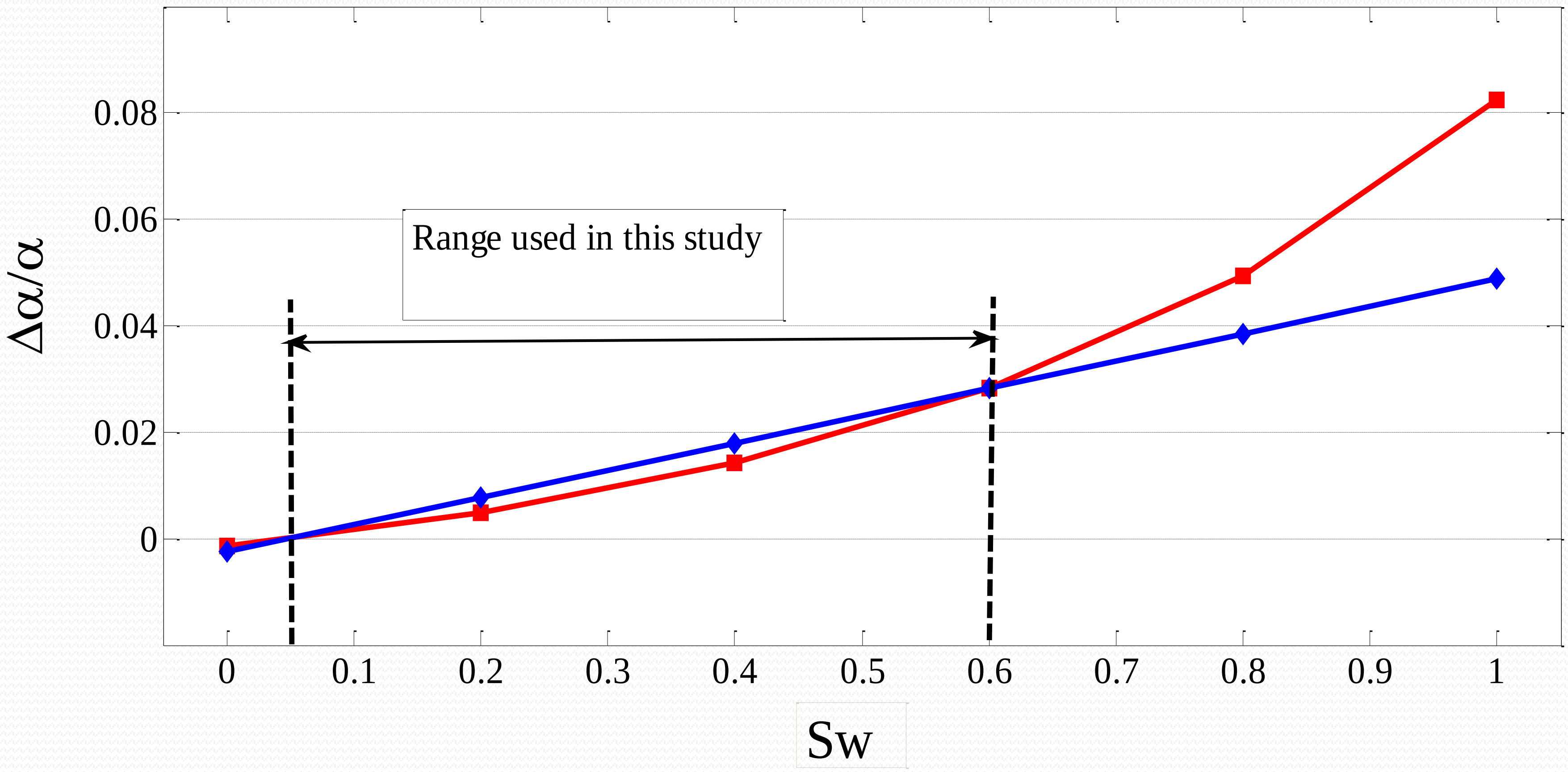
$$\frac{\Delta\rho_2}{\rho_2} = \left[M_\rho \Delta\phi_2\right]_{\Delta\phi} + \left[K_\rho \Delta S_w\right]_{\phi_C}$$

(after Røste et al., 2007)

Here, $M_\alpha, K_\alpha, L_\alpha$ etc. are derived using well log and rock physics models

- Now, $\Delta\phi_2$ can be replaced into ΔS_w and $\Delta\sigma$, using the equation of Sylte et al. (1999)

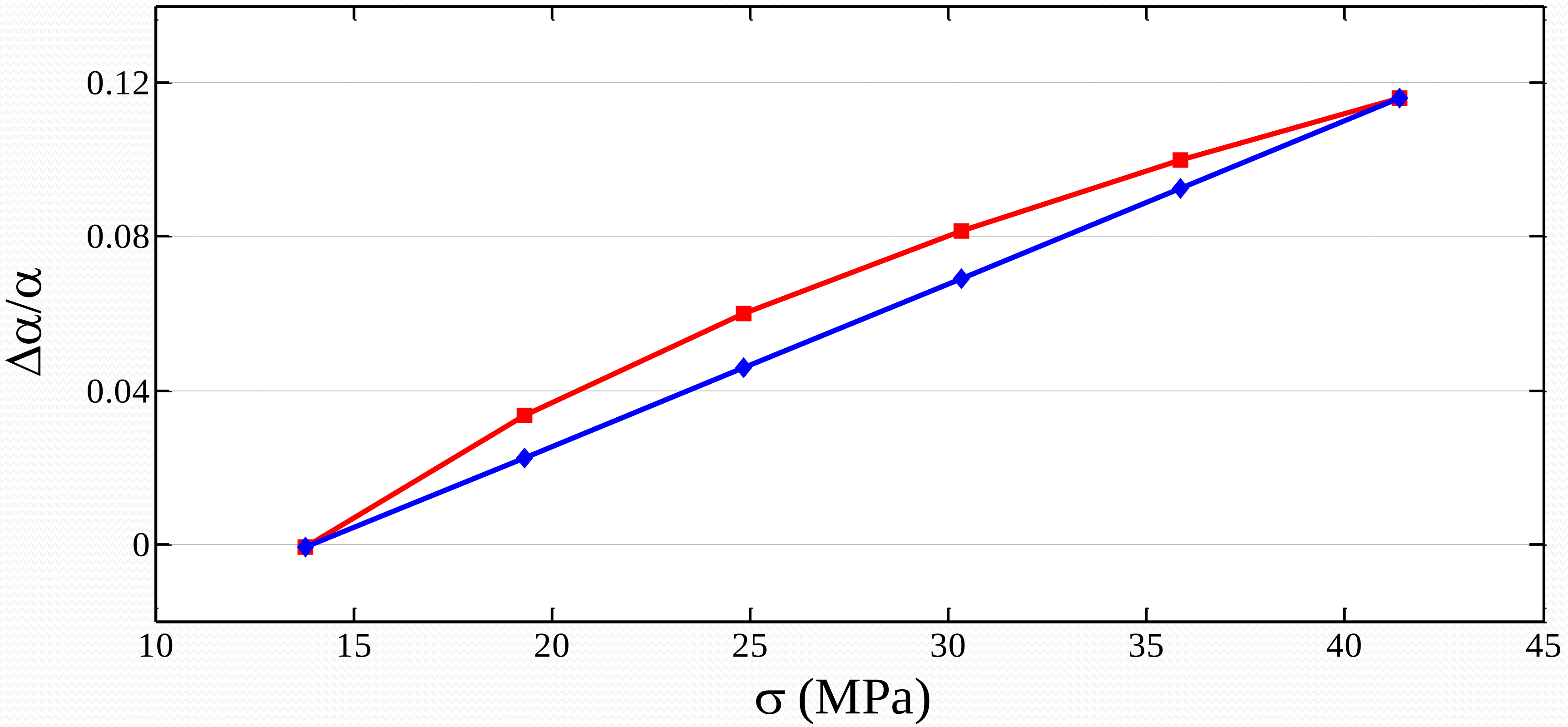
Rock Physics Model



Relative change in P-wave velocity with water saturation

(after Røste et al., 2007)

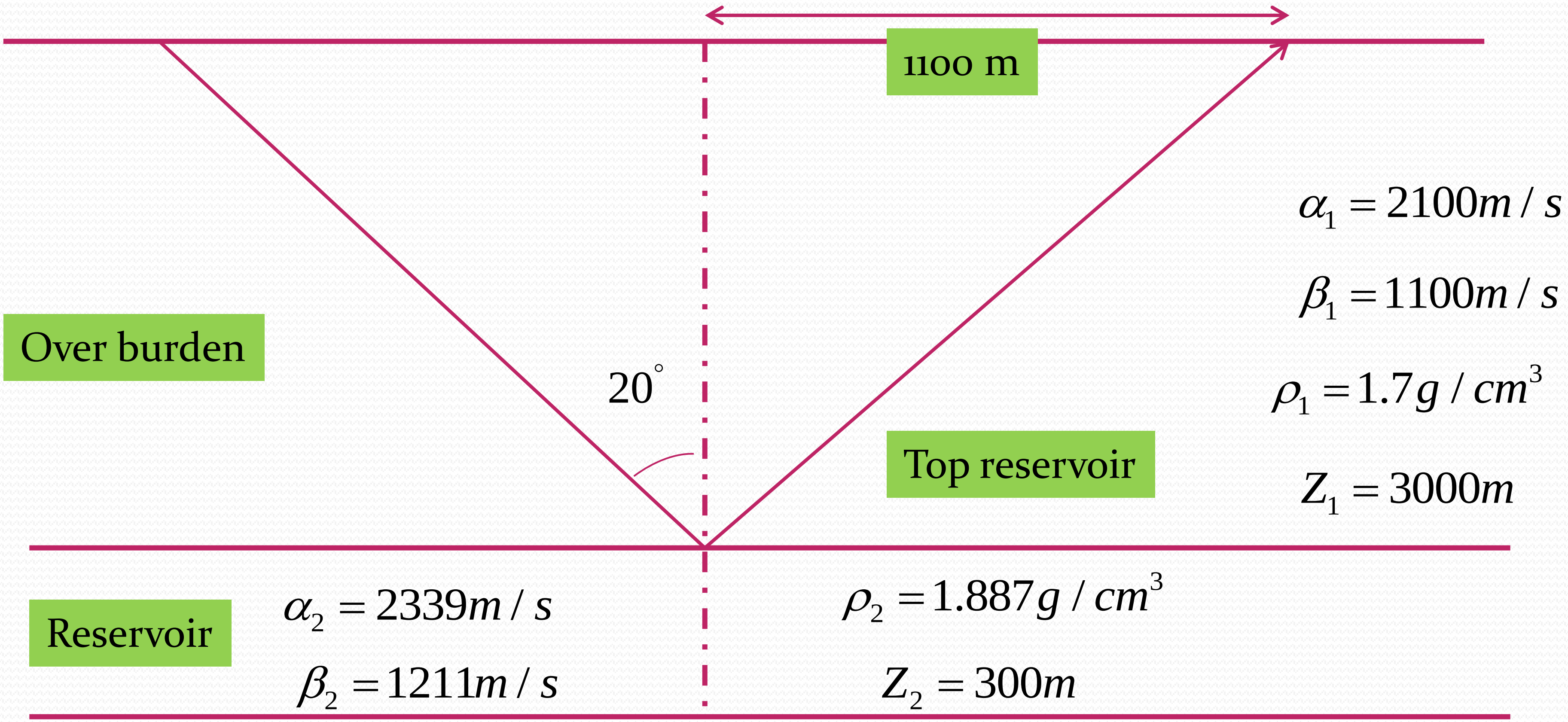
Rock Physics Model



Relative change in P-wave velocity with effective stress

(after Røste et al., 2007)

Simple 2-layer model

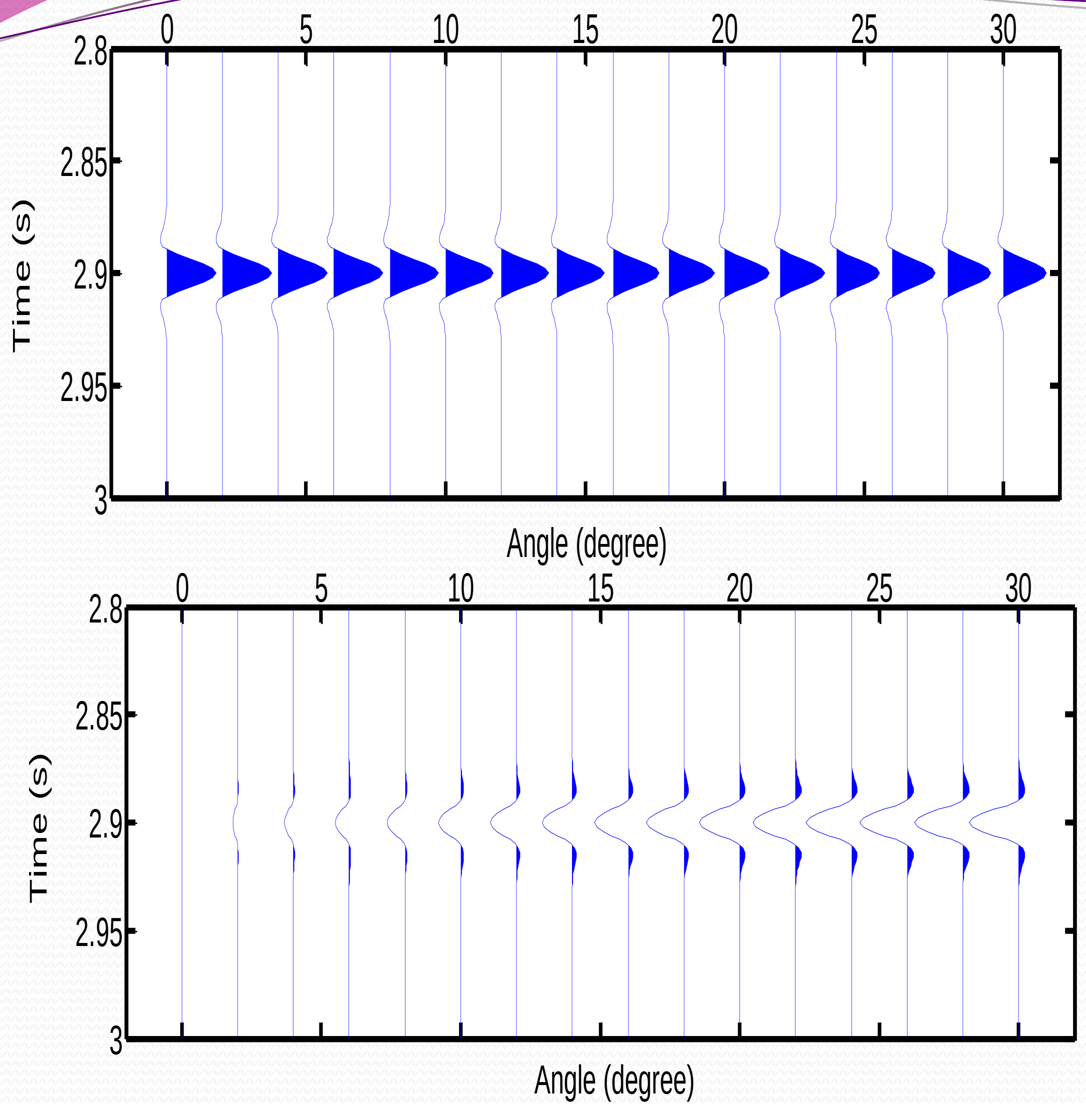


$S_{wI} = 0.05$

$\sigma_I = 13.80 MPa$

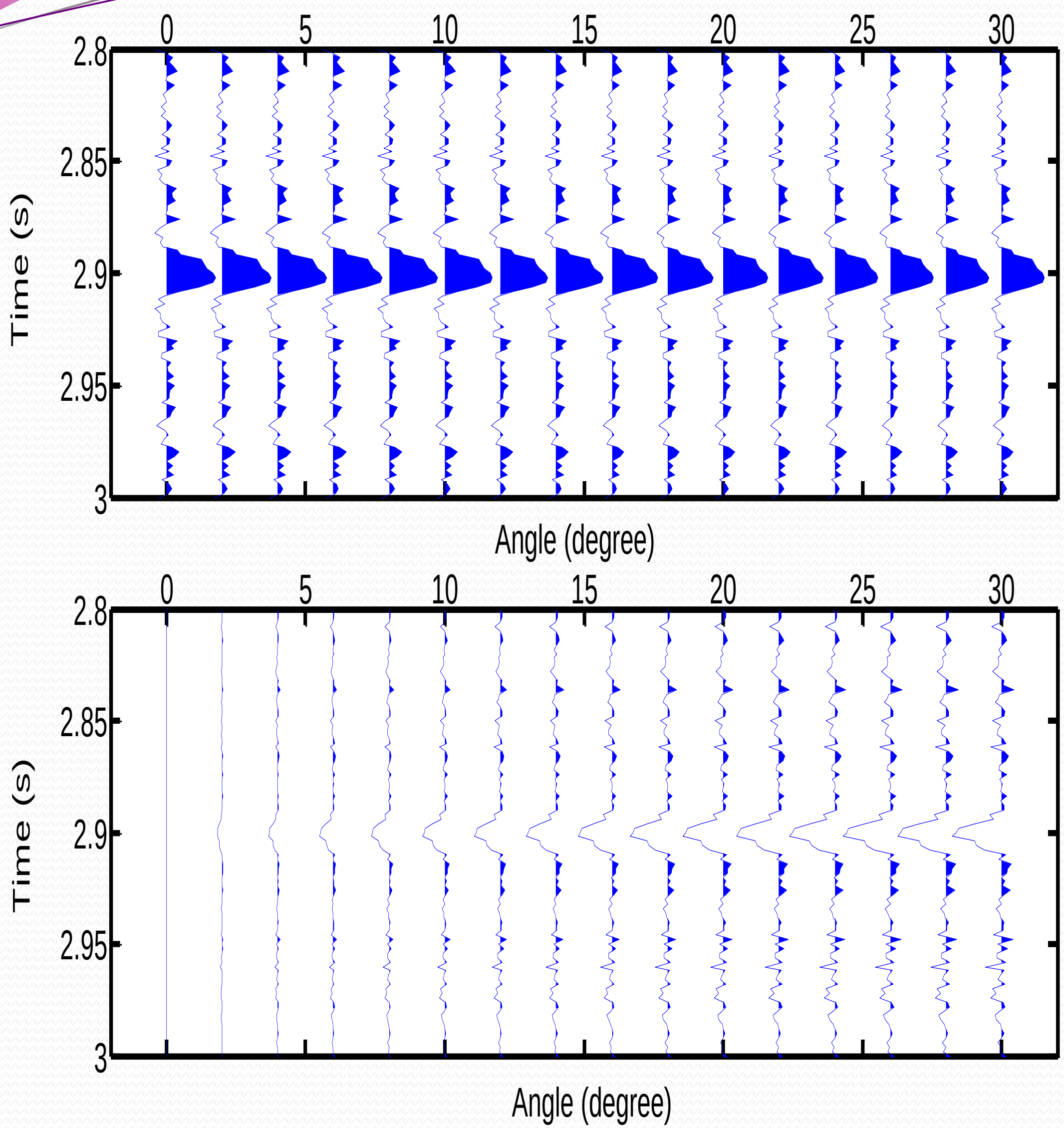
$\phi_I = 42\%$

Values of water saturation, effective stress and porosity at initial reservoir condition



Synthetic seismograms for PP and PS reflections of base case

- Reflection coefficients using Zoeppritz's equation
- Ricker wavelet with 30 Hz central frequency
- Maximum amplitude and corresponding travel time information are taken for both base and monitor



Synthetic seismograms for PP and PS reflections of base case (with random noise, SNR=0.4)

- Reflection coefficients using Zoeppritz's equation
- Ricker wavelet with 30 Hz central frequency
- Maximum amplitude and corresponding travel time information are taken for both base and monitor

- We test 4 different combinations/methods for 10 different reservoir scenarios. Those are:

➢ Method 1 $(\Delta R_0^{PP} - \Delta G)$

➢ Method 2 $(\Delta R^{PP} - \Delta R^{PS})$

➢ Method 3 $(\Delta R^{PP} - \Delta T_0^{PP})$

➢ Method 4 $(\Delta R^{PS} - \Delta T_0^{PP})$

- We calculate absolute error as

$$Abs_{error} = ABS(V_i^T - V_i^E)$$

where, V_i^T and V_i^E are true value and estimated value for the ith model

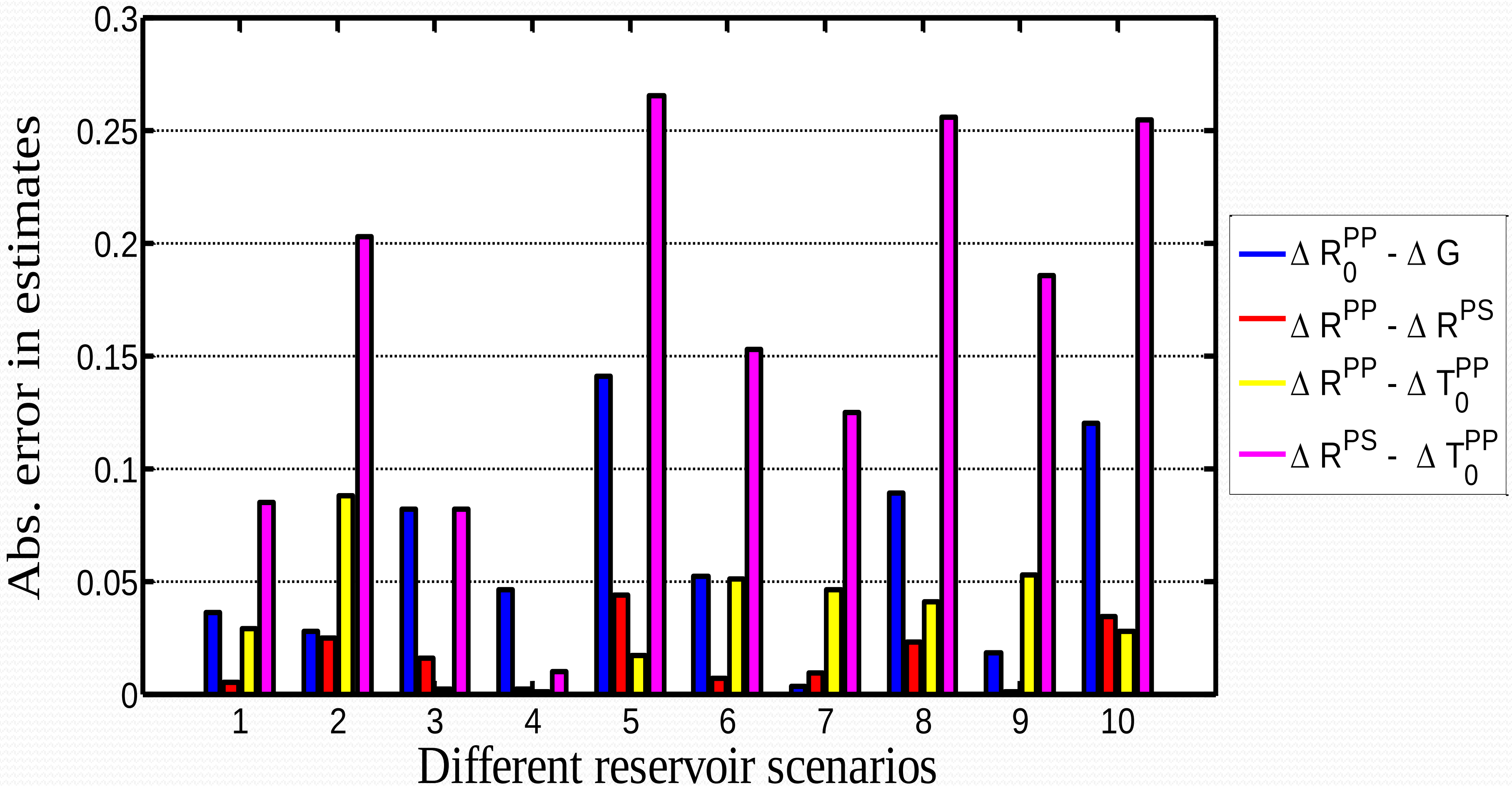
- We calculate root-mean-square (rms) error as

$$RMS_{error} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(V_i^T - V_i^E)^2}$$

Results (Saturation Estimations)

Different Combinations ⇨		ΔR_0^{PP} & ΔG (Method-1)	ΔR^{PP} & ΔR^{PS} (Method-2)	ΔR^{PP} & ΔT_0^{PP} (Method-3)	ΔR^{PS} & ΔT_0^{PP} (Method-4)
S_{w1} / S_{w2}	Real Change in Saturation	Est. Change in Saturation	Est. Change in Saturation	Est. Change in Saturation	Est. Change in Saturation
0.05/0.25	**0.200**	**0.236**	**0.195**	**0.171**	**0.285**
0.05/0.10	**0.050**	**0.022**	**0.025**	**-0.038**	**0.253**
0.05/0.35	**0.300**	**0.382**	**0.316**	**0.298**	**0.382**
0.05/0.30	**0.250**	**0.296**	**0.252**	**0.249**	**0.260**
0.05/0.45	**0.400**	**0.541**	**0.444**	**0.383**	**0.666**
0.05/0.40	**0.350**	**0.402**	**0.343**	**0.299**	**0.503**
0.05/0.05	**0.000**	**-0.003**	**-0.009**	**-0.046**	**0.125**
0.05/0.35	**0.300**	**0.389**	**0.323**	**0.259**	**0.556**
0.05/0.15	**0.100**	**0.118**	**0.099**	**0.047**	**0.286**
0.05/0.40	**0.350**	**0.470**	**0.384**	**0.322**	**0.605**

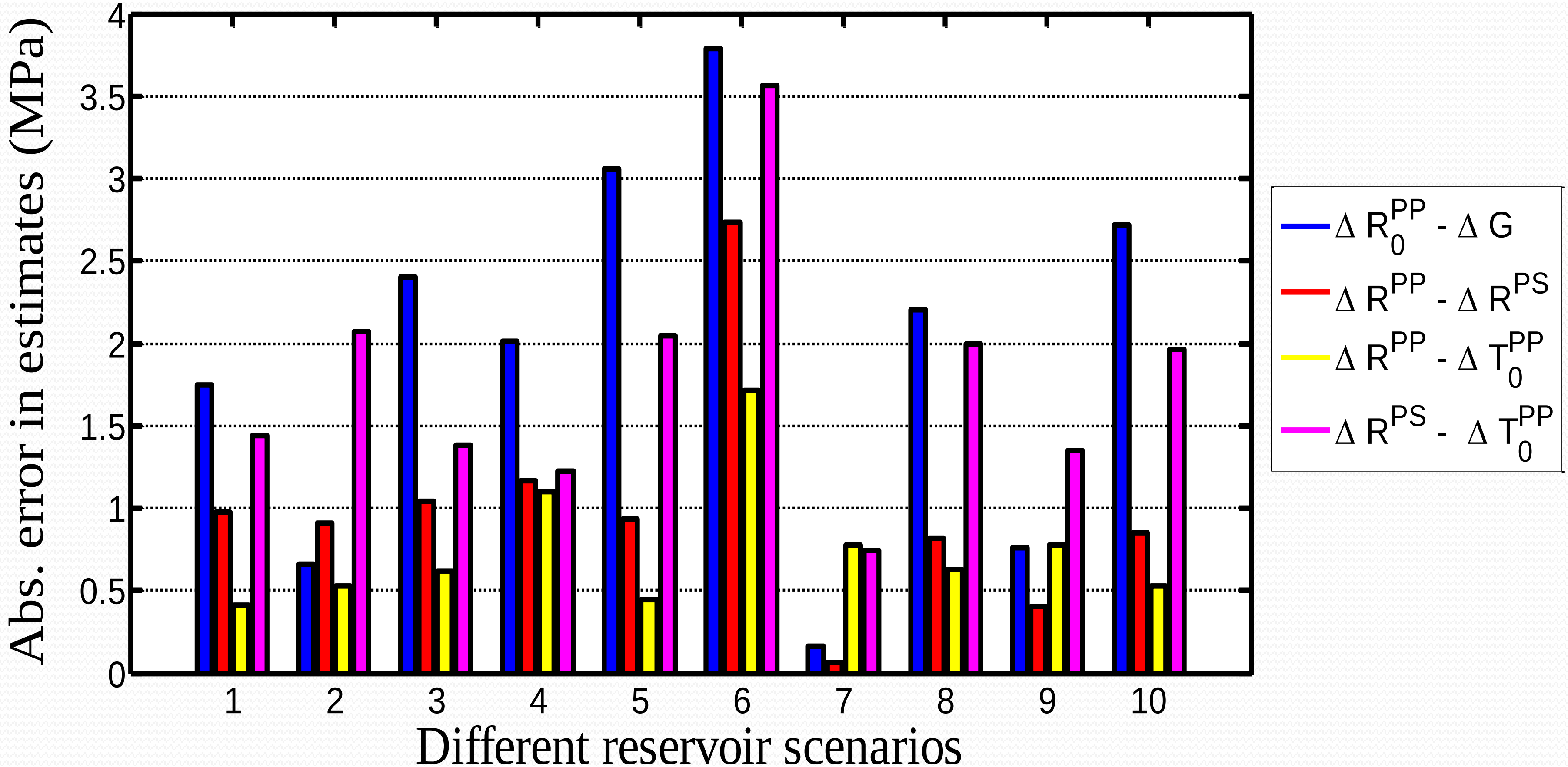
Results (Saturation Estimations)



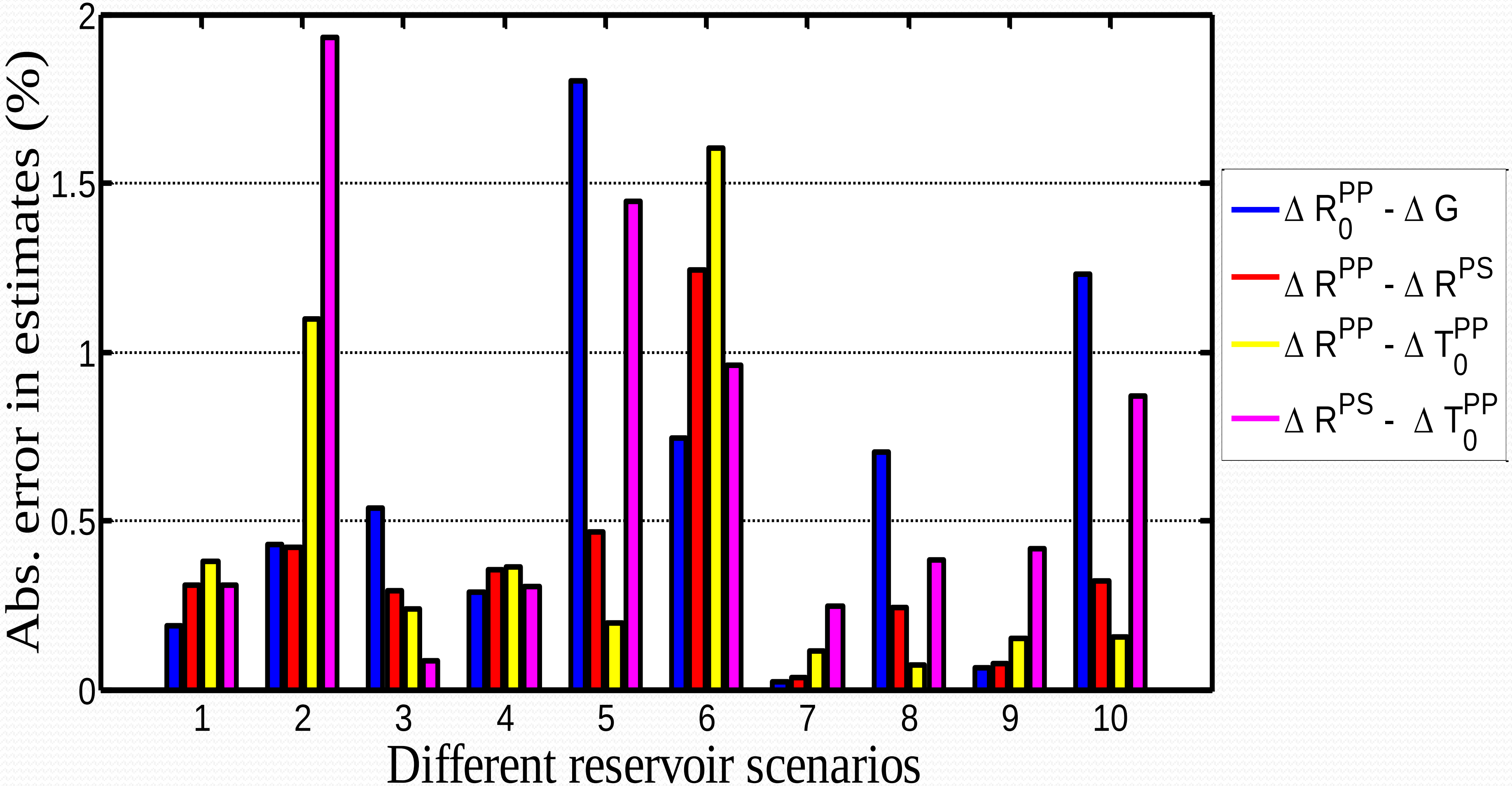
Results (Pressure Estimations)

Different Combinations ⟹		ΔR_0^{PP} & ΔG **(Method-1)**	ΔR^{PP} & ΔR^{PS} **(Method-2)**	ΔR^{PP} & ΔT_0^{PP} **(Method-3)**	ΔR^{PS} & ΔT_0^{PP} **(Method-4)**
σ_1 / σ_2 (MPa)	Real Change in stress (MPa)	Est. Change in stress (MPa)	Est. Change in stress (MPa)	Est. Change in stress (MPa)	Est. Change in stress (MPa)
13.80/24.13	**10.342**	**8.598**	**9.363**	**9.935**	**8.901**
13.80/27.58	**13.790**	**13.128**	**12.879**	**14.314**	**11.721**
13.80/20.68	**6.895**	**4.488**	**5.854**	**6.274**	**5.516**
13.80/24.13	**10.342**	**8.329**	**9.177**	**9.239**	**9.122**
13.80/13.80	**0.000**	**-3.054**	**-0.931**	**0.441**	**-2.048**
13.80/34.47	**20.684**	**16.899**	**17.954**	**18.974**	**17.120**
13.80/17.24	**3.447**	**3.282**	**3.385**	**4.220**	**2.703**
13.80/17.24	**3.447**	**1.241**	**2.627**	**4.075**	**1.455**
13.80/18.96	**5.171**	**4.413**	**4.771**	**5.943**	**3.827**
13.80/15.51	**1.724**	**-0.993**	**0.876**	**2.248**	**-0.241**

Results (Pressure Estimations)



Results (Porosity Estimations)



Results- noise free data

Methods	RMS error in ΔS_w	RMS error in $\Delta\sigma$ (MPa)	RMS error in $\Delta\phi$ (%)
ΔR_0^{PP} - ΔG^{PP}	**0.075**	**2.232**	**0.801**
ΔR^{PP} - ΔR^{PS}	**0.022**	**1.188**	**0.492**
ΔR^{PP} - ΔT_0^{PP}	**0.043**	**0.838**	**0.649**
ΔR^{PS} - ΔT_0^{PP}	**0.182**	**1.919**	**0.899**

Results – noisy data

Methods	**RMS error in ΔS_w** (with random noise, Where SNR=0.4)	**RMS error in $\Delta\sigma$** (MPa) (with random noise, Where SNR=0.4)	**RMS error in $\Delta\phi$ (%)** (with random noise, Where SNR=0.4)
ΔR_0^{PP} - ΔG^{PP}	**0.286**	**33.401**	**20.619**
ΔR^{PP} - ΔR^{PS}	**0.123**	**10.953**	**4.942**
ΔR^{PP} - ΔT_0^{PP}	**0.074**	**5.521**	**1.928**
ΔR^{PS} - ΔT_0^{PP}	**0.692**	**24.175**	**25.630**

Discussions and Conclusions

- Adding other 4D attributes to PP-AVO improves the 4D estimates of pressure, saturation and porosity changes
- PP-PS amplitude combination reduces the uncertainty in the estimated saturation, effective stress and porosity changes; than PP-AVO
- PP–amplitude and travel time combination further reduces the uncertainty of the pressure estimates
- For noisy data, PP-amplitude and travel time combination provides best estimates of pressure, saturation and porosity changes
- Various combination works better for different 4D estimates, we could use all the attributes as an over determined system to estimate these 4D changes
- In this example we have assumed a chalk reservoir with 42 % porosity. For other initial porosities, values can be different.
- The Gassmann and Hertz-Mindlin equations are the basic equations used in the rock physics model. The validity of these equations for a chalk reservoir is questionable.

Acknowledgements

- Total E&P Norge for sponsoring my research
- The sponsors of the Rose Consortium

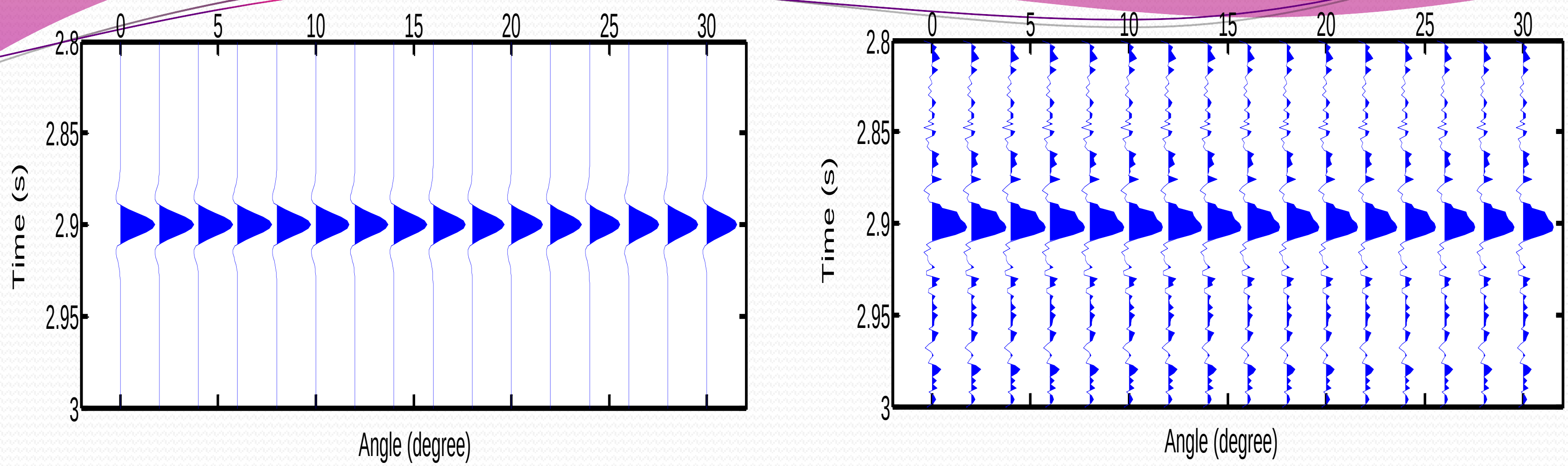
Questions ??????????

Results- noise free data

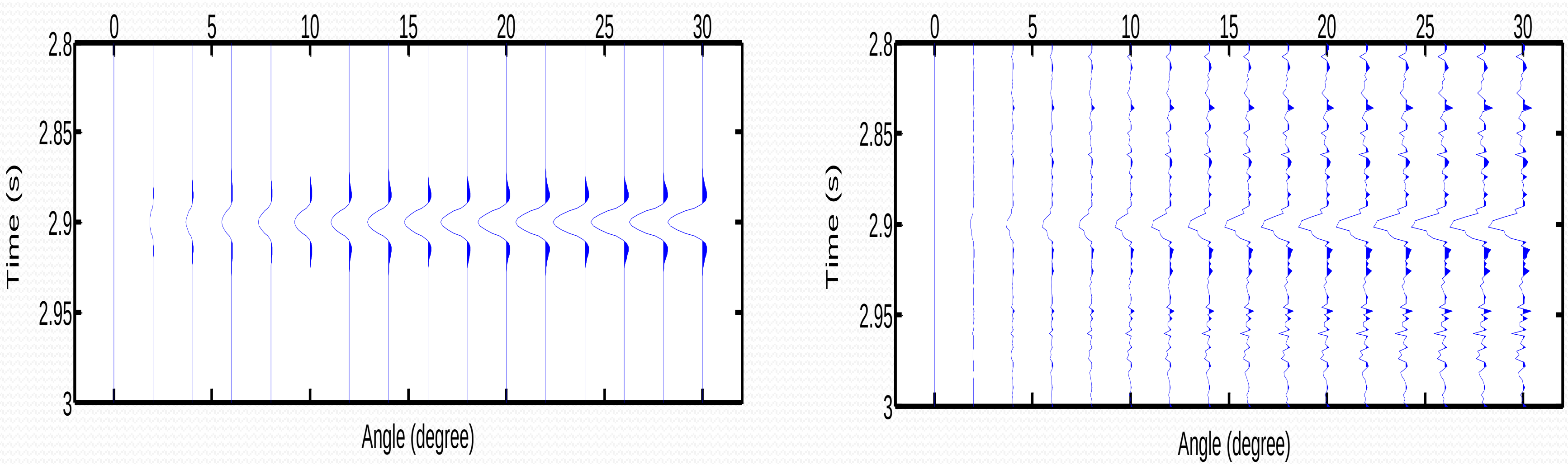
Methods	RMS error in ΔS_w	RMS error in $\Delta\sigma$ (MPa)	RMS error in $\Delta\phi$ (%)
ΔR_0^{PP} - ΔG^{PP}	**0.075**	**2.232**	**0.801**
ΔR^{PP} - ΔR^{PS}	**0.022**	**1.188**	**0.492**
ΔR^{PP} - ΔT_0^{PP}	**0.043**	**0.838**	**0.649**
ΔR^{PS} - ΔT_0^{PP}	**0.182**	**1.919**	**0.899**
ΔR^{PP} ΔR^{PS} ΔT_0^{PP}	**0.031**	**0.824**	**0.568**
ΔR_0^{PP} ΔG^{PP} ΔR^{PP} ΔR^{PS} ΔT_0^{PP}	**0.076**	**1.621**	**0.481**

Results – noisy data

Methods	**RMS error in ΔS_w** (with random noise, Where SNR=0.4)	**RMS error in** $\Delta\sigma$ (MPa) (with random noise, Where SNR=0.4)	**RMS error in** $\Delta\phi$ **(%)** (with random noise, Where SNR=0.4)
ΔR_0^{PP} - ΔG^{PP}	**0.286**	**33.401**	**20.619**
ΔR^{PP} - ΔR^{PS}	**0.123**	**10.953**	**4.942**
ΔR^{PP} - ΔT_0^{PP}	**0.074**	**5.521**	**1.928**
ΔR^{PS} - ΔT_0^{PP}	**0.692**	**24.175**	**25.630**
ΔR^{PP} ΔR^{PS} ΔT_0^{PP}	**0.055**	**1.330**	**0.693**
ΔR_0^{PP} ΔG^{PP} ΔR^{PP} ΔR^{PP} ΔT_0^{PP}	**0.293**	**4.887**	**2.067**



Synthetic seismograms for PP reflections



Synthetic seismograms for PS reflections

Results (Saturation Estimation)

- For ΔR^{PS} and ΔT_0^{PP} combination

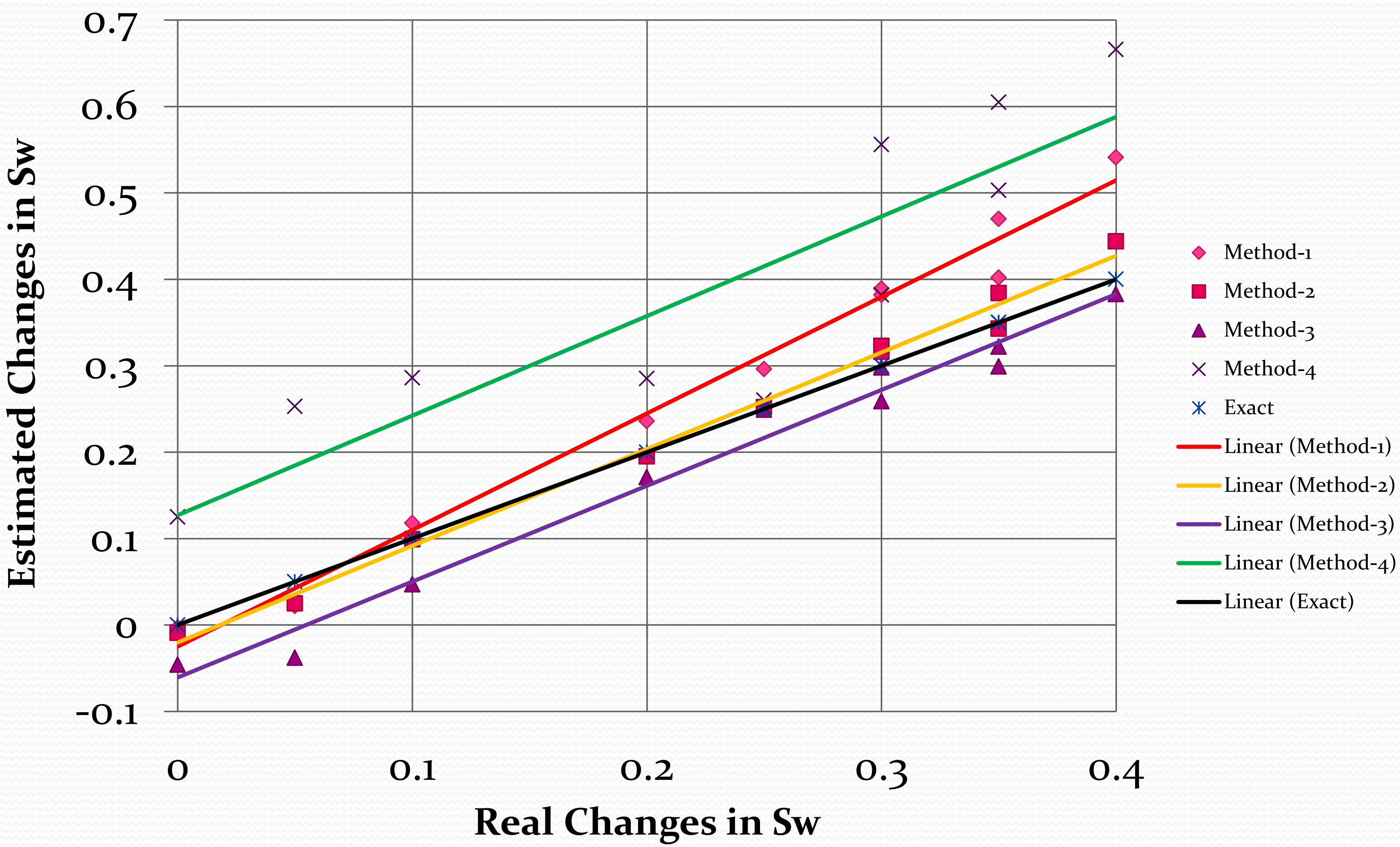
Different Combinations ⟹		ΔR_0^{PP} & ΔG	ΔR^{PP} & ΔR^{PS}	ΔR^{PP} & ΔT_0^{PP}	ΔR^{PS} & ΔT_0^{PP}
S_{w1} / S_{w2}	Real Change in Saturation	Est. Change in Saturation	Est. Change in Saturation	Est. Change in Saturation	Est. Change in Saturation
0.05/0.25	**0.200**	**0.236**	**0.195**	**0.171**	**0.285**
0.05/0.10	**0.050**	**0.022**	**0.025**	**-0.038**	**0.253**
0.05/0.35	**0.300**	**0.382**	**0.316**	**0.298**	**0.382**
0.05/0.30	**0.250**	**0.296**	**0.252**	**0.249**	**0.260**
0.05/0.45	**0.400**	**0.541**	**0.444**	**0.383**	**0.666**
0.05/0.40	**0.350**	**0.402**	**0.343**	**0.299**	**0.503**
0.05/0.05	**0.000**	**-0.003**	**-0.009**	**-0.046**	**0.125**
0.05/0.35	**0.300**	**0.389**	**0.323**	**0.259**	**0.556**
0.05/0.15	**0.100**	**0.118**	**0.099**	**0.047**	**0.286**
0.05/0.40	**0.350**	**0.470**	**0.384**	**0.322**	**0.605**

Results (Pressure Estimation)

- For ΔR^{PS} and ΔT_0^{PP} combination

Different Combinations ⟹		ΔR_0^{PP} & ΔG	ΔR^{PP} & ΔR^{PS}	ΔR^{PP} & ΔT_0^{PP}	ΔR^{PS} & ΔT_0^{PP}
σ_1 / σ_2 (kpsi)	Real Change in stress	Est. Change in stress	Est. Change in stress	Est. Change in stress	Est. Change in stress
2.0/3.5	**1.500**	**1.247**	**1.358**	**1.441**	**1.291**
2.0/4.0	**2.000**	**1.904**	**1.868**	**2.076**	**1.700**
2.0/3.0	**1.000**	**0.651**	**0.849**	**0.910**	**0.800**
2.0/2.5	**1.500**	**1.208**	**1.331**	**1.340**	**1.323**
2.0/2	**0.000**	**-0.443**	**-0.135**	**0.064**	**-0.297**
2.0/5	**3.000**	**2.451**	**2.604**	**2.752**	**2.483**
2.0/2.5	**0.500**	**0.476**	**0.491**	**0.612**	**0.392**
2.0/2.5	**0.500**	**0.180**	**0.381**	**0.591**	**0.211**
2.0/2.75	**0.750**	**0.640**	**0.692**	**0.862**	**0.555**
2.0/2.25	**0.250**	**-0.144**	**0.127**	**0.326**	**-0.035**

Results (Saturation Estimations)

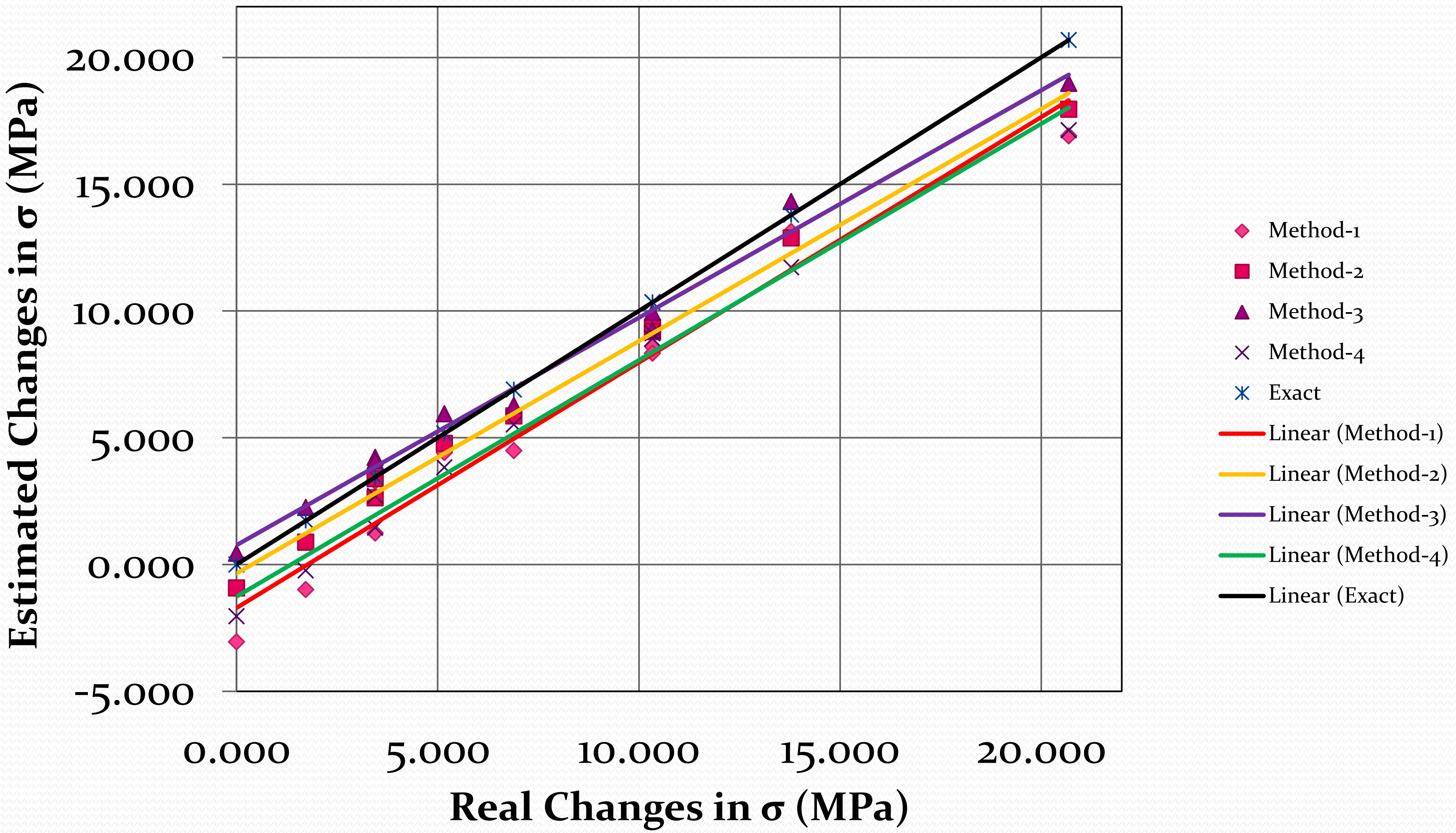


Results (Porosity Estimations)

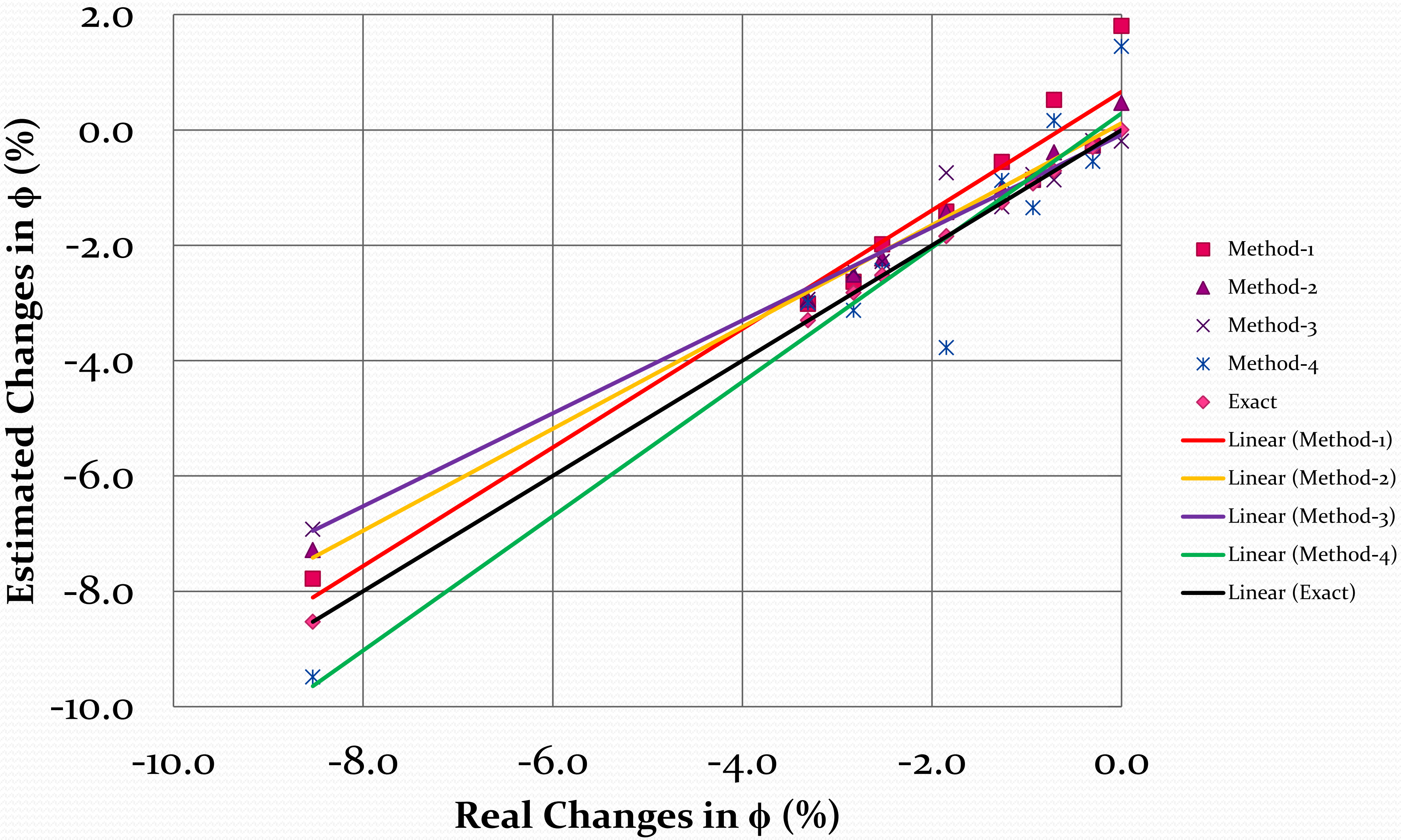
Different Combinations ⇨	ΔR_0^{PP} & ΔG (Method-1)	ΔR^{PP} & ΔR^{PS} (Method-2)	ΔR^{PP} & ΔT_0^{PP} (Method-3)	ΔR^{PS} & ΔT_0^{PP} (Method-4)
Real Change in porosity (%)	Est. Change in porosity (%)	Est. Change in porosity (%)	Est. Change in porosity (%)	Est. Change in porosity (%)
-2.825	**-2.635**	**-2.514**	**-2.446**	**-3.133**
-1.846	**-1.416**	**-1.425**	**-0.747**	**-3.778**
-2.523	**-1.984**	**-2.229**	**-2.284**	**-2.438**
-3.305	**-3.017**	**-2.949**	**-2.943**	**-2.999**
0.000	**1.801**	**0.465**	**-0.195**	**1.445**
-8.529	**-7.784**	**-7.287**	**-6.926**	**-9.491**
-0.302	**-0.278**	**-0.268**	**-0.189**	**-0.550**
-1.262	**-0.557**	**-1.017**	**-1.336**	**-0.878**
-0.932	**-0.869**	**-0.856**	**-0.779**	**-1.351**
-0.711	**0.520**	**-0.389**	**-0.868**	**0.157**

Avg. RMS Error	**0.801**	**0.492**	**0.649**	**0.899**

Results (Pressure Estimations)



Results (Porosity Estimations)



Results

- Saturation Estimation with random noise (SNR =0.4)

Different Combinations ⟹		ΔR_0^{PP} & ΔG	ΔR^{PP} & ΔR^{PS}	ΔR^{PP} & ΔT_0^{PP}	ΔR^{PS} & ΔT_0^{PP}
S_{w1} / S_{w2}	Real Change in Saturation	Est. Change in Saturation	Est. Change in Saturation	Est. Change in Saturation	Est. Change in Saturation
0.05/0.25	**0.200**	**0.469**	**0.330**	**0.179**	**0.878**
0.05/0.10	**0.050**	**0.260**	**0.184**	**0.077**	**0.572**
0.05/0.35	**0.300**	**0.607**	**0.421**	**0.196**	**1.236**
0.05/0.30	**0.250**	**0.524**	**0.367**	**0.247**	**0.801**
0.05/0.45	**0.400**	**0.775**	**0.584**	**0.487**	**0.934**
0.05/0.40	**0.350**	**0.626**	**0.443**	**0.194**	**1.344**
0.05/0.05	**0.000**	**0.221**	**0.094**	**0.038**	**0.298**
0.05/0.35	**0.300**	**0.612**	**0.421**	**0.246**	**1.051**
0.05/0.15	**0.100**	**0.339**	**0.189**	**0.031**	**0.764**
0.05/0.40	**0.350**	**0.689**	**0.468**	**0.303**	**1.066**

Results

- Pressure Estimation with random noise (SNR =0.4)

Different Combinations ⟹		ΔR_0^{PP} & ΔG	ΔR^{PP} & ΔR^{PS}	ΔR^{PP} & ΔT_0^{PP}	ΔR^{PS} & ΔT_0^{PP}
σ_1 / σ_2 (kpsi)	Real Change in stress	Est. Change in stress	Est. Change in stress	Est. Change in stress	Est. Change in stress
2.0/3.5	**1.500**	**3.340**	**2.735**	**1.080**	**4.078**
2.0/4.0	**2.000**	**0.916**	**3.454**	**1.272**	**5.225**
2.0/3.0	**1.000**	**5.397**	**2.483**	**0.579**	**4.029**
2.0/2.5	**1.500**	**-8.036**	**3.267**	**0.452**	**5.554**
2.0/2	**0.000**	**7.055**	**1.294**	**-0.746**	**2.950**
2.0/5	**3.000**	**5.541**	**3.999**	**2.514**	**5.205**
2.0/2.5	**0.500**	**-2.627**	**2.982**	**-1.038**	**6.246**
2.0/2.5	**0.500**	**0.461**	**1.412**	**0.529**	**2.129**
2.0/2.75	**0.750**	**7.433**	**2.783**	**-0.148**	**5.162**
2.0/2.25	**0.250**	**-2.781**	**1.824**	**-0.431**	**3.654**