Influence of frequency and saturation on AVO attributes in partially saturated rocks

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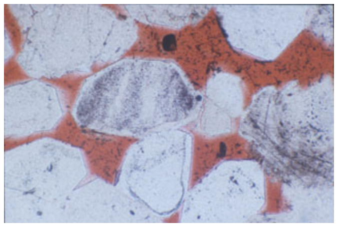
Outline

- Introduction: why poroelasticity and AVO data ?
- Theories: wave propagation in porous media and patchy saturation
- Method to extract AVO attributes
- Results: influence of frequency and saturation

Global workflow

Porosity, fluid and solid parameters....

MICRO-SCALE PARAMETERS



Seismic wave propagation in multiphasic media

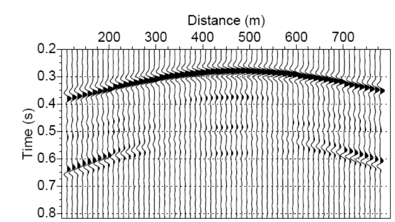
Forward problem

Inverse problem

Quantitative imaging of poroelastic parameters

Seismograms

MACRO-SCALE DATA

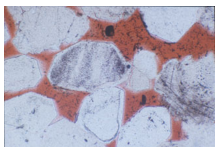


Seismogram with injection

Forward problem

Porosity, fluid and solid parameters....

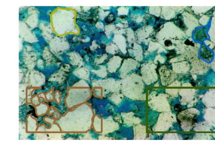
MICRO-SCALE PARAMETERS



UPSCALING

Effective porous parameters

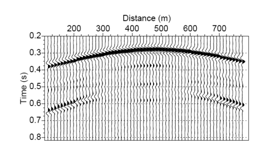
MACRO-SCALE PARAMETERS



MODELING

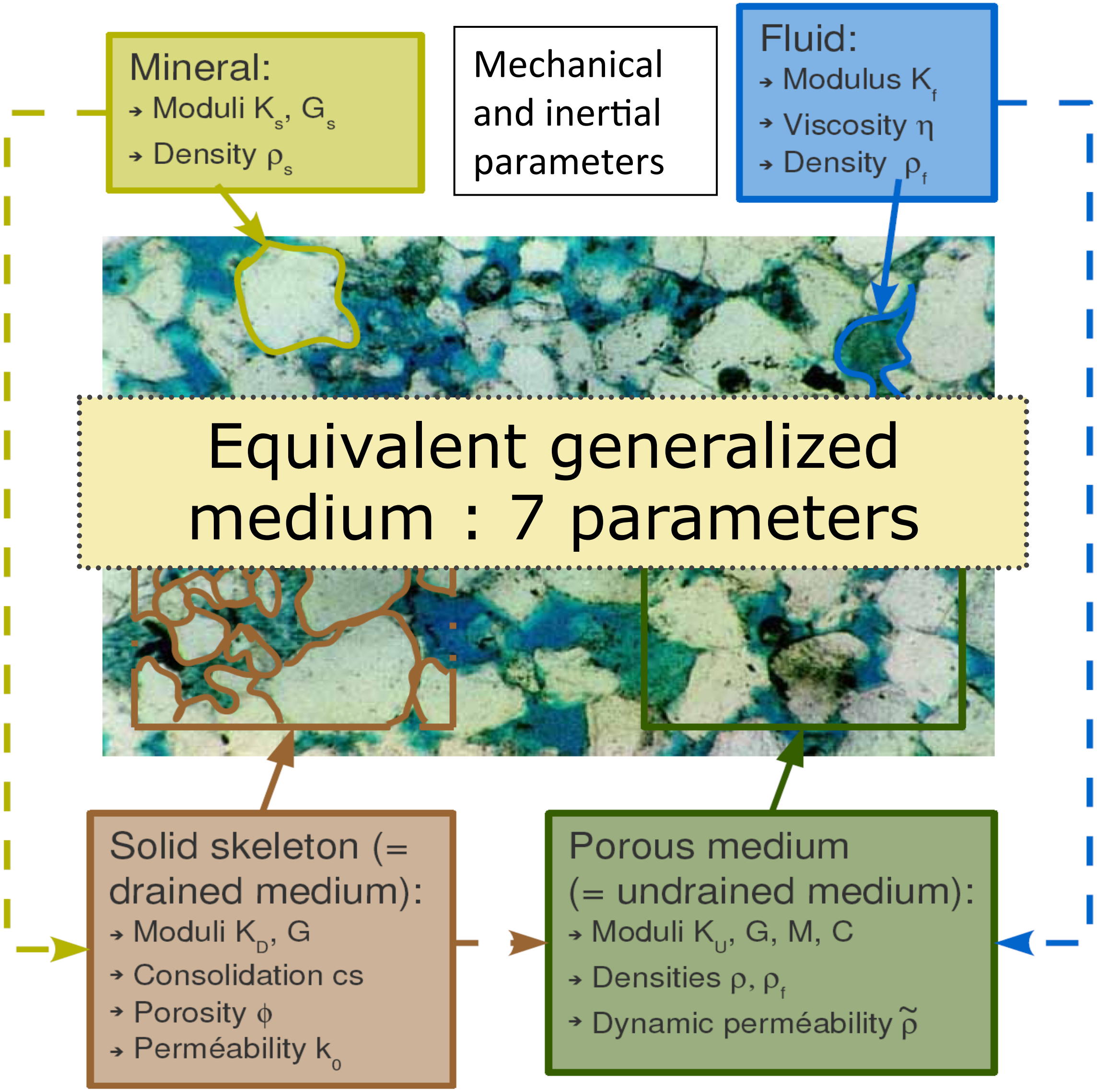
Forward problem

MACRO-SCALE DATA



Seismograms

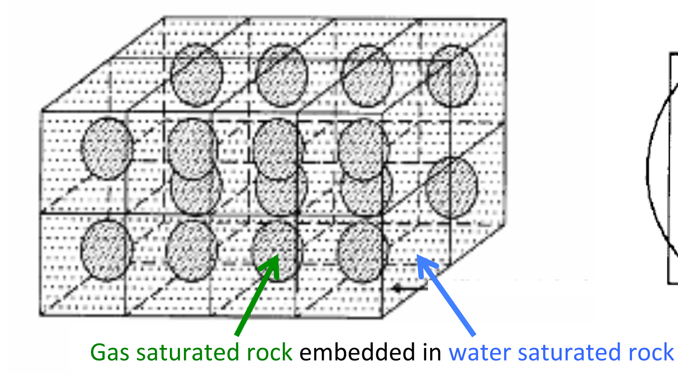
« Simple » upscaling (Biot-Gassmann)

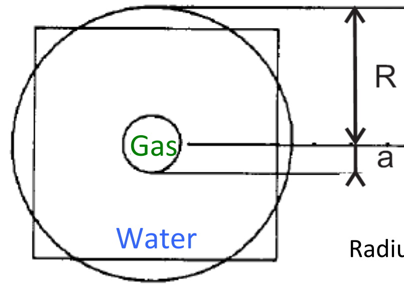


Analytic relations

De Barros, 2007

« Complex » upscaling: patchy saturation

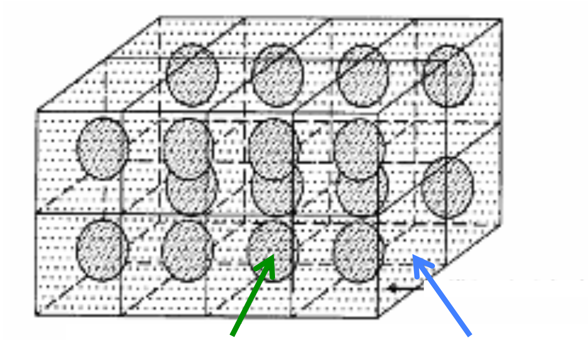




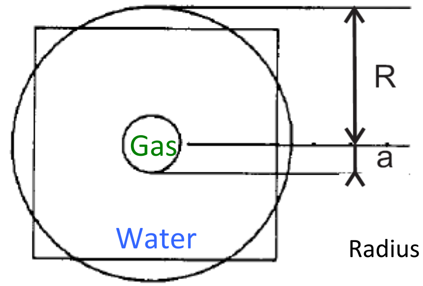
Radius of patches = a

Physical description (*White, 1975; Pride et al., 2004*): 16 parameters

« Complex » upscaling: patchy saturation



Gas saturated rock embedded in water saturated rock

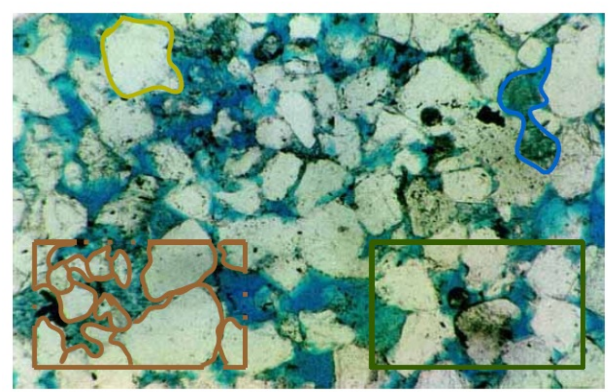


Radius of patches = a

Physical description (*White, 1975; Pride et al., 2004*): 16 parameters

Analytic relations for **low** and **high** saturations

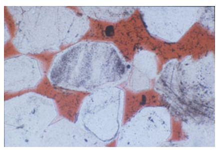
Equivalent generalized Biot-Gassmann medium: 7 parameters



Forward problem

Porosity, fluid and solid parameters....

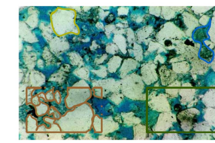
MICRO-SCALE PARAMETERS



UPSCALING

Effective porous parameters

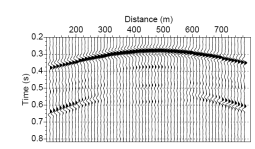
MACRO-SCALE PARAMETERS



MODELING

Forward problem

MACRO-SCALE DATA



Seismograms

Poroelastodynamic equations

$$\left\{\begin{array}{ll} \nabla.\boldsymbol{\tau} = -\,\omega^2\,(\rho\,\vec{u} + \rho_f\,\vec{w}) & \textit{Equations of motion} \\ \boldsymbol{\tau} = [K_U\,\nabla.\vec{u} + C\,\nabla.\vec{w}]\,\boldsymbol{I} + G\,[\nabla\vec{u} + (\nabla\vec{u})^t - 2/3\,\nabla.\vec{u}\boldsymbol{I}] & \\ -P = C\,\nabla.\vec{u} + M\,\nabla.\vec{w} & \textit{Mechanical behaviour laws} \\ -\nabla P = -\,\omega^2\,(\rho_f\,\vec{u} + \tilde{\rho}\,\vec{w}) & \textit{Equations of motion} \end{array}\right.$$

Elastic fields
Poroelastic fields

8 unknowns in 2D :

- Solid u_x and u_z and relative fluid/solid w_x and w_z displacements
- Stresses τ_{xx}, τ_{zz}, τ_{xz} and fluid pressure P

7 parameters :

- *Inertial terms:* ρ, ρ_f and $\tilde{\rho}$
- *Mechanical moduli:* K_U, G, C and M

Poroelastodynamic equations

$$\begin{cases} \nabla.\boldsymbol{\tau} = -\,\omega^2\,(\rho\,\vec{u} + \rho_f\,\vec{w}) \\ \boldsymbol{\tau} = [K_U\,\nabla.\vec{u} + C\,\nabla.\vec{w}]\,\boldsymbol{I} + G\,[\nabla\vec{u} + (\nabla\vec{u})^t - 2/3\,\nabla.\vec{u}\boldsymbol{I}] \\ -P = C\,\nabla.\vec{u} + M\,\nabla.\vec{w} \\ -\nabla P = -\,\omega^2\,(\rho_f\,\vec{u} + \tilde{\rho}\,\vec{w}) \end{cases}$$

Simple upscaling

<u>Frequency dependence:</u> ω

– *Simple upscaling:* $\tilde{\rho}(\omega)$ ➔ flow resistance term

Poroelastodynamic equations

$$\begin{cases} \nabla . \boldsymbol{\tau} = -\,\omega^2\,(\rho\,\vec{u} + \rho_f\,\vec{w}) \\ \boldsymbol{\tau} = [K_U\,\nabla.\vec{u} + C\,\nabla.\vec{w}]\,\boldsymbol{I} + G\,[\nabla\vec{u} + (\nabla\vec{u})^t - 2/3\,\nabla.\vec{u}\boldsymbol{I}] \\ -P = C\,\nabla.\vec{u} + M\,\nabla.\vec{w} \\ -\nabla P = -\,\omega^2\,(\rho_f\,\vec{u} + \tilde{\rho}\,\vec{w}) \end{cases}$$

Complex upscalings

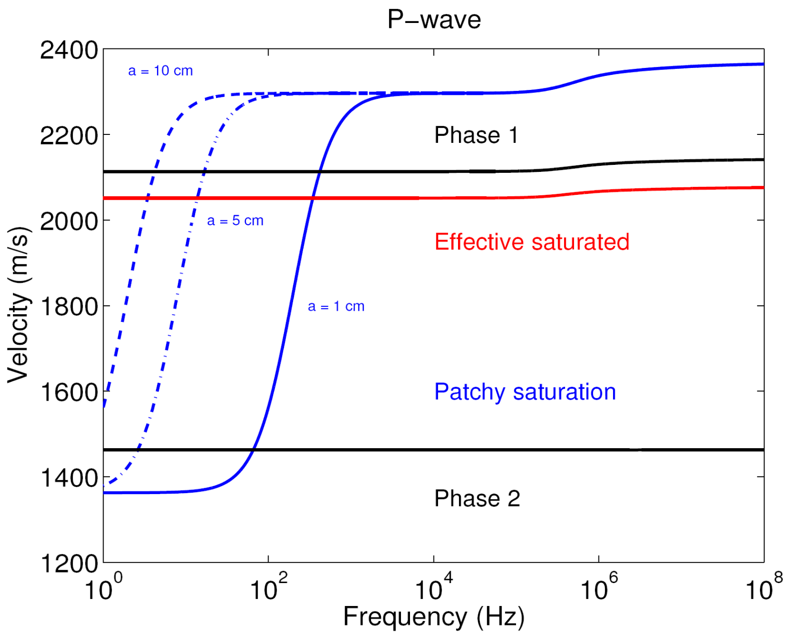
Simple upscaling

<u>Frequency dependence:</u> ω

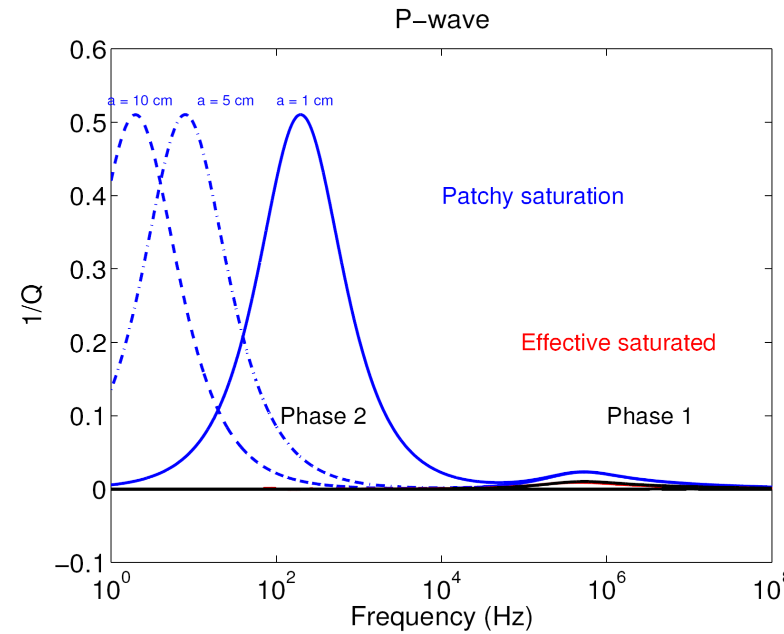
- *Simple upscaling:* $\tilde{\rho}$ (ω) ➔ flow resistance term
- *Complex upscalings:* $\tilde{\rho}$ (ω)

  K_U (ω), G (ω), C (ω) and M (ω) ➔ mechanic moduli

Partial saturation: effective attributes



P-waves velocities

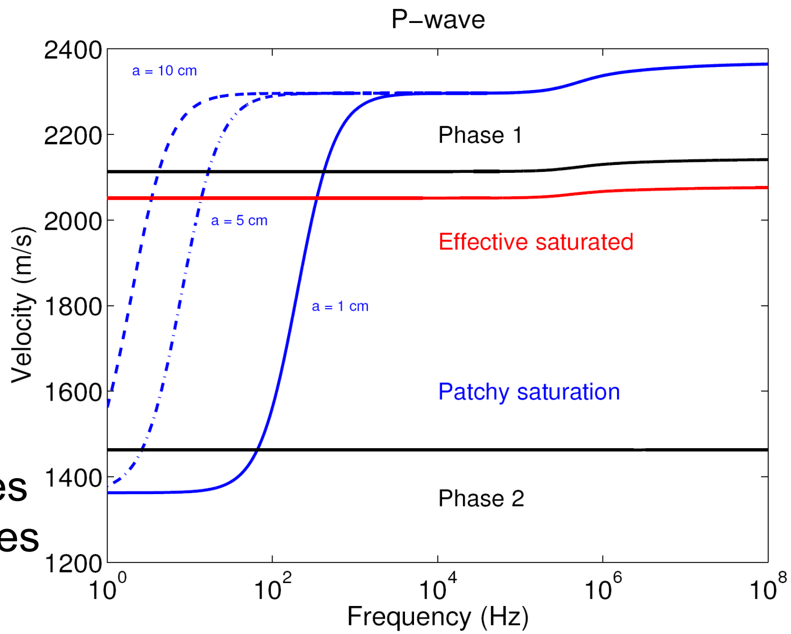


P-waves attenuations

Patchy saturation results with various patches sizes a

Effective fluid phase results (computed using averages equations and plugged in Biot saturated theory)

Partial saturation: effective attributes



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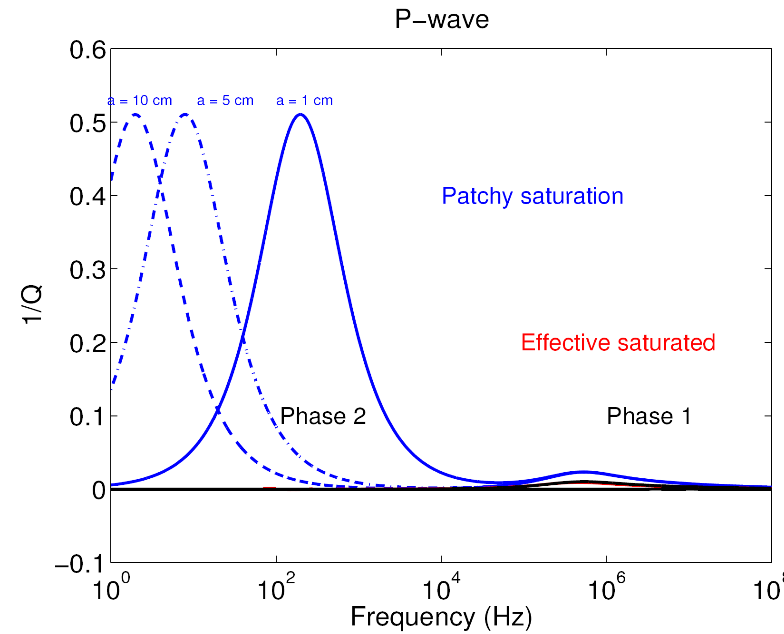
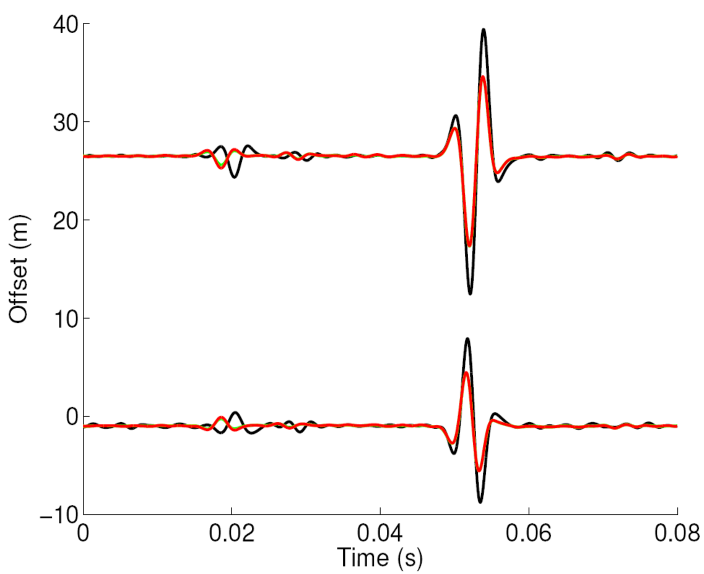
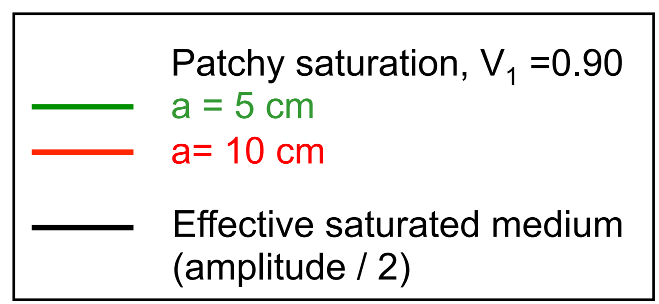


P-waves attenuations

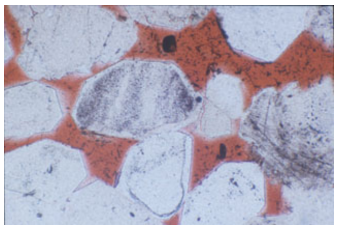




Inverse problem

Porosity, fluid and solid parameters….

MICRO-SCALE PARAMETERS

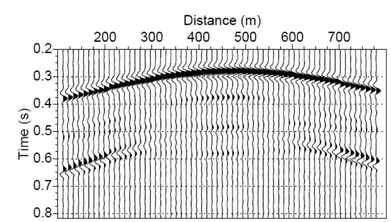


Inverse problem

Quantitative imaging of poroelastic parameters

Seismograms

MACRO-SCALE DATA



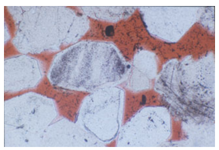
Seismogram with injection

Two-steps inversion

Porosity, solid and fluid parameters….

MICRO-SCALE PARAMETERS

Between 10 and 18 parameters



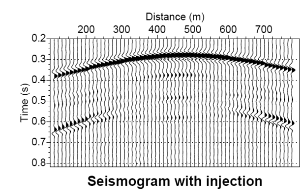
Two-steps inversion:

- seismic imaging: local optimization
- downscaling: semi-global optimization

DOWNSCALING

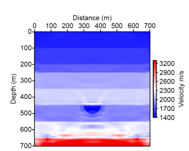
Grid search: Monte-Carlo, NA, GA, SA…

Inverse problem



MACRO-SCALE ATTRIBUTES

- Propagation velocities: V_P, V_S
- Attenuations : Q_P, Q_S
- AVO attributes
- Phase velocities



SEISMIC IMAGING

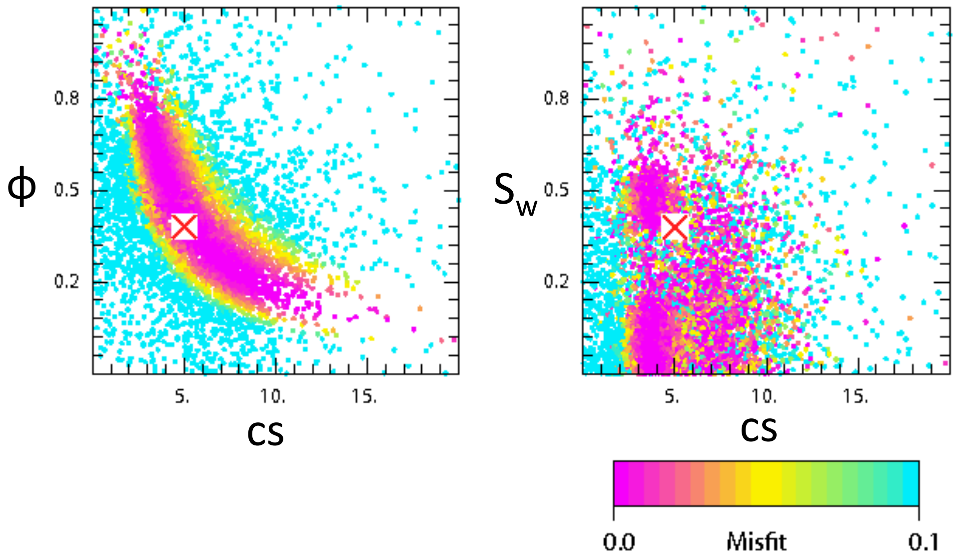
- Arrival times tomography
- FWI
- AVO analysis
- MASW

MACRO-SCALE DATA

- Arrival times
- Attenuations
- Full waveforms
- Polarization
- Surface waves dispersion

Skeleton and saturation parameters downscaling (unsaturated medium)

<u>Fit:</u>
φ = 34 %
cs = 22 %
S_w = 70 %



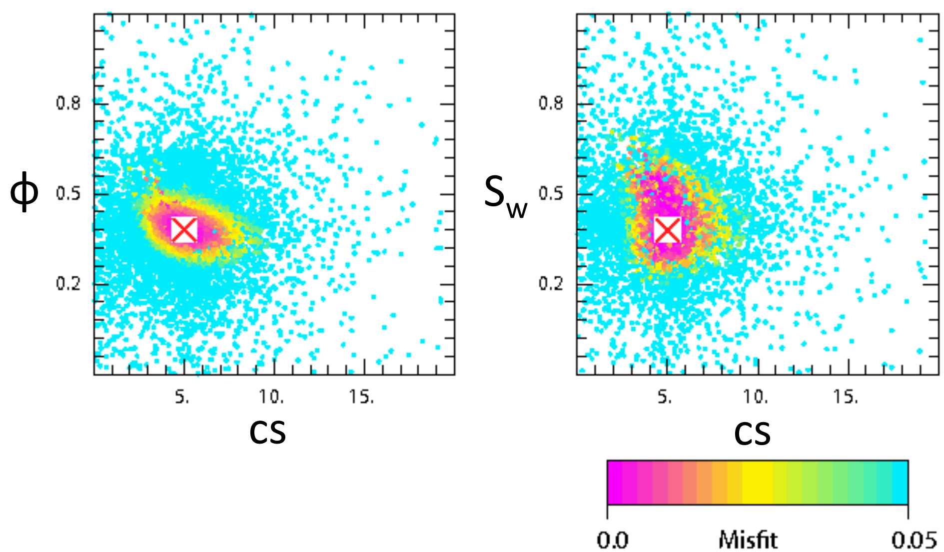
× True model

V_P, V_S

<u>A priori known parameters:</u>

- Fluid phases: K_f, ρ_f, η
- Solid phase: K_s, G_s, ρ_s

<u>Fit:</u>
φ = 0.14 %
cs = 0.6 %
S_w = 0.5 %



V_P, Q_P, ρ

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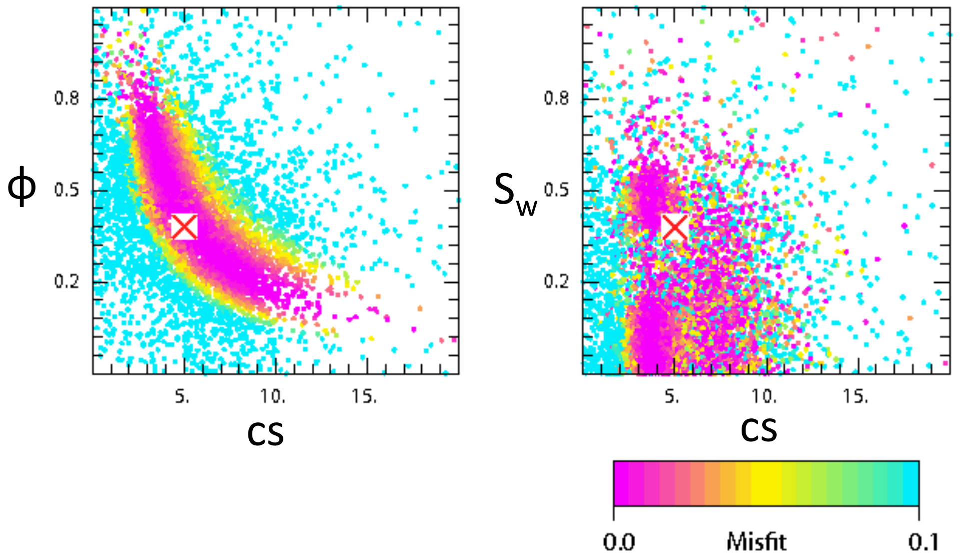

✕ True model

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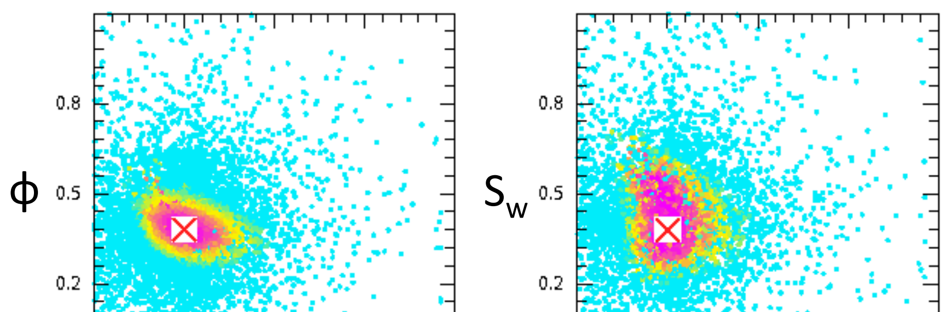
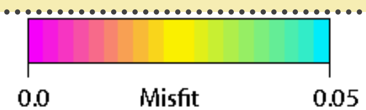
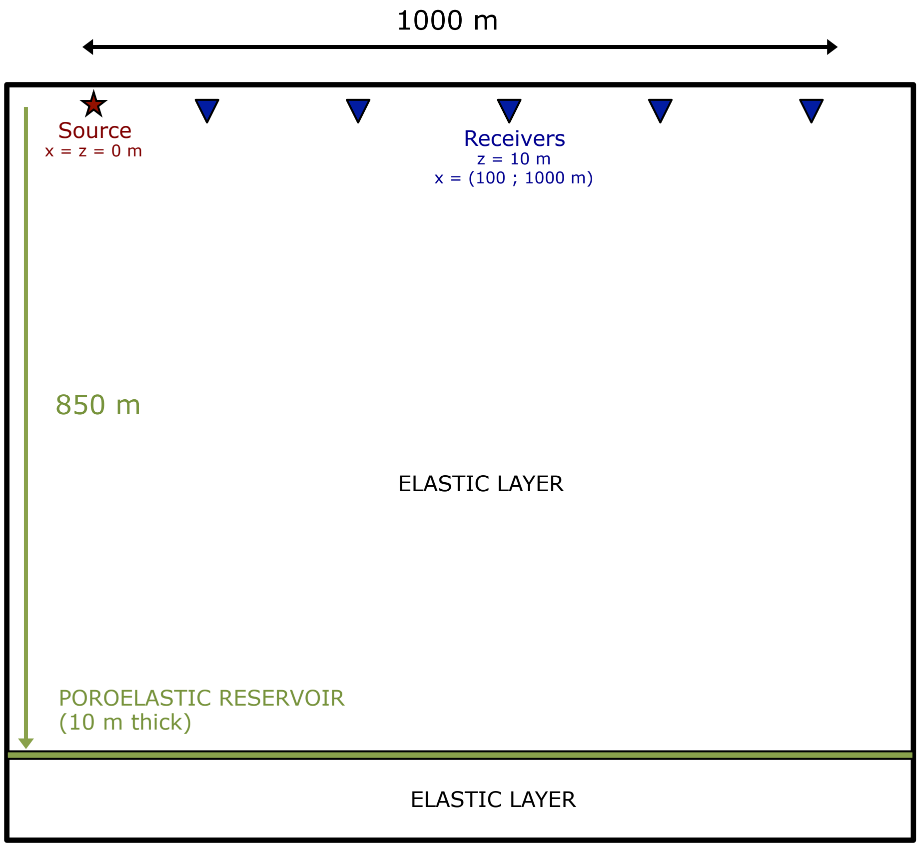


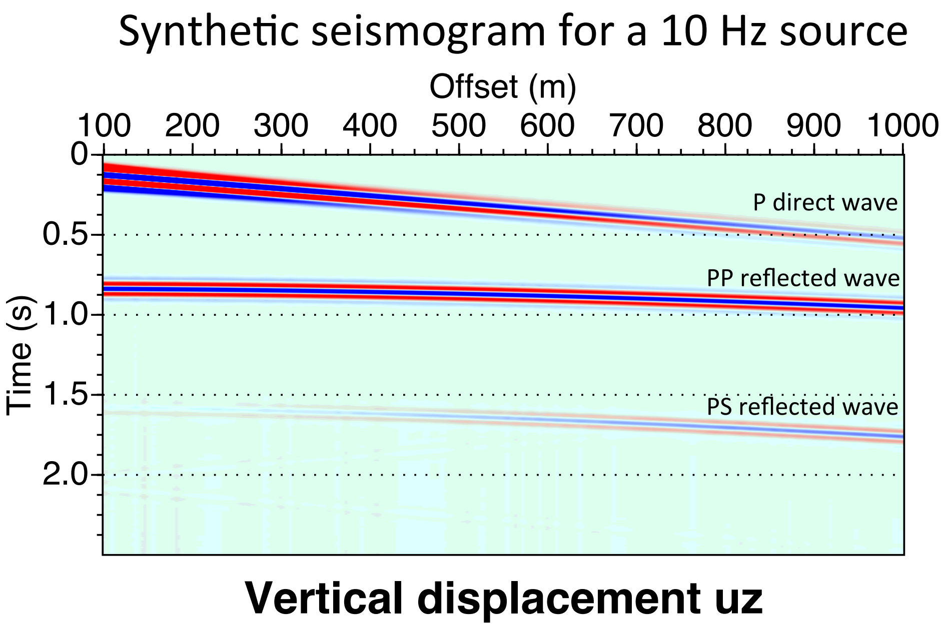
V_P, Q_P, ρ

➔ Need of amplitude data to estimate saturation => AVO data



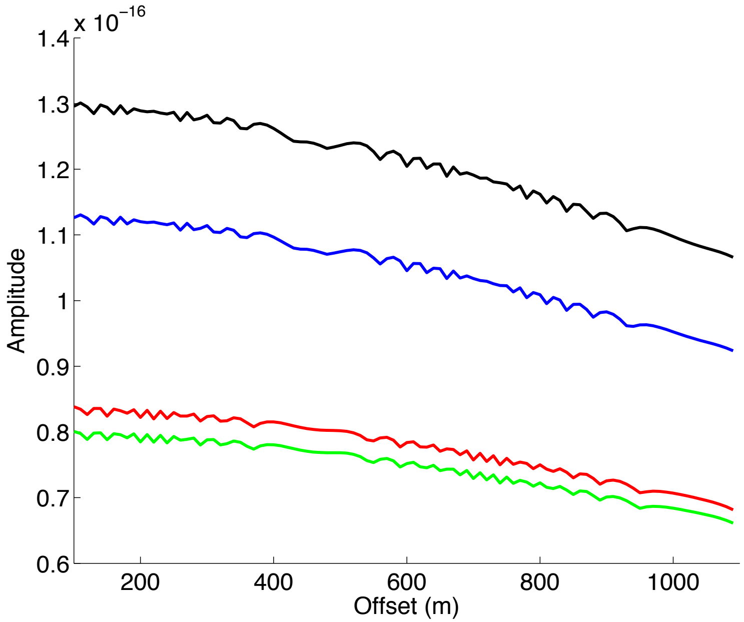
3D three layers model



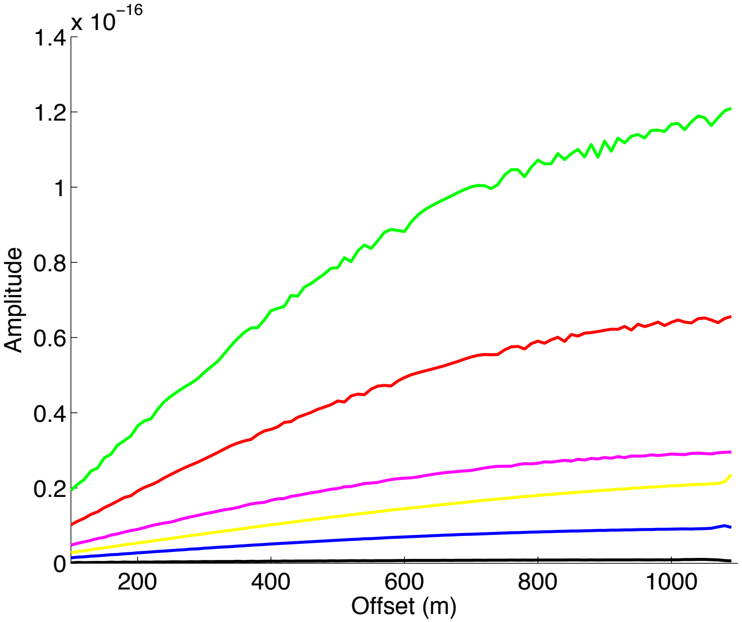


Explosive source
Source function = Ricker wavelet
Central frequency = 10 to 60 Hz

AVO curves for PP and PS events

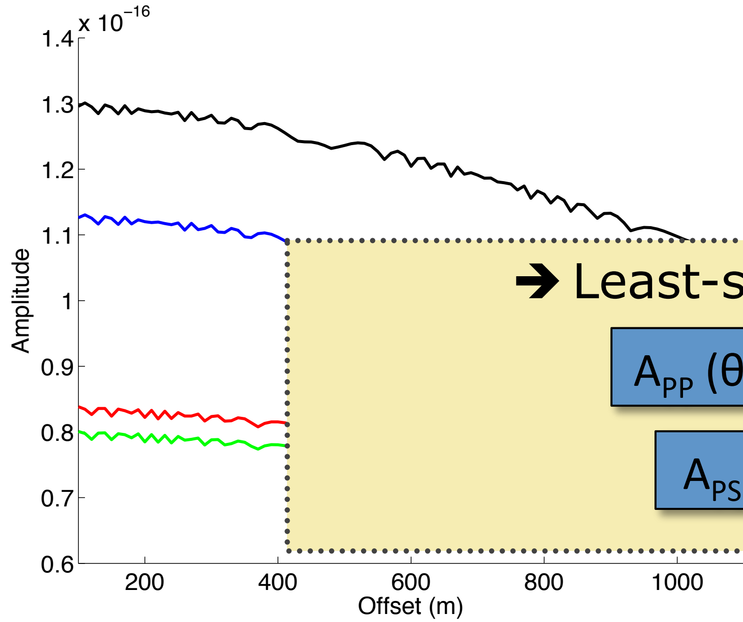


PP event
Vertical displacement u_z
Source: 40 Hz
High water saturation: 90 and 80 %
Low water saturation: 10 and 20 %



PS event
Horizontal displacement u_x
Low water saturation: 20 %
Several source frequencies:
10, 20, 30, 40, 50 and 60 Hz

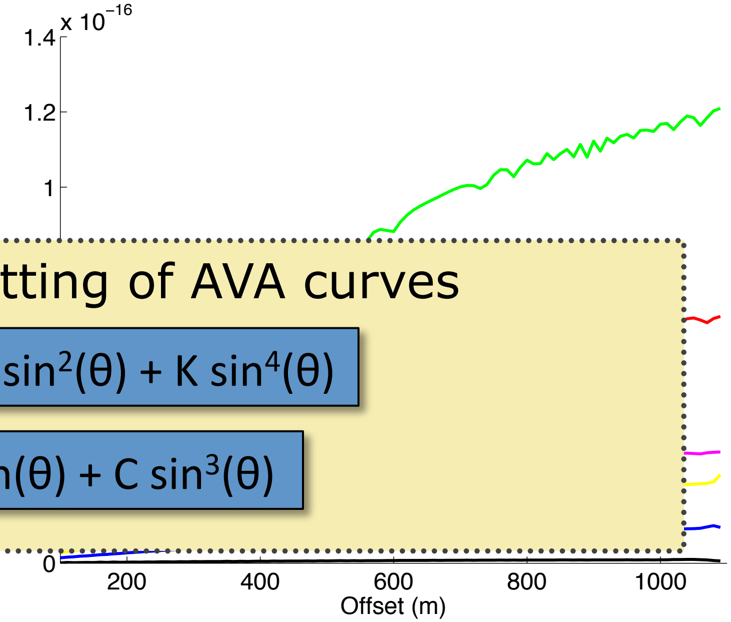
AVO curves for PP and PS events



➔ Least-square fitting of AVA curves

$$A_{PP}(\theta) = R_0 + G\sin^2(\theta) + K\sin^4(\theta)$$

$$A_{PS}(\theta) = B\sin(\theta) + C\sin^3(\theta)$$



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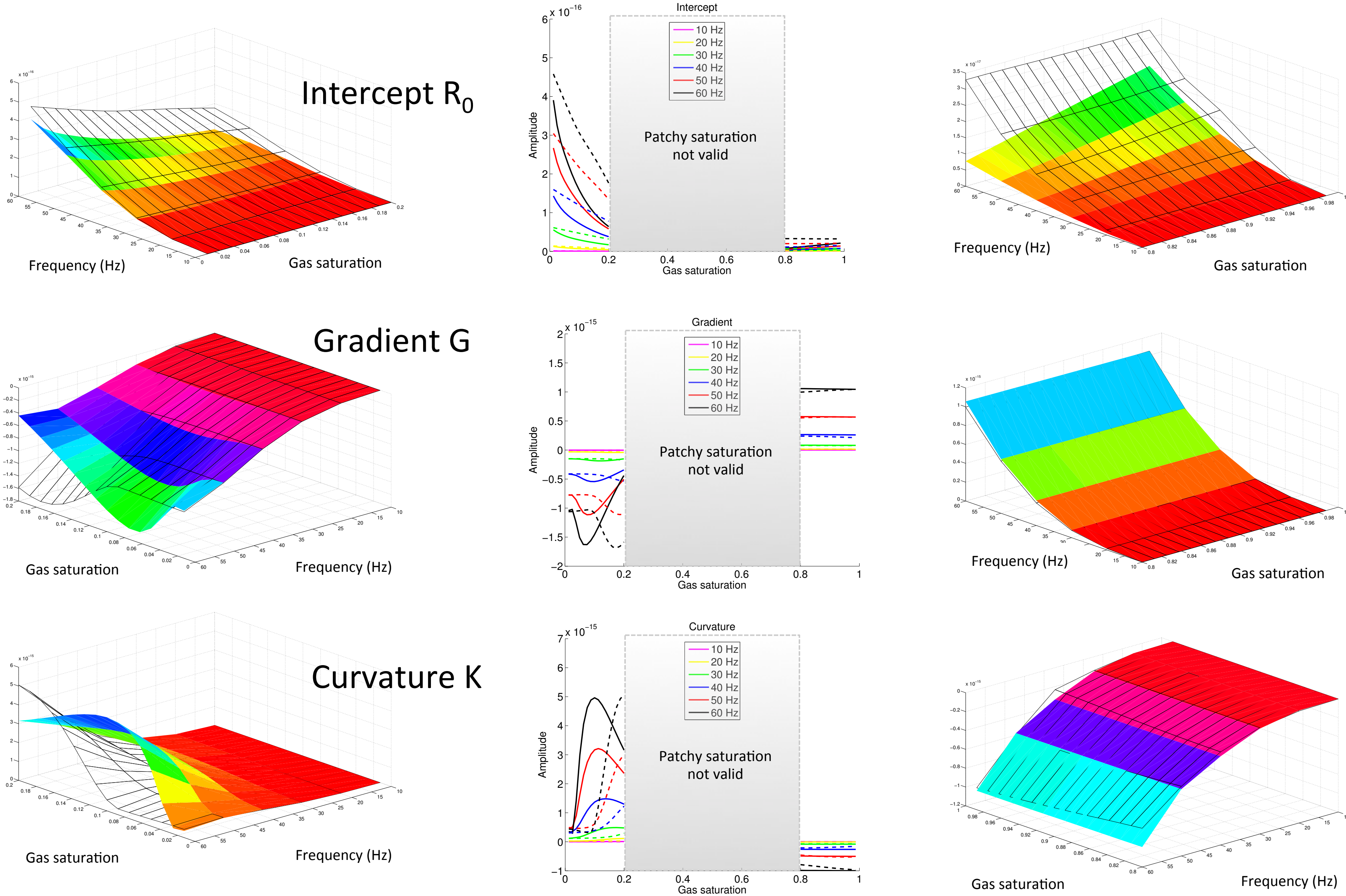
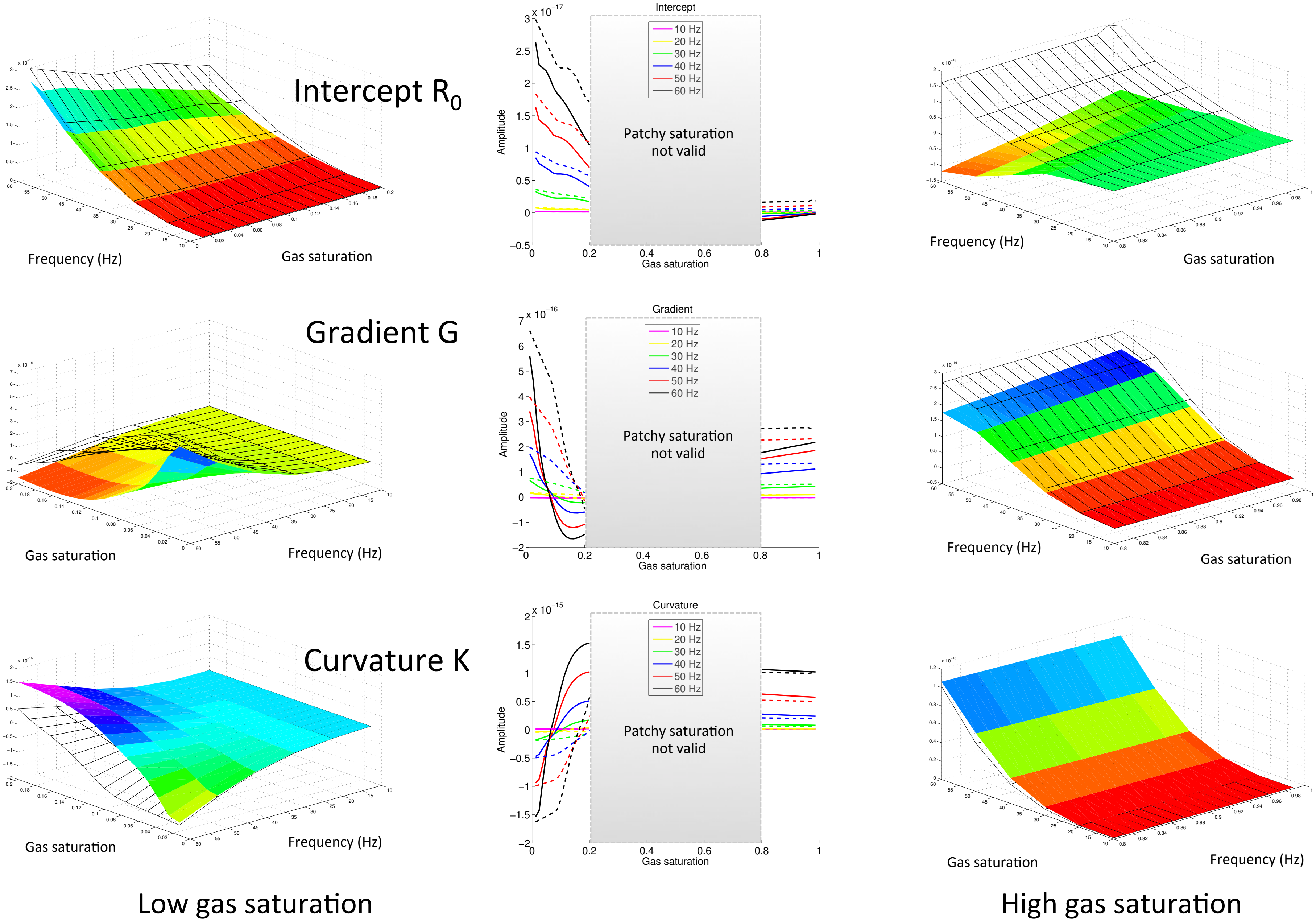


Low gas saturation

High gas saturation

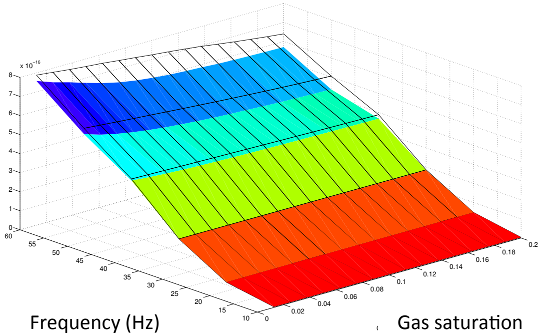
PP event, vertical displacement u_z

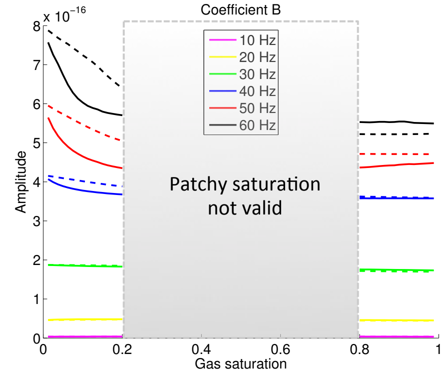
$$A_{PP}(\theta) = R_0 + G\sin^2(\theta) + K\sin^4(\theta)$$

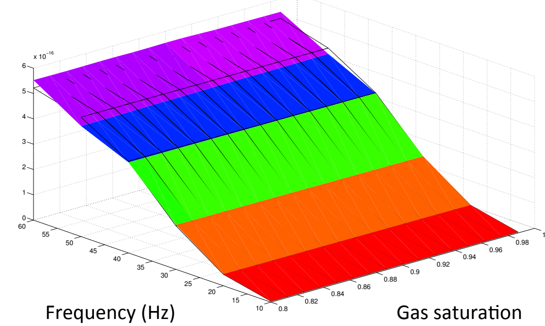


PP event, horizontal displacement u_x

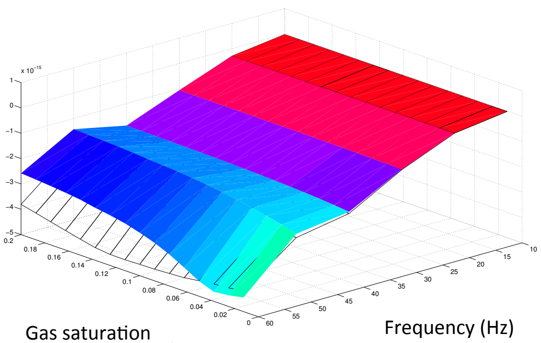
$$A_{PP}(\theta) = R_0 + G\sin^2(\theta) + K\sin^4(\theta)$$

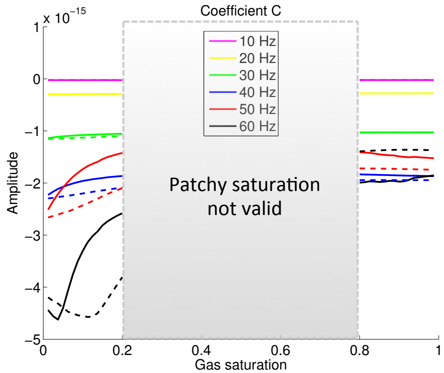


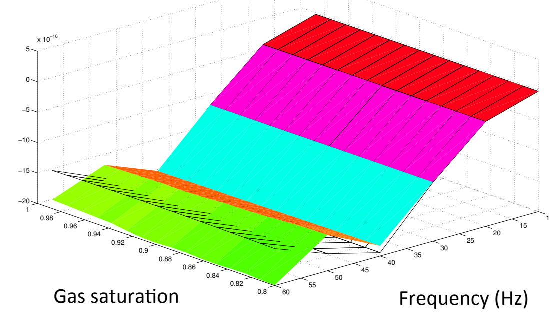




Intercept B







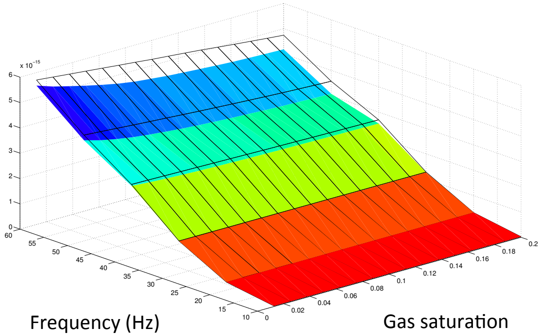
Gradient C

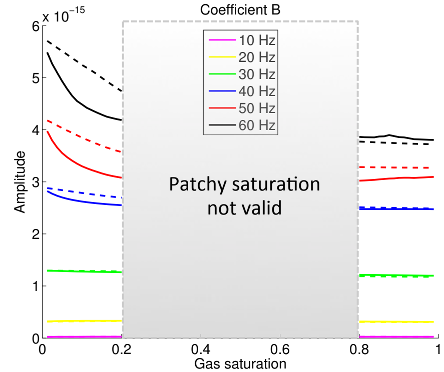
Low gas saturation

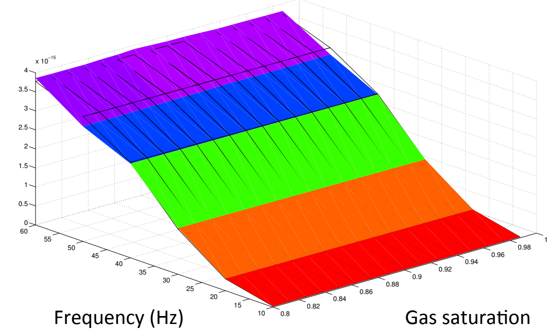
High gas saturation

PS event, vertical displacement u_z

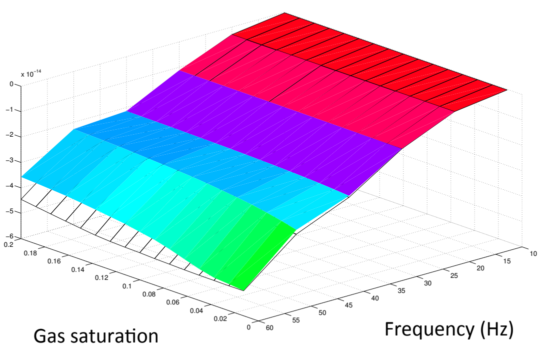
$$A_{PS}(\theta) = B \sin(\theta) + C \sin^3(\theta)$$

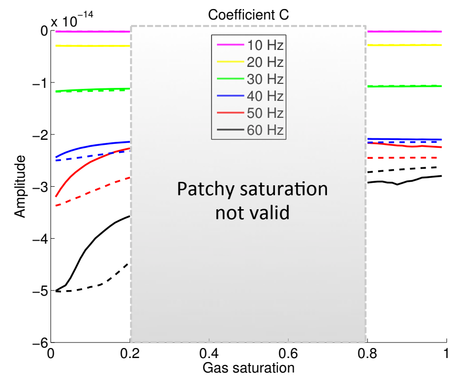


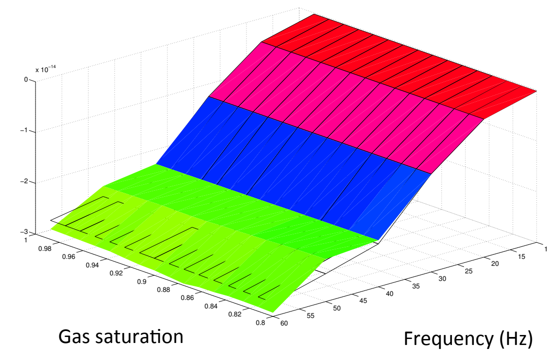




Intercept B







Gradient C

Low gas saturation

High gas saturation

PS event, horizontal displacement u_x

$A_{PS}(\theta) = B \sin(\theta) + C \sin^3(\theta)$

Conclusions

- Strong frequency dependence of AVO attributes, especially at high frequency
- For high and low fluid saturation scenarios, the effect of saturation on the attributes is minor (except at high frequency)
- Different behaviors between horizontal u_x and vertical u_z results
- Strong differences between patchy saturation and averages results, mainly for PP results.

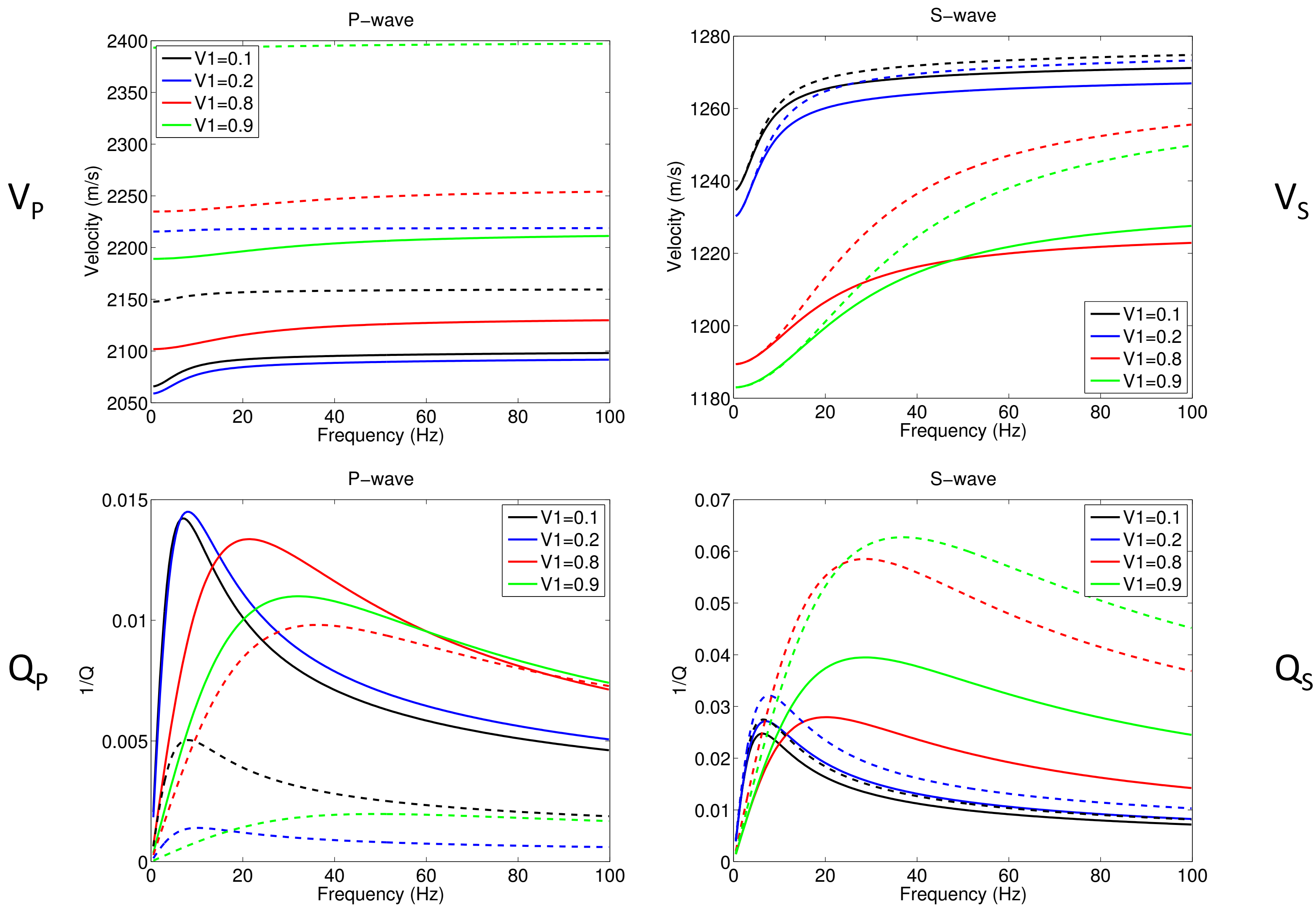
➔ The AVO analysis can give us some extra-information on wave amplitudes

- Road ahead:
  - Real data examples
  - Inversion approach using AVO attributes
  - 4D applications

- Acknowledgements:
  - Louis de Barros (GEOAZUR, Nice) and Stéphane Garambois (ISTERRE, Grenoble) for their poroelastic reflectivity numerical code
  - The ROSE project for financial support

- Bibliography:
  - Biot (1956), *Theory of propagation of elastic waves in a fluid-saturated porous solid*, JASA
  - De Barros and Dietrich (2008), *Perturbations of the seismic reflectivity of a fluid saturated depth-dependent poroelastic medium*, JASA
  - Dupuy, De Barros, Garambois and Virieux (2011), *Wave propagation in heterogeneous porous media formulated in the frequency-space domain using a discontinuous Galerkin method*, Geophysics
  - Gassmann (1951), *Uber die elastizität poröser medien*, VNG in Zürich
  - Pride, Berryman and Harris (2004). *Seismic attenuation due to wave-induced flow*, JGR
  - White (1975), *Computed seismic speeds and attenuation in rocks with partial gas saturation*, Geophysics

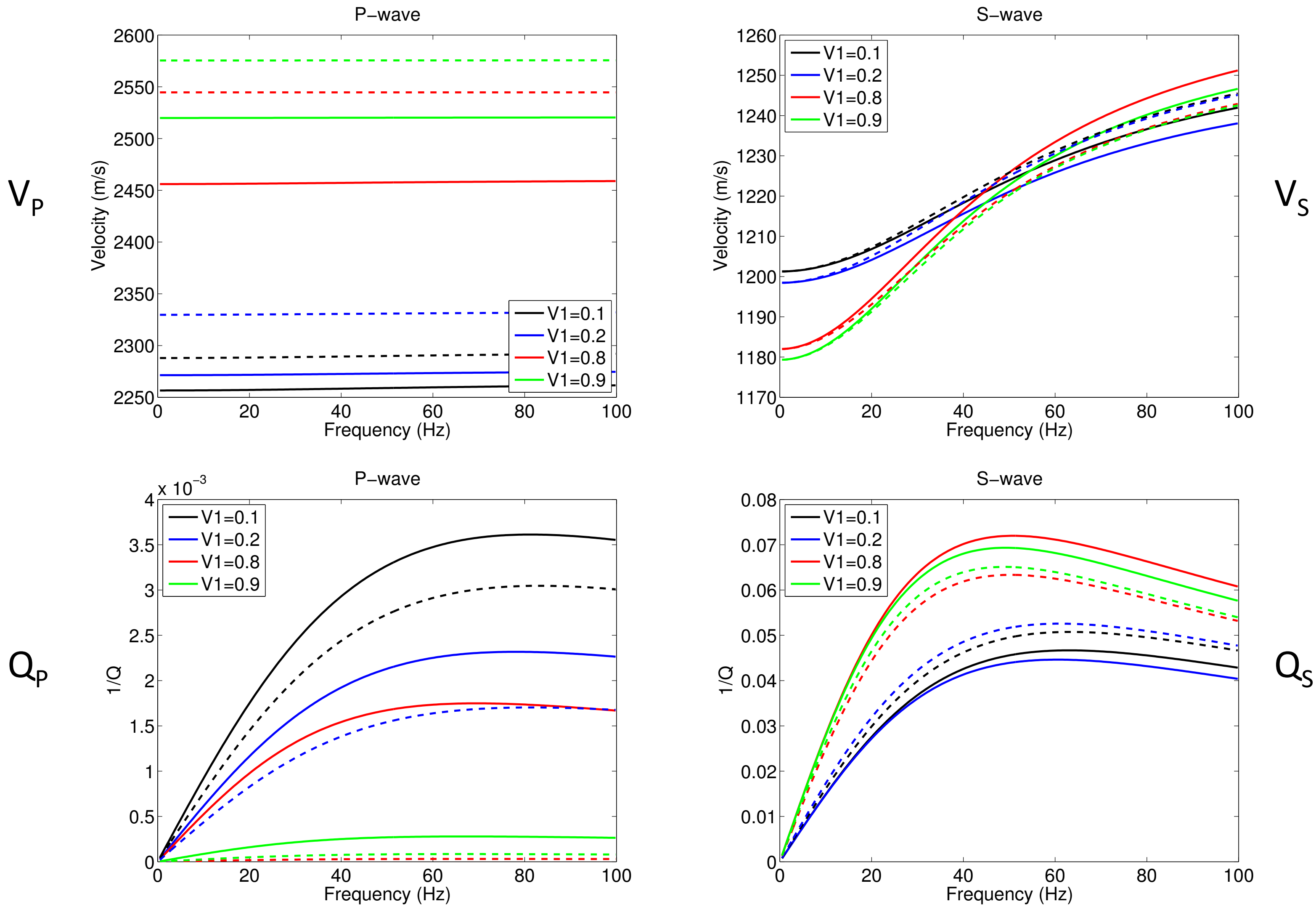
Models: gas-water systems



—— Patchy saturation

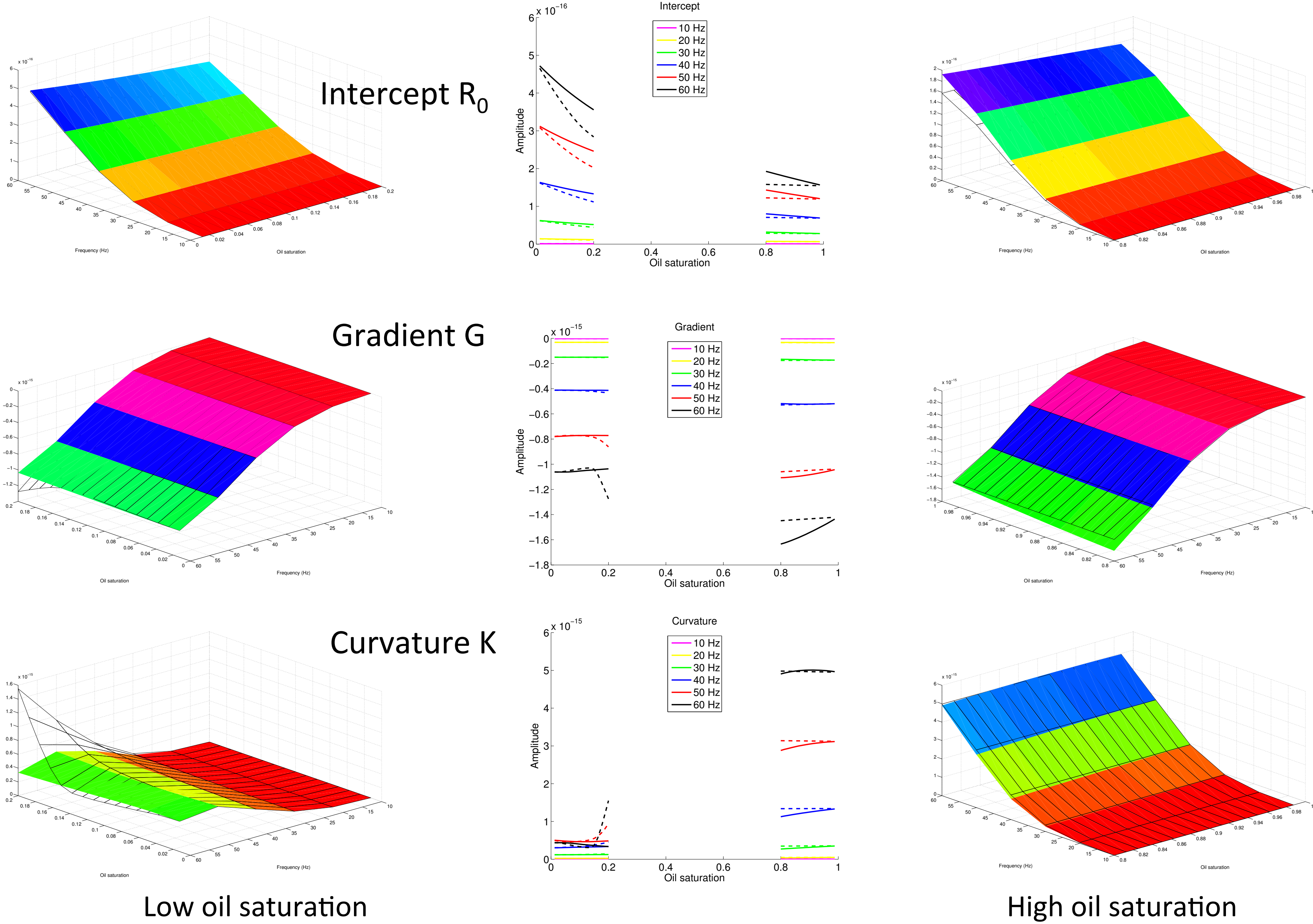
----- Simple averages

Models: oil-water systems



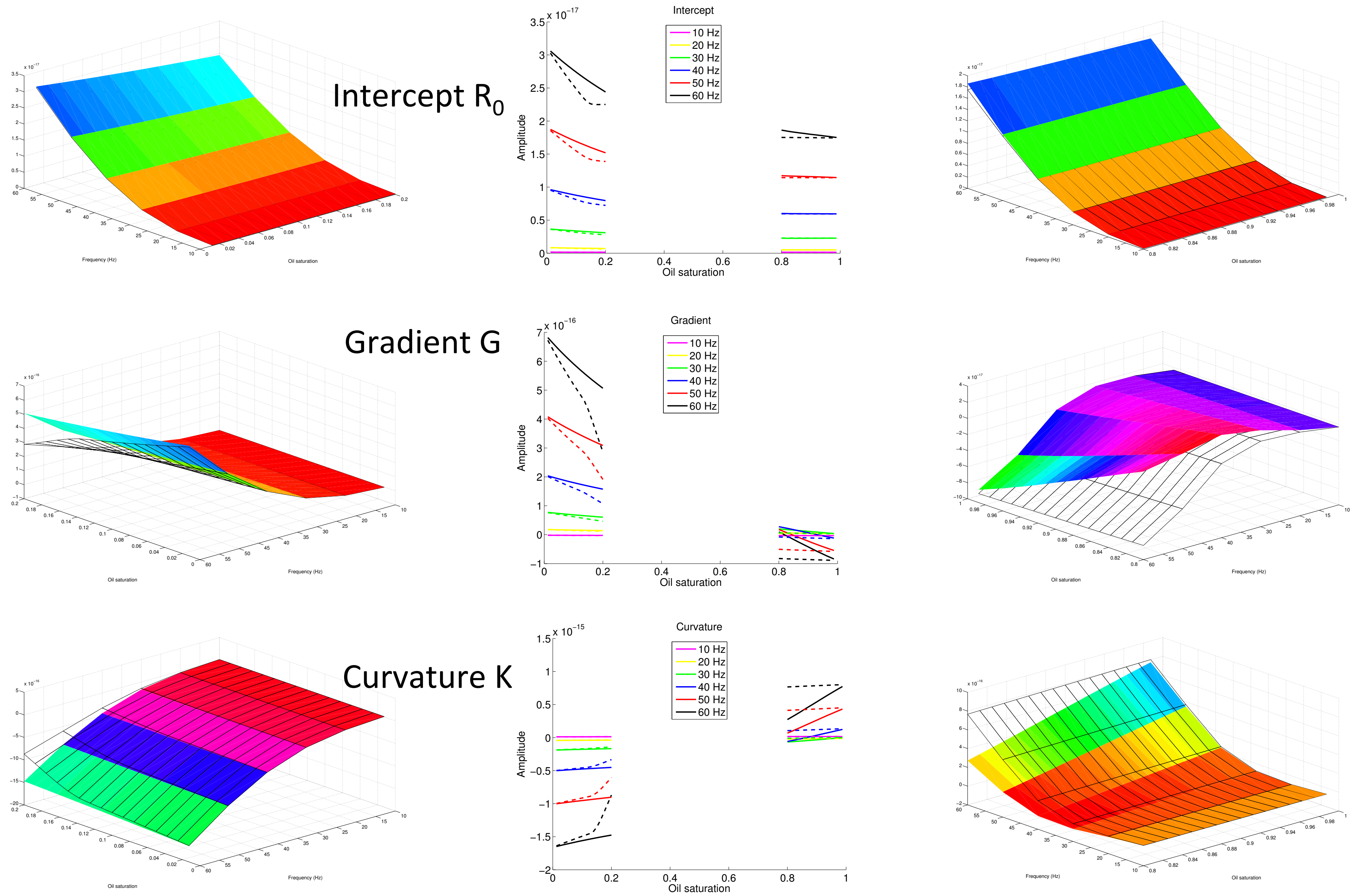
—— Patchy saturation

----- Simple averages



PP event, vertical displacement u_z

$$A_{PP}(\theta) = R_0 + G \sin^2(\theta) + K \sin^4(\theta)$$

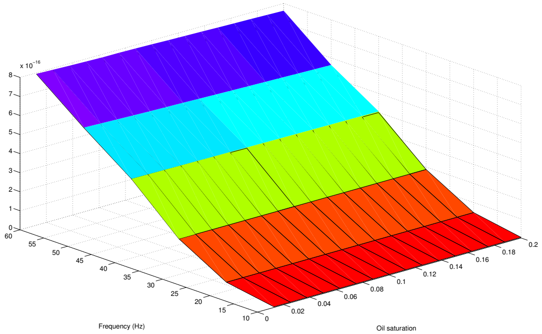


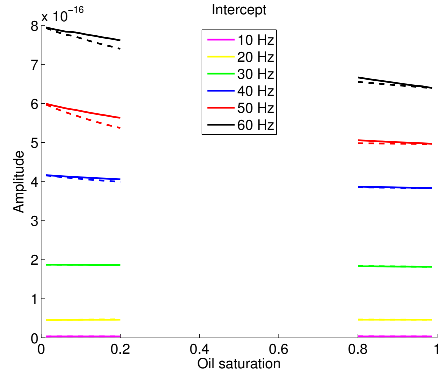
Low oil saturation

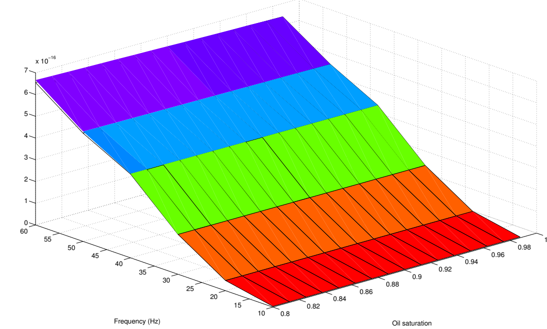
High oil saturation

PP event, horizontal displacement u_x

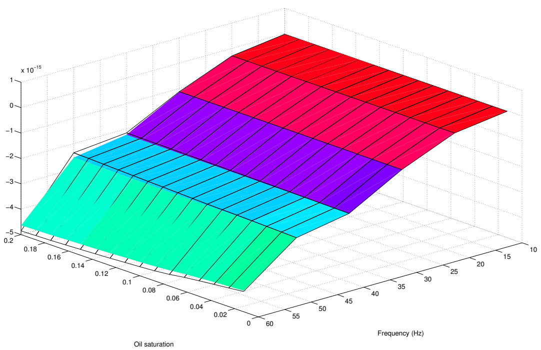
$$A_{PP}(\theta) = R_0 + G\sin^2(\theta) + K\sin^4(\theta)$$

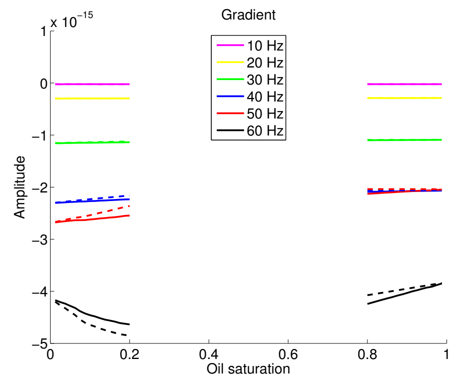


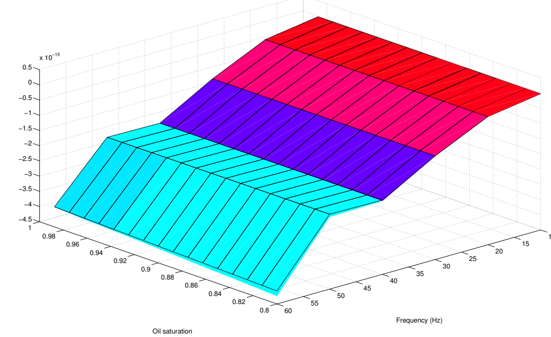




Intercept B







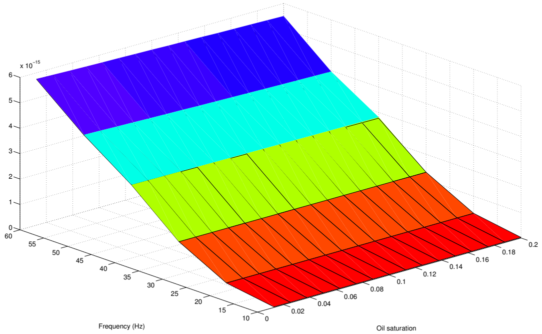
Gradient C

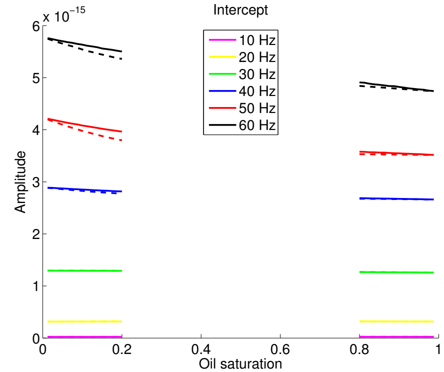
Low oil saturation

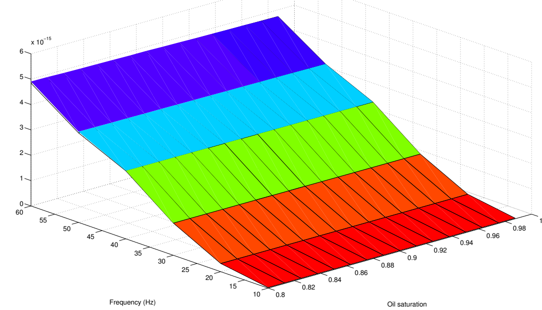
High oil saturation

PS event, vertical displacement u_z

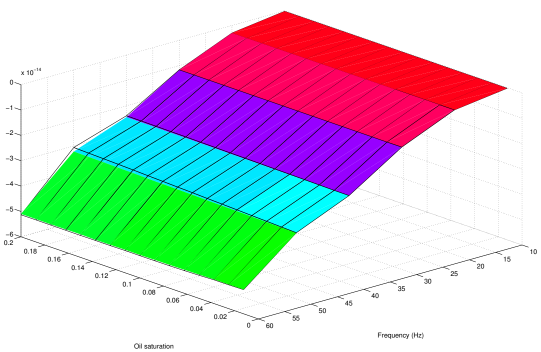
$$A_{PS}(\theta) = B \sin(\theta) + C \sin^3(\theta)$$

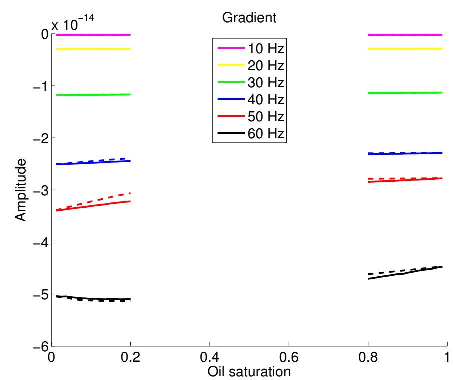


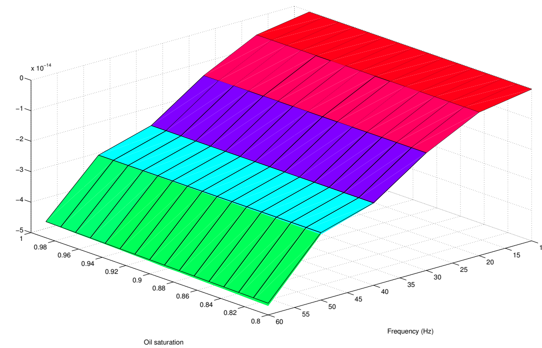




Intercept B







Gradient C

Low oil saturation

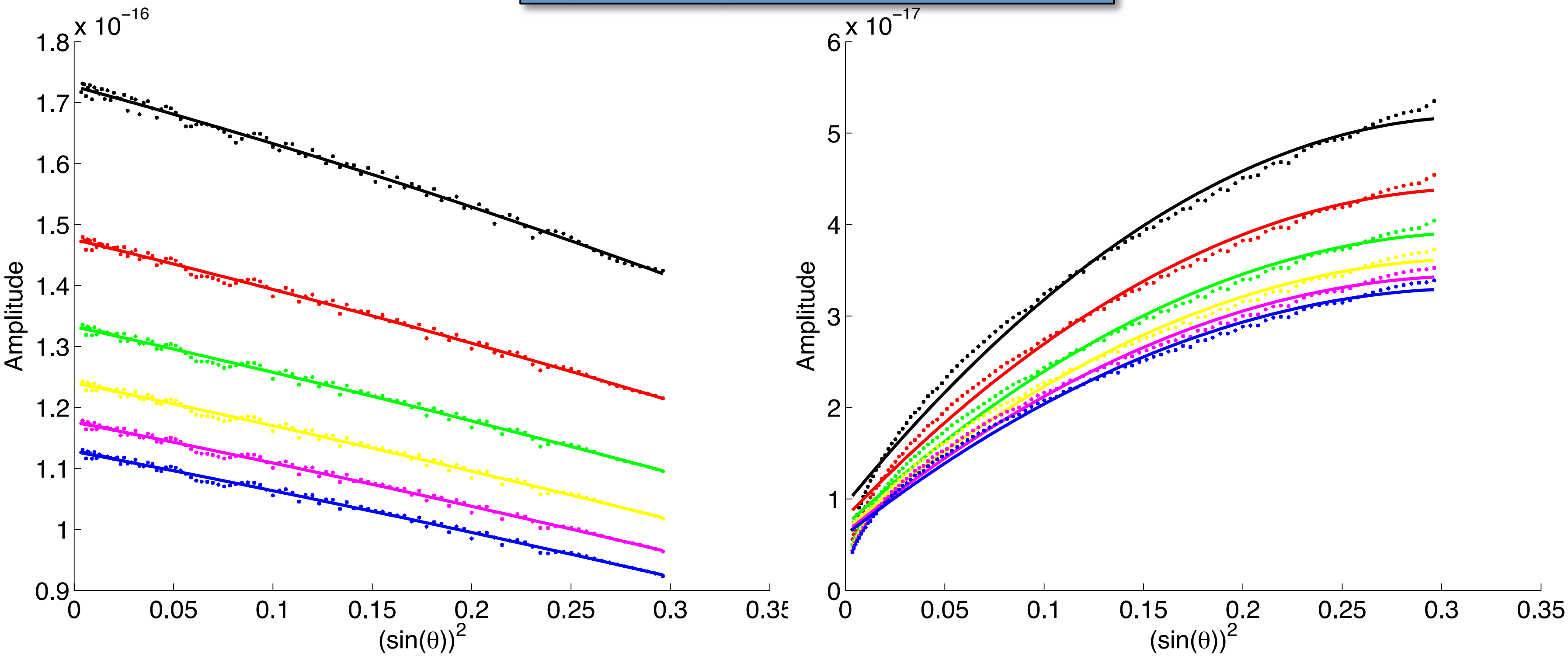
High oil saturation

PS event, horizontal displacement u_x

$$A_{PS}(\theta) = B \sin(\theta) + C \sin^3(\theta)$$

Least-square fitting

$A_{PP}(\theta) = R_0 + G \sin^2(\theta) + K \sin^4(\theta)$



PP event

Vertical displacement u_z

Source: 40 Hz

Horizontal displacement u_x

High water saturation:

98.75, 95, 91.25, 87.5, 83.75 and 80 %

Extraction of AVO information

<u>Method:</u>

1. Computation of full waveform seismograms in 3D stratified three layers medium,
2. Extraction of maximum amplitude for each event (PP and PS) using a time windowing,
3. Computation of AVA curves (amplitude A with respect to the incidence angle θ),
4. Least-square fitting of these curves with polynoms to compute the attributes as

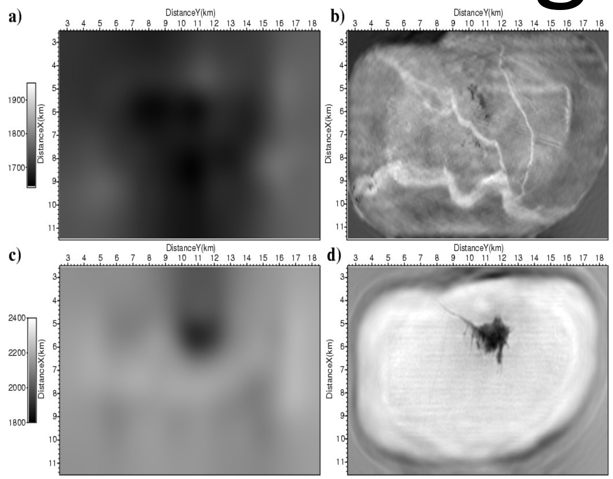
$$A_{PP}(\theta) = R_0 + G\sin^2(\theta) + K\sin^4(\theta)$$

$$A_{PS}(\theta) = B\sin(\theta) + C\sin^3(\theta)$$

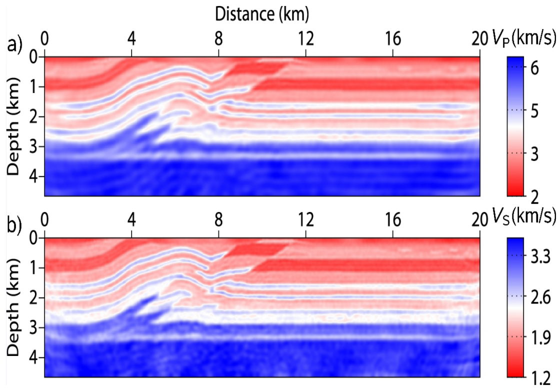
where R_0 and B are the intercept, G and C are the gradient and K is the curvature.

5. Plot of each attributes with respect to the frequency and the saturation

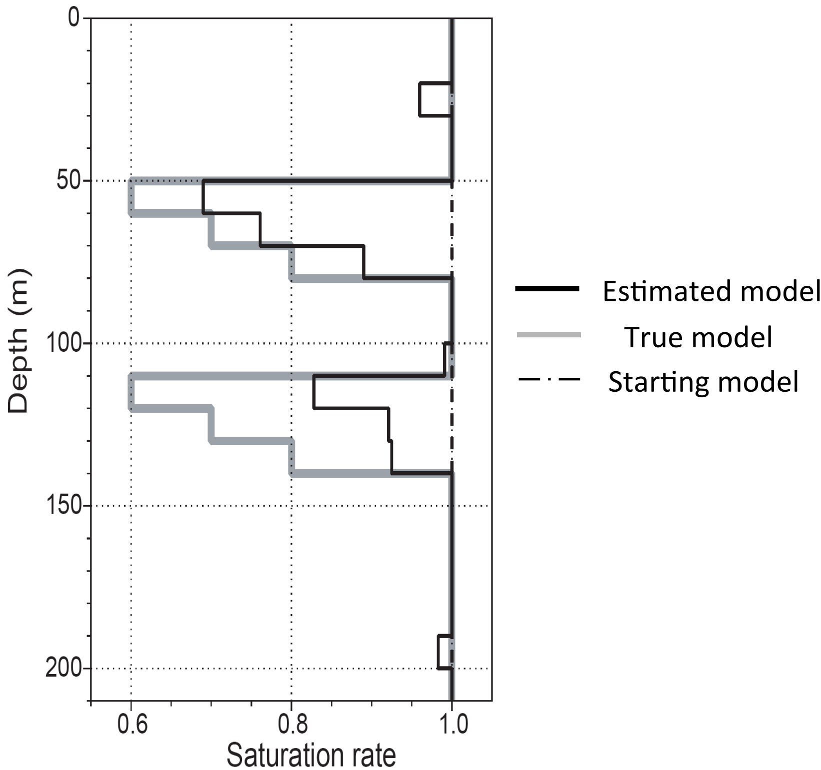
Seismic imaging: poroelastic FWI



3D acoustic FWI *(Sirgue et al, 2010)* ➔ **high resolution images**



2D elastic FWI *(Brossier et al, 2009)* ➔ **V_P and V_S high resolution 2D images**



Poroelastic FWI *(De Barros et al, 2010)* ➔ **differential approach**

Downscaling

MICRO-SCALE PARAMETERS

DOWNSCALING

MACRO-SCALE ATTRIBUTES

MODELS

$\overrightarrow{m}$

- Skeleton parameters: φ and K_D, G_D
- Fluid phase properties: K_f, ρ_f and η
- Unsaturated medium : φ, K_D and V_1

$$\overrightarrow{d} = g(\overrightarrow{m})$$

$V_P = g\,(\phi, K_D, S_w, \ldots)$

Non linear inverse problem

Discrepancy between model and data: L_2 norm

$$misfit = \left[\left(\overrightarrow{d_{obs}} - g(\overrightarrow{m})\right)^T \left(\overrightarrow{d_{obs}} - g(\overrightarrow{m})\right) \right]^{1/2}$$

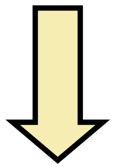
$\overrightarrow{d}$

V_P, V_S, Q_P, Q_S, ρ

DATA

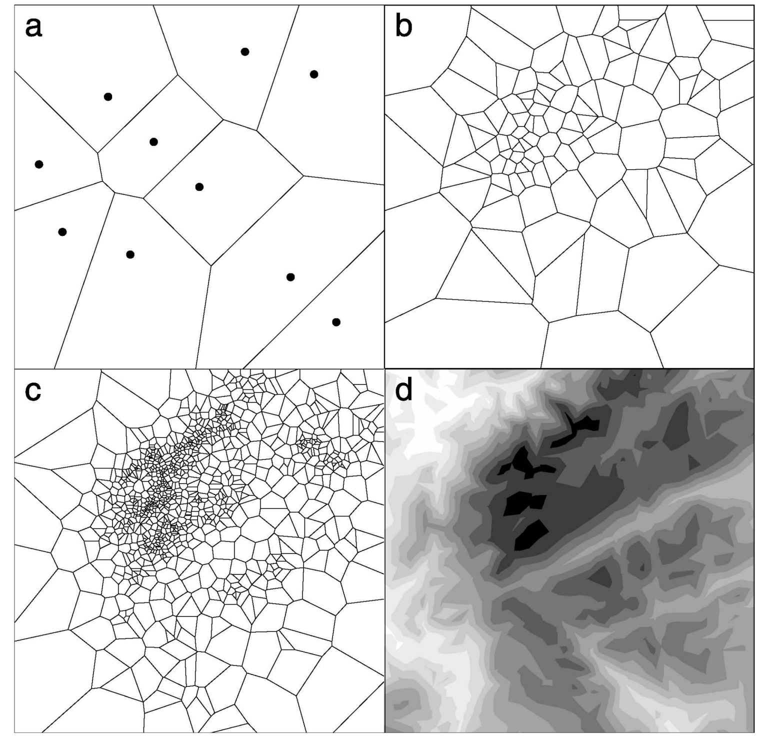
Semi-global optimization

Fast and analytic forward problem



Neighbourhood algorithm (NA, *Sambridge, 1999*):

- Only 2 control parameters
- Model space guided exploration
- Fit quality and uncertainty



Number of generated models:
a) 10
b) 100
c) 1000
d) Fit map

Skeleton parameters sensitivity (saturated medium)

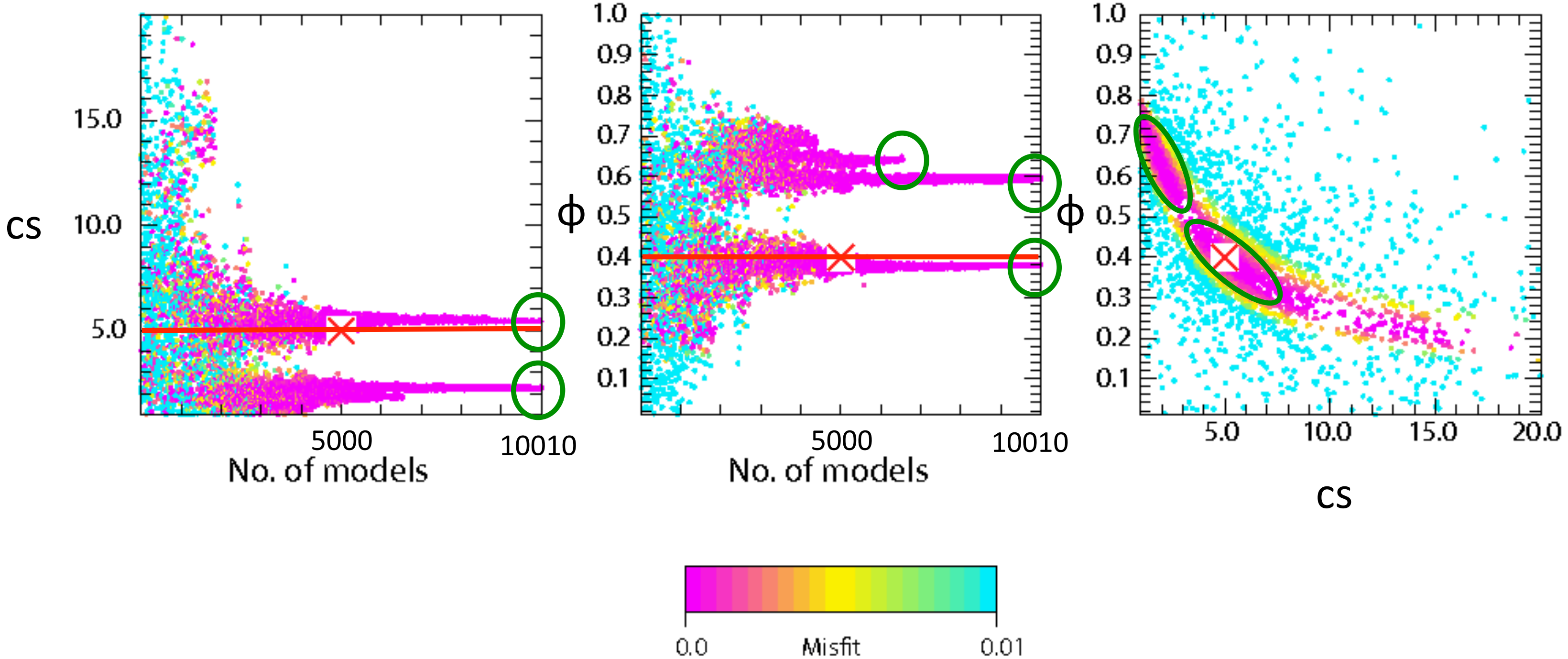
A priori known parameters:

- Fluid phase: K_f, ρ_f, η
- Solid phase: K_s, G_s, ρ_s

True model

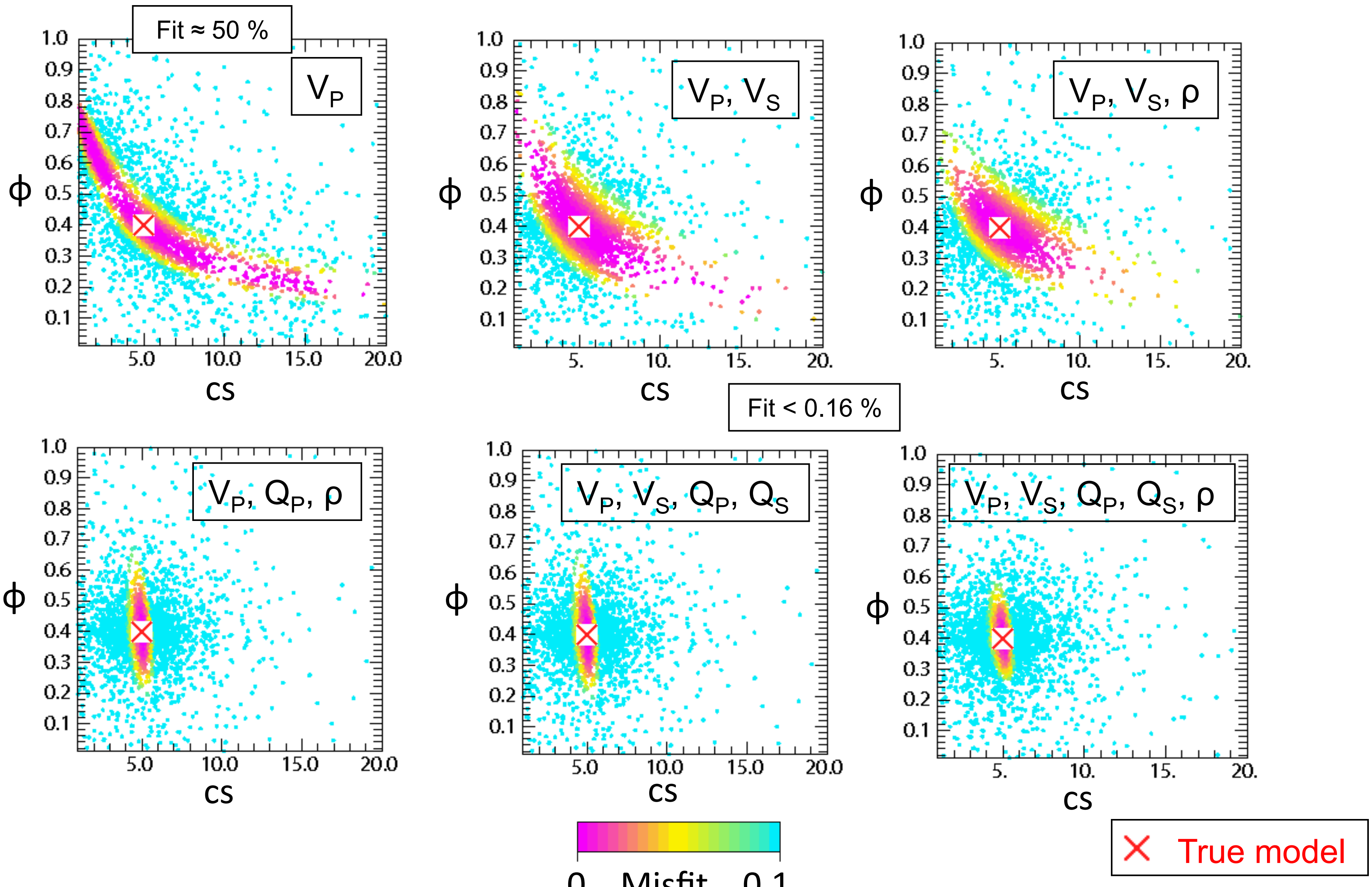
Data: V_P

Fit between true model – estimated model ≈ 50 %



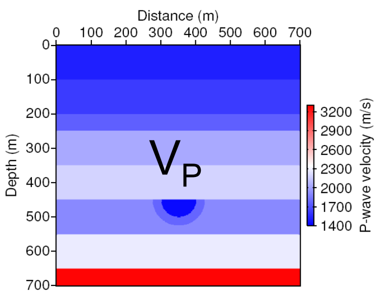
➔ Local minima, low constraining

Skeleton parameters: additional data input

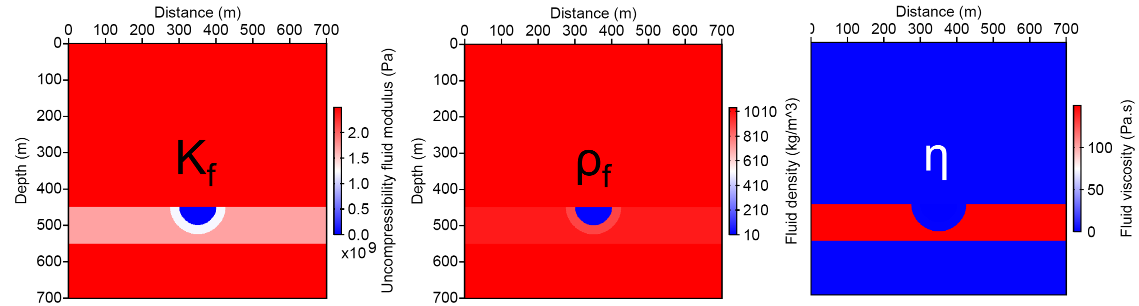


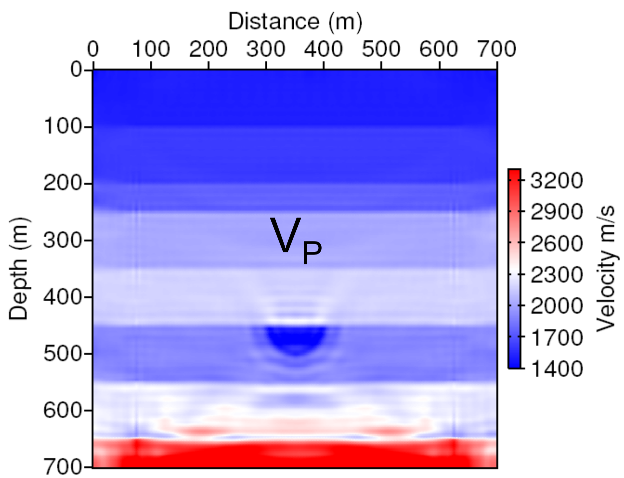
➔ Best constraining φ and cs estimation when we use more data

Downscaling after injection



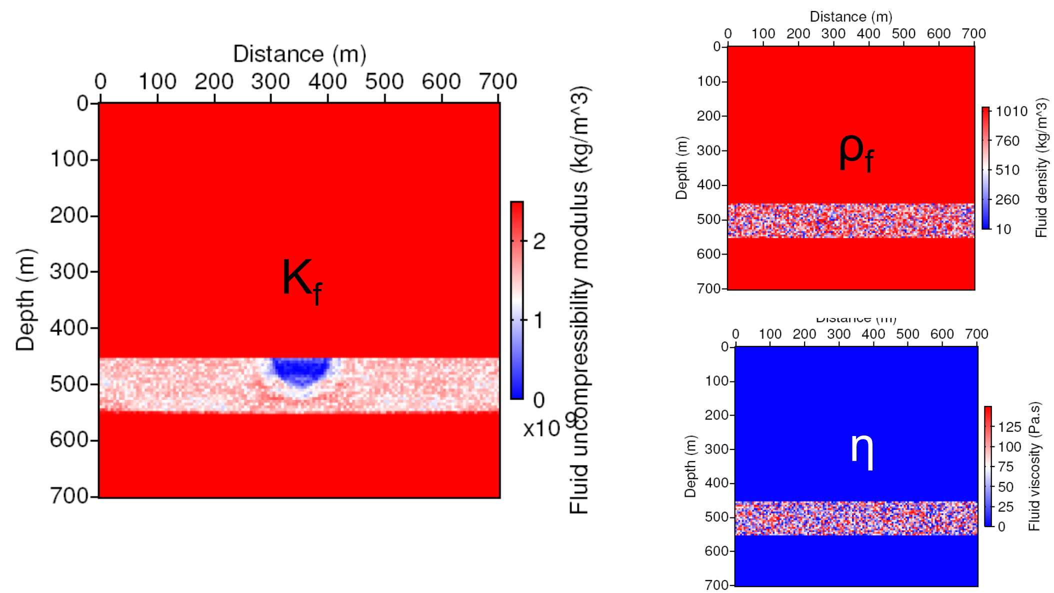
True models





V_P estimated by acoustic differential FWI

(Asnaashari, 2011)



Fluid phase estimated by downscaling