Advances in rock physics modelling and improved estimation of CO_2 saturation

Giorgos Papageorgiou

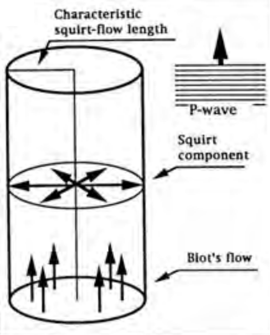
University of Edinburgh

UKSCCSRC Geophysical Modelling for CO_2 Storage, Monitoring and Appraisal Specialist Meeting
Leeds, 2015

THE UNIVERSITY *of* EDINBURGH

The squirt flow mechanism

- Seismic waves create pressure gradients
- Depending on time/length scale, different types of flow (hence dispersion) occur
- Model "local" flow using idealised pore geometries:

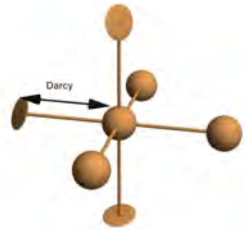


The squirt flow mechanism

- Seismic waves create pressure gradients
- Depending on time/length scale, different types of flow (hence dispersion) occur
- Model "local" flow using idealised pore geometries: donut+disk

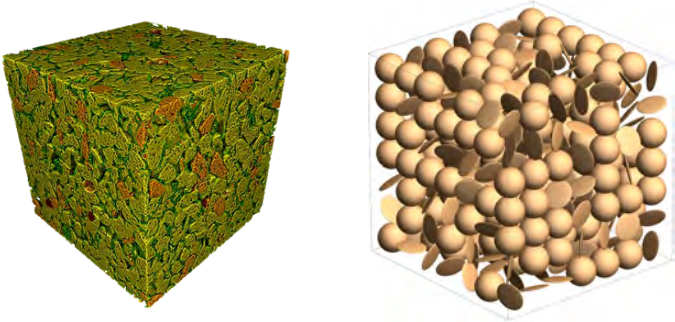
The squirt flow mechanism

- Seismic waves create pressure gradients
- Depending on time/length scale, different types of flow (hence dispersion) occur
- Model “local” flow using idealised pore geometries: coins+spheres



A minimal model

Minimally, to model the squirt flow effect replace the rock by a collection of coin-shaped cracks $\ominus$ and sphere-shaped pores $\odot$



Extending to two fluids

How do we model partial saturation?

Assume two fluids in each pore

Solve Darcy's law in the frequency domain:

$$\partial_t m_1^{\ominus} = \frac{\rho_1 k_1 \zeta}{\eta_1} \, (P_1^{\odot} - P_1^{\ominus}), \quad m_1^{\ominus} = S_1 \rho_1^{\ominus} \phi^{\ominus}$$
$$\partial_t m_2^{\ominus} = \frac{\rho_2 k_2 \zeta}{\eta_2} \, (P_2^{\odot} - P_2^{\ominus}), \quad m_2^{\ominus} = (1 - S_1) \rho_2^{\ominus} \phi^{\ominus}.$$

and use the result in Eshelby's expansion (obtain complex valued bulk modulus):

$$\mathcal{K}_{\text{eff}}(\omega) = \mathcal{K}_d + \phi_0^{\ominus} \left(\frac{K_m}{\sigma_c} + 1 \right) \frac{P^{\ominus}(\omega)}{\sigma(\omega)} \; + \; \phi_0^{\odot} \left(\frac{3K_m}{4\mu} + 1 \right) \frac{P^{\odot}(\omega)}{\sigma(\omega)}.$$

Appeal of this method is that $K_{\text{eff}}(0) = \mathcal{K}_{Gassmann}$

Assume two fluids in each pore

Solve Darcy's law in the frequency domain:

$$\partial_t m_1^{\ominus} = \frac{\rho_1 k_1 \zeta}{\eta_1} \left(P_1^{\odot} - P_1^{\ominus}\right), \quad m_1^{\ominus} = S_1 \rho_1^{\ominus} \phi^{\ominus}$$

$$\partial_t m_2^{\ominus} = \frac{\rho_2 k_2 \zeta}{\eta_2} \left(P_2^{\odot} - P_2^{\ominus}\right), \quad m_2^{\ominus} = (1 - S_1) \rho_2^{\ominus} \phi^{\ominus}.$$

and use the result in Eshelby's expansion (obtain complex valued bulk modulus):

$$\mathcal{K}_{\text{eff}}(\omega) = \mathcal{K}_d + \phi_0^{\ominus} \left(\frac{K_m}{\sigma_c} + 1\right) \frac{P^{\ominus}(\omega)}{\sigma(\omega)} + \phi_0^{\odot} \left(\frac{3K_m}{4\mu} + 1\right) \frac{P^{\odot}(\omega)}{\sigma(\omega)}.$$

There is some ambiguity as to which pressure to use here!

Assume two fluids in each pore

Solve Darcy's law in the frequency domain:

$$\partial_t m_1^{\ominus} = \frac{\rho_1 k_1 \zeta}{\eta_1} \left(P_1^{\odot} - P_1^{\ominus}\right), \quad m_1^{\ominus} = S_1 \rho_1^{\ominus} \phi^{\ominus}$$

$$\partial_t m_2^{\ominus} = \frac{\rho_2 k_2 \zeta}{\eta_2} \left(P_2^{\odot} - P_2^{\ominus}\right), \quad m_2^{\ominus} = (1 - S_1) \rho_2^{\ominus} \phi^{\ominus}.$$

and use the result in Eshelby's expansion (obtain complex valued bulk modulus):

$$\mathcal{K}_{\text{eff}}(\omega) = \mathcal{K}_d + \phi_0^{\ominus} \left(\frac{K_m}{\sigma_c} + 1\right) \frac{P^{\ominus}(\omega)}{\sigma(\omega)} + \phi_0^{\odot} \left(\frac{3K_m}{4\mu} + 1\right) \frac{P^{\odot}(\omega)}{\sigma(\omega)}.$$

There is some ambiguity as to which pressure to use here!

Assume two fluids in each pore

Solve Darcy's law in the frequency domain:

$$\partial_t m_1^{\ominus} = \frac{\rho_1 k_1 \zeta}{\eta_1}\,(P_1^{\odot} - P_1^{\ominus}), \quad m_1^{\ominus} = S_1 \rho_1^{\ominus} \phi^{\ominus}$$

$$\partial_t m_2^{\ominus} = \frac{\rho_2 k_2 \zeta}{\eta_2}\,(P_2^{\odot} - P_2^{\ominus}), \quad m_2^{\ominus} = (1 - S_1) \rho_2^{\ominus} \phi^{\ominus}.$$

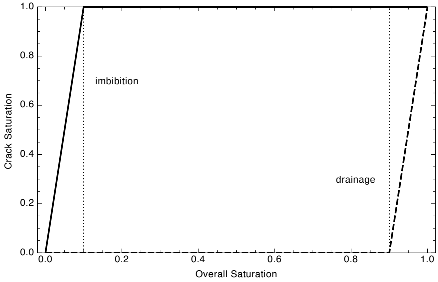
and use the result in Eshelby's expansion (obtain complex valued bulk modulus):

$$\mathcal{K}_{\text{eff}}(\omega) = \mathcal{K}_d + \phi_0^{\ominus}\left(\frac{K_m}{\sigma_c} + 1\right)\frac{P^{\ominus}(\omega)}{\sigma(\omega)} + \phi_0^{\odot}\left(\frac{3K_m}{4\mu} + 1\right)\frac{P^{\odot}(\omega)}{\sigma(\omega)}.$$

There is some ambiguity as to which saturation to use here!

Inclusion-Dependent Saturation

The “observable” saturation can differ from the saturation in the cracks/pores. This leads to a way of modelling imbibition/drainage phenomena.[1]

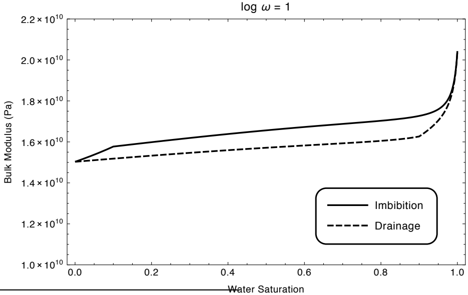


---

[1] G Papageorgiou and M Chapman. “Multifluid squirt flow and hysteresis effects on the bulk modulus–water saturation relationship”. In: *Geophysical Journal International* 203.2 (2015), pp. 814–817.

Inclusion-Dependent Saturation

The "observable" saturation can differ from the saturation in the cracks/pores. This leads to a way of modelling imbibition/drainage phenomena.[1]

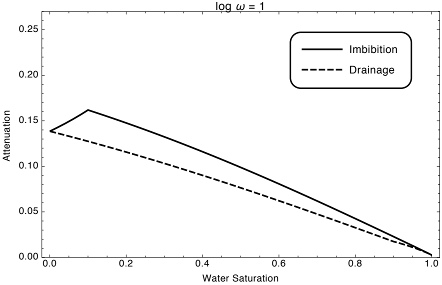


---

[1] G Papageorgiou and M Chapman. "Multifluid squirt flow and hysteresis effects on the bulk modulus–water saturation relationship". In: *Geophysical Journal International* 203.2 (2015), pp. 814–817.

Inclusion-Dependent Saturation

The “observable” saturation can differ from the saturation in the cracks/pores. This leads to a way of modelling imbibition/drainage phenomena.[1]

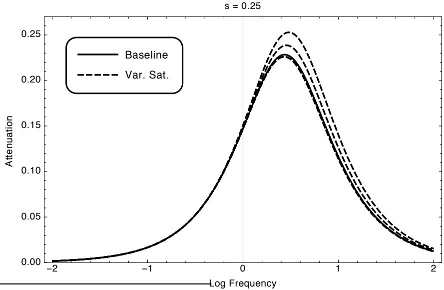


---

[1] G Papageorgiou and M Chapman. “Multifluid squirt flow and hysteresis effects on the bulk modulus–water saturation relationship”. In: *Geophysical Journal International* 203.2 (2015), pp. 814–817.

Inclusion-Dependent Saturation

The "observable" saturation can differ from the saturation in the cracks/pores. This leads to a way of modelling imbibition/drainage phenomena.[1]



---

[1] G Papageorgiou and M Chapman. "Multifluid squirt flow and hysteresis effects on the bulk modulus–water saturation relationship". In: *Geophysical Journal International* 203.2 (2015), pp. 814–817.

Pressure discontinuity

Use capillary pressure equation $\Delta C = q\Delta P_{\mathrm{w}}$ constrained within $-1 < q < 0$. Assume, the balancing pressure in Eshelby's formula can jump from that of the non-wetting to that of the wetting fluid in a discontinuous way. Think of the low frequency limit (Gassmann limit) of this model. [2]

---

[2] presented in SEG 2015 and under revision in GJI

A wet Gassmann model

Different effective pressure choices correspond to different models:

$$P^{(1)} \simeq P_{\mathrm{w}}$$

$$P^{(2)} \simeq P_{\mathrm{nw}}$$

A wet Gassmann model

Different effective pressure choices correspond to different models:

$$P^{(1)} \simeq P_{\mathrm{w}}$$
$$P^{(2)} \simeq P_{\mathrm{nw}}$$

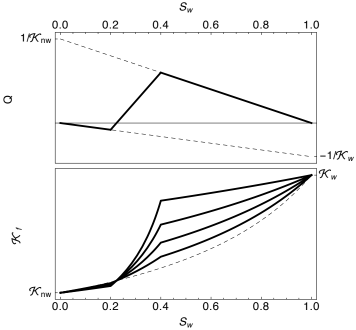
... and different effective fluid moduli:

$$\frac{1}{\mathcal{K}_f^{(1)}(q)} \simeq \frac{S_{\mathrm{w}}}{\mathcal{K}_{\mathrm{w}}} + \frac{S_{\mathrm{nw}}(1-q)}{\mathcal{K}_{\mathrm{nw}}} = \frac{1}{\mathcal{K}_{GW}} - q\frac{1-S_{\mathrm{w}}}{\mathcal{K}_{\mathrm{nw}}}$$
$$\frac{1}{\mathcal{K}_f^{(2)}(q)} \simeq \frac{S_{\mathrm{w}}(1+q)}{\mathcal{K}_{\mathrm{w}}} + \frac{S_{\mathrm{nw}}}{\mathcal{K}_{\mathrm{nw}}} = \frac{1}{\mathcal{K}_{GW}} + q\frac{S_{\mathrm{w}}}{\mathcal{K}_{\mathrm{w}}}$$

That depend on this parameter q

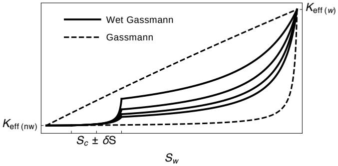
A wet Gassmann model

Think of these as a non-wetted and wetted extremes and join them somewhere in between. Depending on where this transition happens and how fast, different models are obtained (keep q as a scaling parameter):



A wet Gassmann model

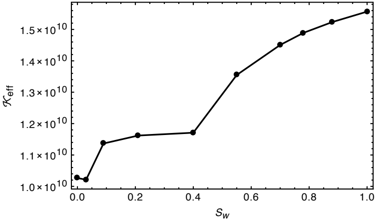
As a result, a jump appears in the bulk modulus VS saturation relationship:



Here $\phi = 30\%, \mathcal{K}_m = 4\mathcal{K}_d = 8\mathcal{K}_{\mathrm{w}} = 800\mathcal{K}_{\mathrm{nw}}$ similar to gas/water in sandstone. Still not clear if parameter q affects the frequency dependence of the theory and how.

Ultrasonic experiments

Do these models have any reason to exist? Observed “jump”[3] in $\mathcal{K}_{eff}$ normally attributed to frequency effects but could be explained using the static wet Gassmann described here.

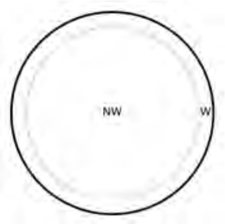


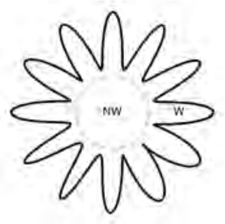
---

[3] Kelvin Amalokwu et al. “Water saturation effects on P-wave anisotropy in synthetic sandstone with aligned fractures”. In: *Geophysical Journal International* 202.2 (2015), pp. 1088–1095.

A speculative explanation

How much saturation is needed to transition from the non-wetted to wetted regime ↔ pore raggedness
How smooth the transition ↔ pore size distribution





But not quantified! Hope is this is the path to petrophysical parameters in this context.

Saner approach: pressure averaging

Scale capillary pressure equation a little differently:

$$P_{\mathsf{nw}} = \alpha \frac{\mathcal{K}_{\mathsf{nw}}}{\mathcal{K}_{\mathsf{w}}} P_{\mathsf{w}}, \qquad 1 \leq \alpha \leq \frac{\mathcal{K}_{\mathsf{w}}}{\mathcal{K}_{\mathsf{nw}}}.$$

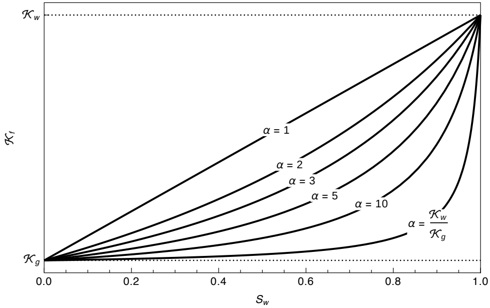
Assume pressure averaging in the inclusions balances stress $P = S_{\mathsf{w}} P_{\mathsf{w}} + (1 - S_{\mathsf{w}}) P_{\mathsf{nw}}$.

Pressure averaging - Low Frequency

At *low frequency approximation* the effective fluid modulus depends on α:

$$\widetilde{K}_f = \frac{S_\mathrm{w}\mathcal{K}_\mathrm{w} + \alpha(1 - S_\mathrm{w})\mathcal{K}_\mathrm{nw}}{S_\mathrm{w} + \alpha(1 - S_\mathrm{w})}, \qquad 1 \leq \alpha \leq \frac{\mathcal{K}_\mathrm{w}}{\mathcal{K}_\mathrm{nw}}$$

which looks like Brie's empirical model.[4]

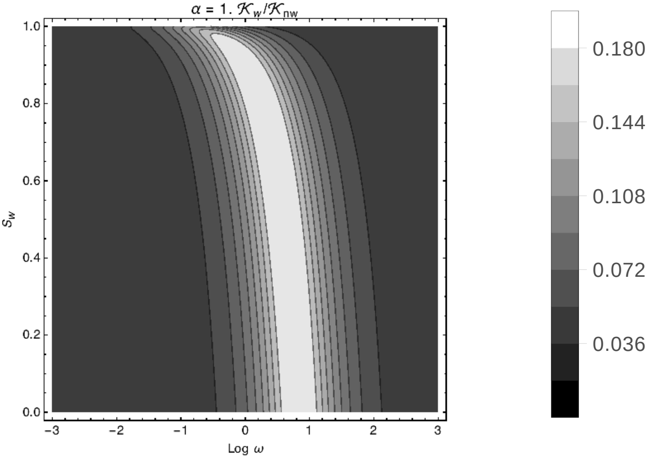


---

[4] Work under review for GP special issue in rock physics

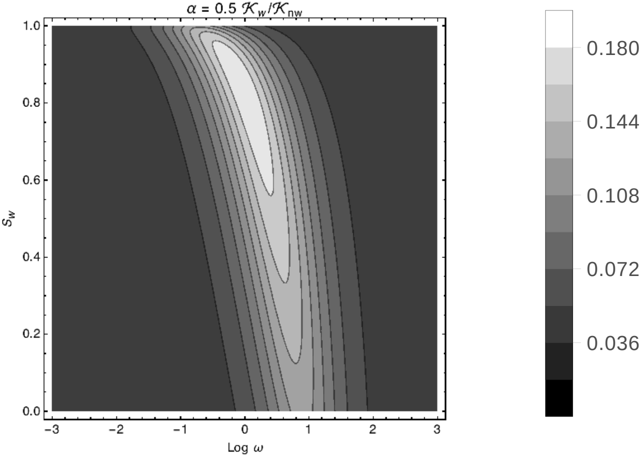
Pressure averaging - Frequency dependence

The characteristic frequency depends on α as well so this model attenuates differently depending on the value of α



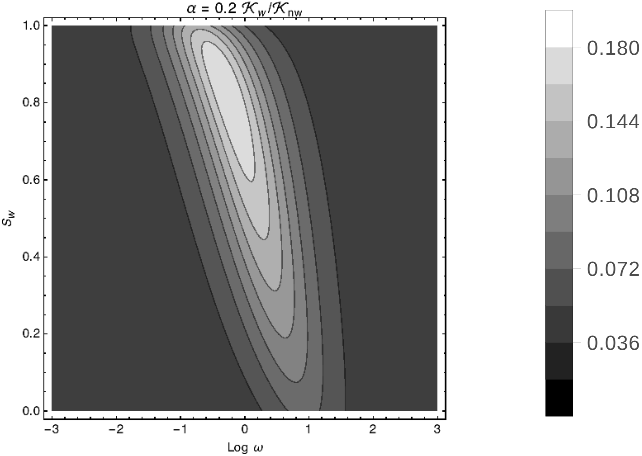
Pressure averaging - Frequency dependence

The characteristic frequency depends on α as well so this model attenuates differently depending on the value of α



Pressure averaging - Frequency dependence

The characteristic frequency depends on α as well so this model attenuates differently depending on the value of α



Using these models

If this interpretation is correct, this parameter is of crucial importance. Even a slight departure from harmonic law, improves gas estimation using rock-physics based inversions:

- f-AVO[5]
- trace inversion[6]
- ...?

We are currently using these ideas to determine if CO_2 saturation in the Sleipner field can be estimated more accurately.

---

[5] Xiaogyang Wu et al, 2004

[6] Current work by Zhaoyu Jin in Edinburgh

Estimating the parameter

Parameter q is given as a function of capillary pressure[7]:

$$q = \frac{1 - S_{\mathrm{w}}(1 - S_{\mathrm{w}})C'(S_{\mathrm{w}})/\mathcal{K}_{\mathrm{w}}}{1 - S_{\mathrm{w}}(1 - S_{\mathrm{w}})C'(S_{\mathrm{w}})/\mathcal{K}_{\mathrm{nw}}}$$

Is it a fiddle factor, is it realistic, can it be tuned with $C(S)$ experimental results?
See whether it is measurable from rock physics experiments[8]

---

[7] Juan E. Santos, Jaime M Corbero, and Jim Douglas Jr. "Static and dynamic behavior of a porous solid saturated by a two-phase fluid". In: *J. Acoust. Soc. Am.* 87.4 (1990), pp. 1426–1438. DOI: `10.1121/1.1908239`.

[8] Data from K. Amalokuw, I. Falcon-Suarez at SOC

To Conclude

- The effect of capillary pressure in rock physics may be significant
- Choice of different saturation in pores/crack with fixed overall saturation, leads to modelling of imbibition/drainage
- Choice of pressure jump leads to modulus discontinuity
- Choice of averaged pressure leads to Brie's law at low frequency and appealing frequency dependent model
- No need to resort to patches
- Feedback welcome!

Thanks!

Thank you!

Acknowledgments:

- Mark Chapman
- EPSRC DiSECCS grant