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A Review of Seismic Attenuation Mechanisms, Measurements, and Inversion Strategies

Seismic Inversion for Marine Overburden Characterization Workshop

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Outline

- Seismic Attenuation Fundamentals
  - Definition
  - Physical Mechanisms
  - Rock Physics Models
- Measuring Seismic Attenuation
  - Isolating Intrinsic Attenuation
  - Signal Processing Approaches
  - Tools in Seismic Interpretation Software
  - Full-waveform Inversion
- Attenuation Inversion
  - Concept
  - Challenges
  - Stochastic Approaches

What is seismic attenuation?

- Attenuation is the loss of energy per cycle of wave
- For a linear, viscoelastic solid:

$$u(x,t) = u_0 \exp[-\alpha(\omega)x] \exp[i(\omega t - kx)]$$

  where α is the attenuation factor.

- Often expressed in terms of “quality factor” (Q)

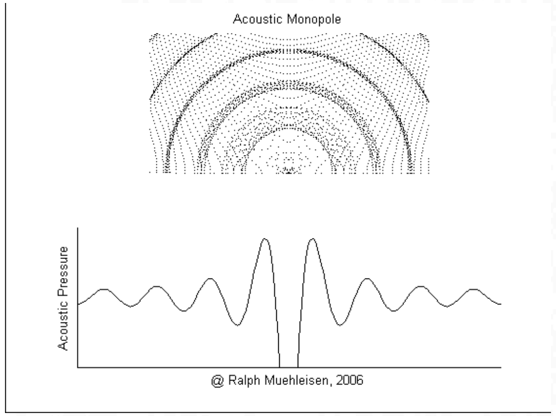
$$\frac{1}{Q} = \frac{M_I}{M_R} = \frac{\Delta W}{2\pi W} \approx \frac{\alpha V}{\pi f}$$

- Some typical values of Q_p: water = 200, sandstone = 60, granite = 250, shale = 30

Scattering vs. Intrinsic Attenuation

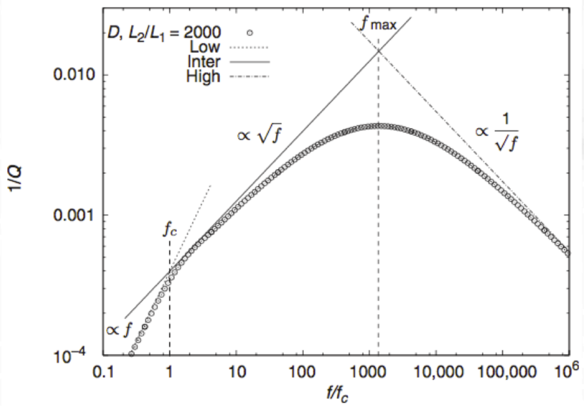
- Scattering Attenuation
- From spreading of wave front, diffraction at interfaces, and other geometrical disturbances
- Some of these are not frequency dependent

- Intrinsic Attenuation
- From frictional and viscous losses in porous media
- Frequency dependent (higher frequencies attenuated more)



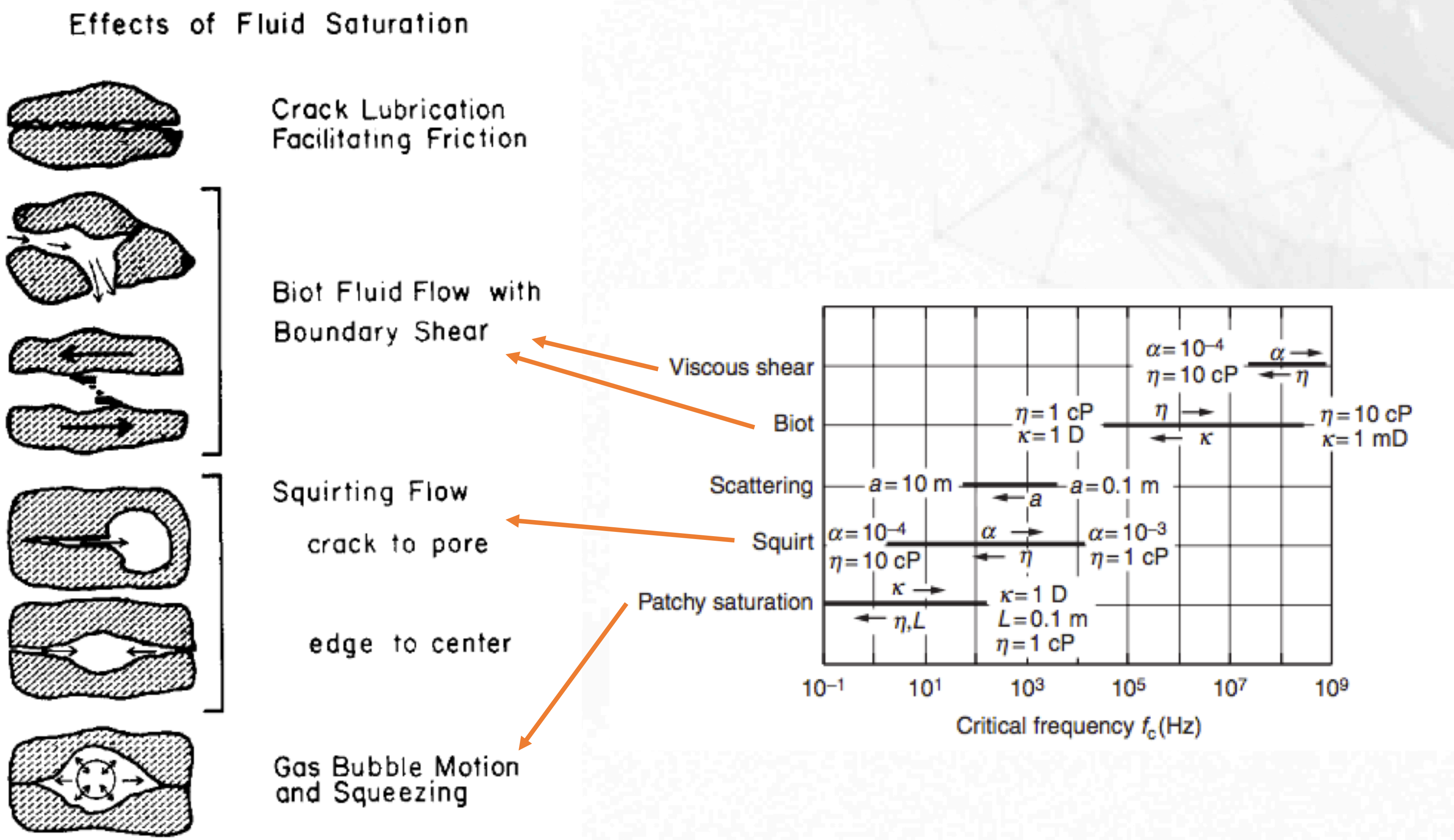
@ Ralph Muehleisen, 2006

$$\frac{1}{Q} = \frac{1}{Q_{scattering}} + \frac{1}{Q_{intrinsic}}$$



Müller, T. M., Gurevich, B., & Lebedev, M. (2010). Seismic wave attenuation and dispersion resulting from wave-induced flow in porous rocks — A review. *Geophysics*, *75*(5), 75A147–75A164. http://doi.org/10.1190/1.3463417

Physical Mechanisms



Rock Physics Models for Intrinsic Attenuation

- Biot theory (1956a,b) gives frequency-dependent velocities of saturated rocks
  - Captures viscous and inertial effects between pore fluid and matrix
  - Solutions to equations give “fast” and “slow” waves
    - Fast: matrix and pore fluid in phase
    - Slow: matrix and pore fluid out of phase

Biot, M. A. (1956a). Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range. *Acoustical Society of America. Journal*, *28*, 168–178.

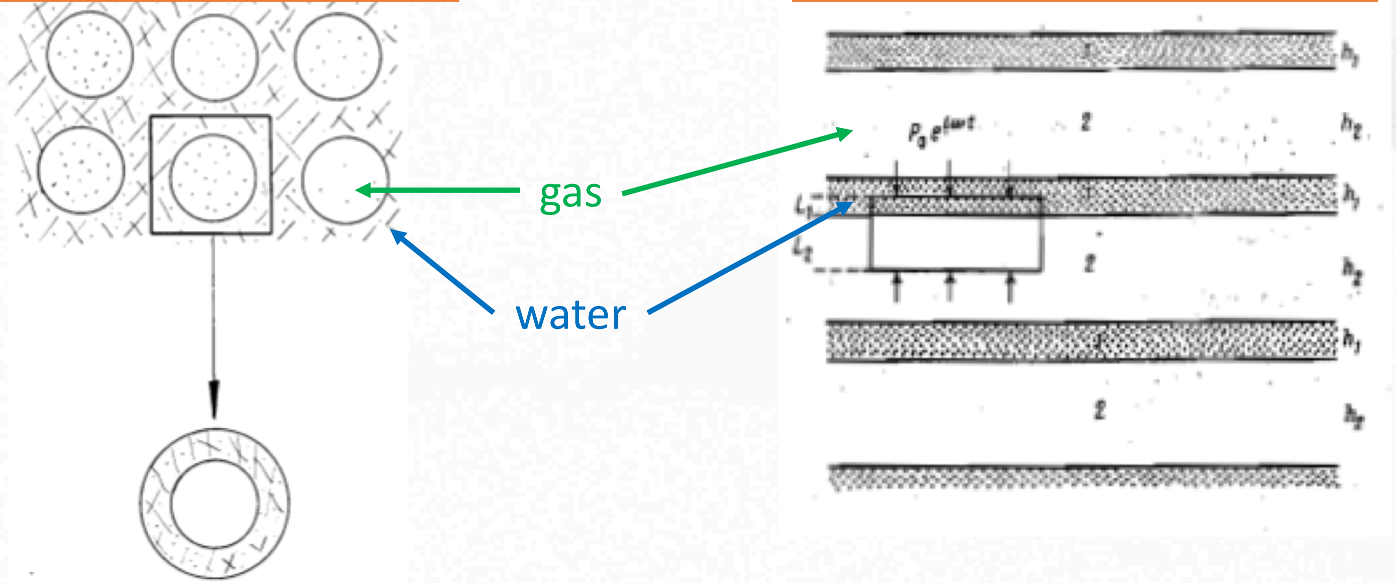
Biot, M. A. (1956b). Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range. *Acoustical Society of America. Journal*, *28*, 179–191.

Rock Physics Models for Intrinsic Attenuation

- White (1975) and White et al. (1975) build on Biot theory and gives frequency-dependent velocity and, thus, attenuation for partially saturated rock. Two geometries were theorized:

Spherical (White, 1975)

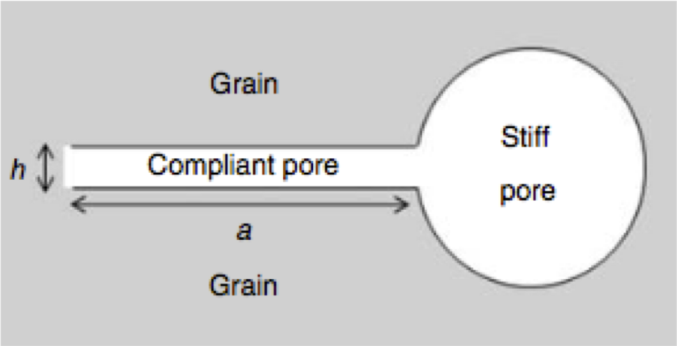
Layered (White et al., 1975)



White, J. E. (1975). Computed seismic speeds and attenuation in rocks with partial gas saturation. *Geophysics*. http://doi.org/10.1190/1.1440520
White, J. E., N. G. Mikhaylova, and F. M. Lyakhovitskiy, (1975). Low-frequency seismic waves in fluid saturated layered rocks: Izvestija Academy of Sciences USSR, Physics of the Solid Earth, **11**, 654–659.

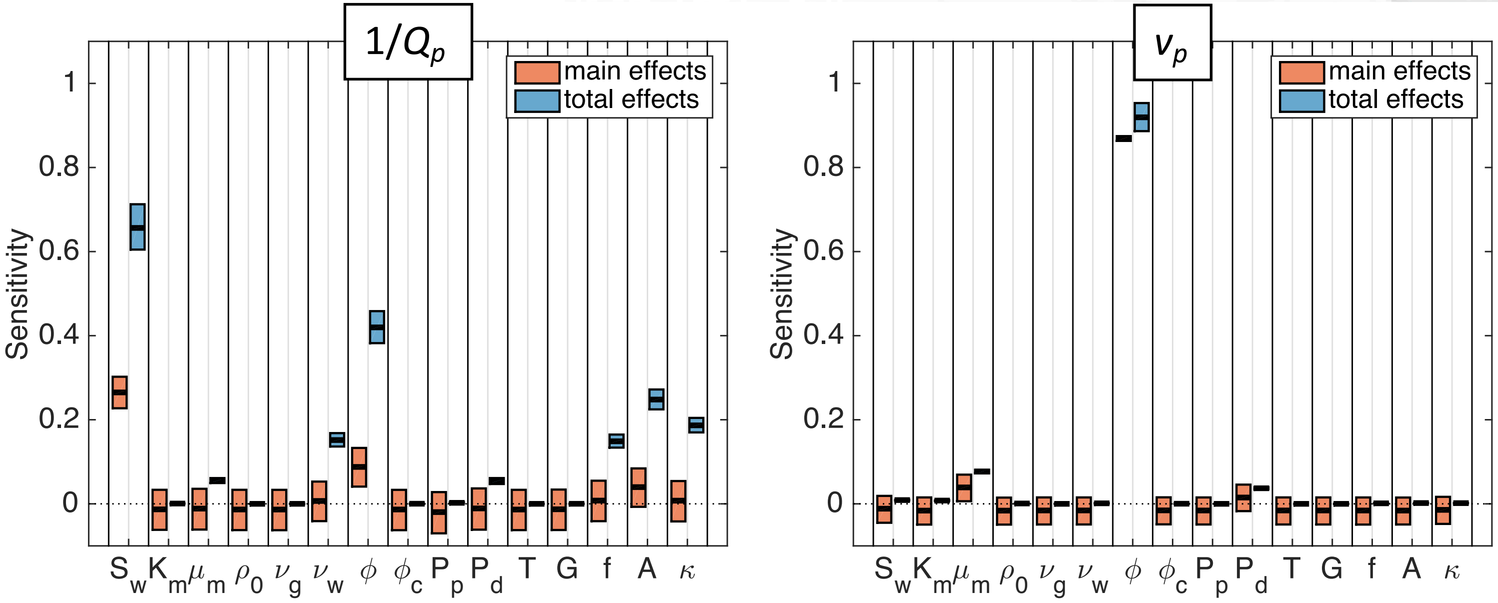
Rock Physics Models for Intrinsic Attenuation

- Squirt flow (or local flow) produces attenuation via viscous effects during flow from a compliant pore to a stiff pore.
  - Compliant pore is disc-shaped, and compressed to a greater degree by the passing wave than the stiff pore
  - Modeled on pore scale, so cannot use poroelasticity equations used in Biot, White, etc. (which average effects over representative volume)
  - Squirt flow models conventionally work with the aspect ratios of the pore spaces (e.g., Mavko and Nur, 1979)



Mavko, G., and A. Nur (1979). Wave propagation in partially saturated rocks: Geophysics, **44**, 161–178.

Sensitivity to Hydraulic Properties



S_w = Water saturation
K_m = Bulk modulus
μ_m = Shear modulus
ρ_0 = Density
ν_g = gas viscosity
ν_w = water viscosity
ϕ = porosity
ϕ_c = critical porosity
P_p = pore pressure
P_d = effective pressure
T = temperature
G = gas specific gravity
f = frequency
A = gas bubble radius
κ = permeability

Global sensitivity analysis using model of: White, J. E. (1975). Computed seismic speeds and attenuation in rocks with partial gas saturation. *Geophysics*. http://doi.org/10.1190/1.1440520

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Isolating Intrinsic Attenuation

- Virtually impossible to remove all scattering attenuation from Q
- But, we can try to minimize its contribution:
  - Correct for geometrical spreading (e.g., t^2 scaling)
  - Look at scattering relaxation frequency for diffraction around heterogeneities:

$$f_s = \frac{V_p}{2\pi h}$$

where *h* is the average scale or thickness of the heterogeneities. One can argue that scattering attenuation is minimal if expected *h* gives f_s outside of bandwidth of survey.

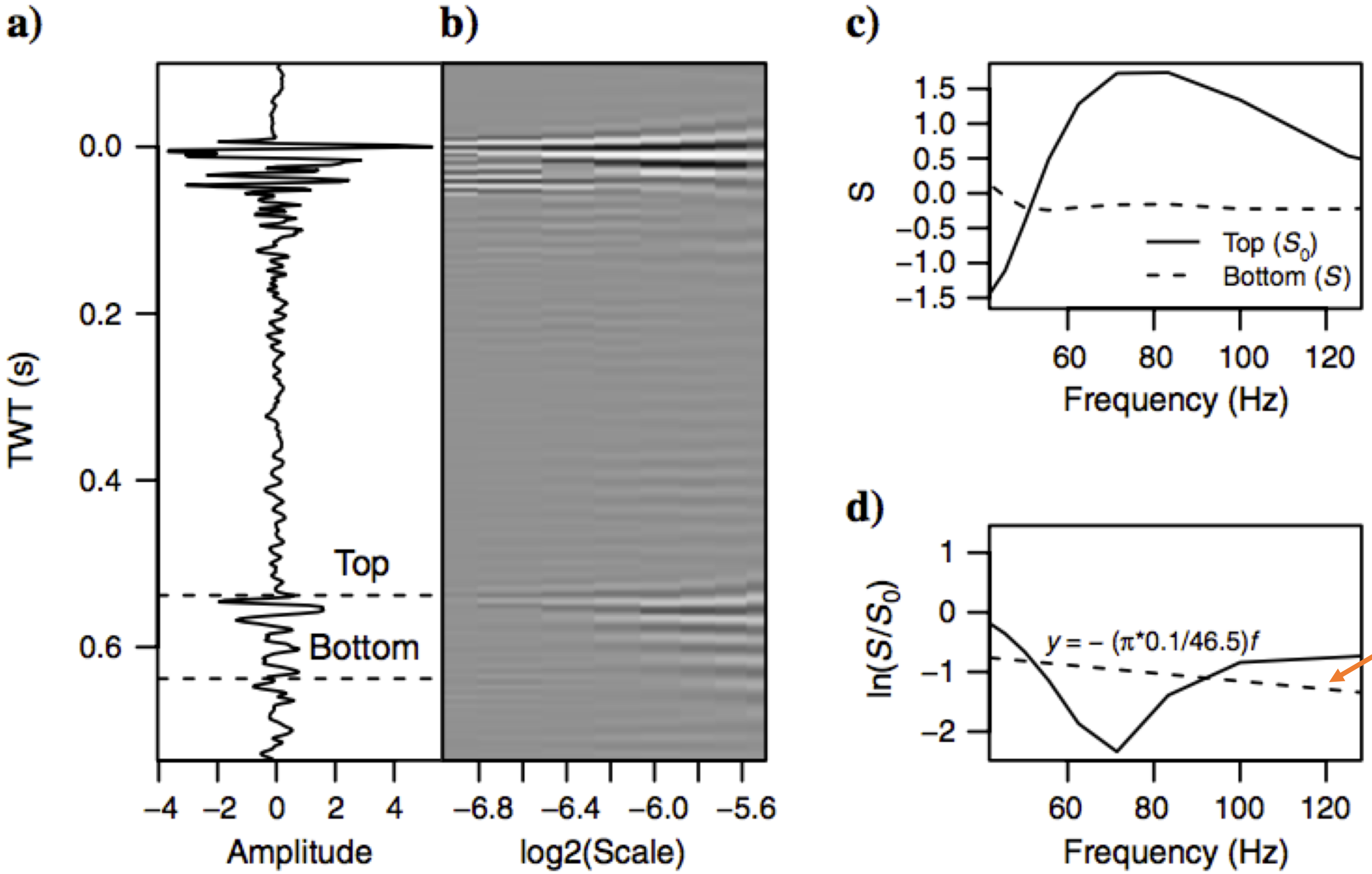
Measuring Attenuation: Signal Processing

- Three common approaches:

1. Spectral Ratio
2. Peak Frequency Shift
3. Centroid Frequency Shift

- Before exercising these methods, one should correct for geometrical spreading, remove multiples, and denoise (e.g., bandpass filter)

Spectral Ratio Method



$$\ln\left(\frac{S(f)}{S_0(f)}\right) = -\frac{\pi\Delta t}{Q}f$$

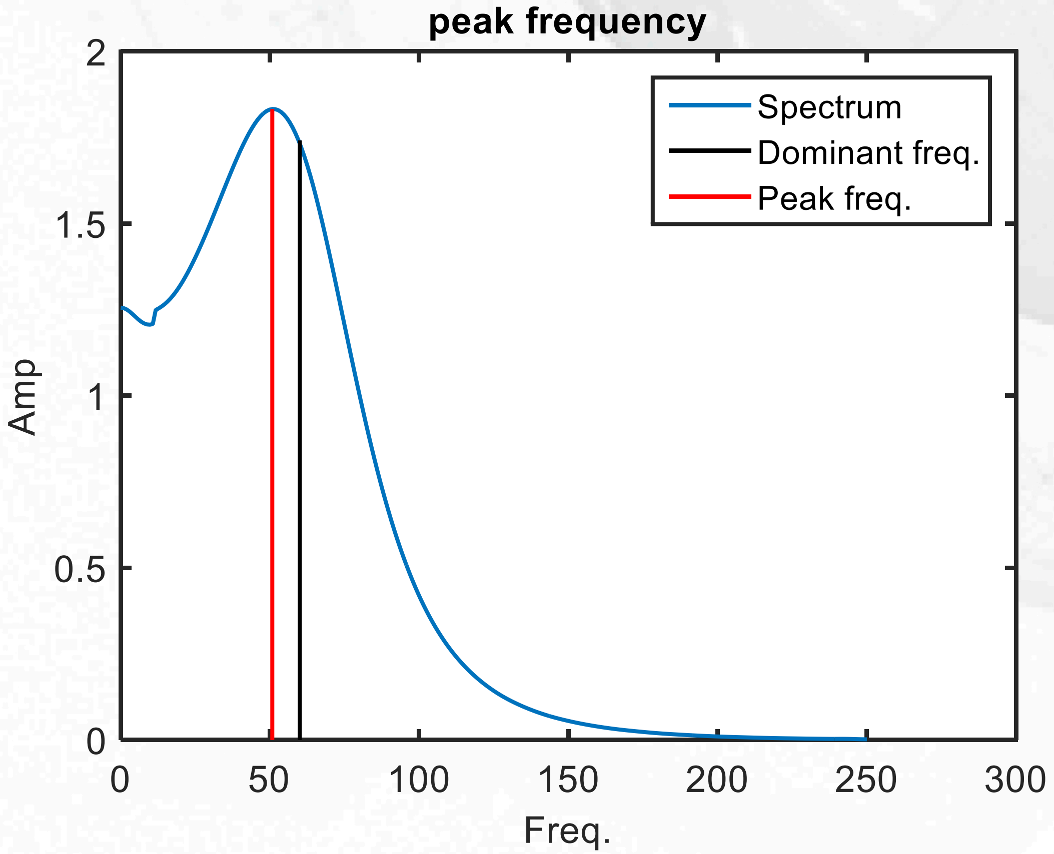
SRM Reference: Reine, C., M. van der Baan, and R. Clark, 2009, The robustness of seismic attenuation measurements using fixed- and variable-window time-frequency transforms: *Geophysics*, 74, no. 2, WA123–WA135, doi: 10 .1190/1.3043726.

Figure source: Morgan, E. C., Vanneste, M., Lecomte, I., Baise, L. G., Longva, O., & McAdoo, B. (2012). Estimation of free gas saturation from seismic reflection surveys by the genetic algorithm inversion of a P-wave attenuation model. *Geophysics*, *77*(4), R175–R187. http://doi.org/10.1190/GEO2011-0291.1

Peak Frequency Shift Method

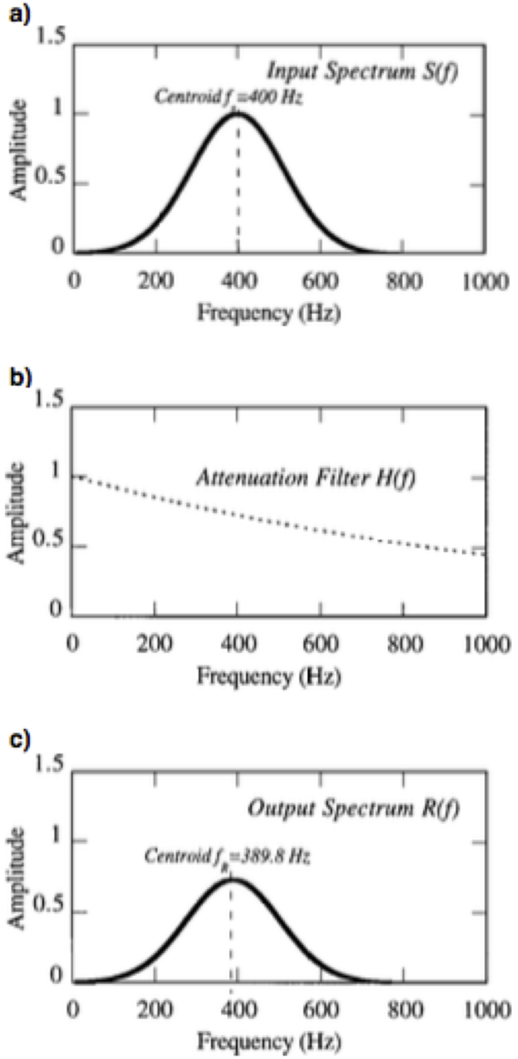
Gets quality factor from comparison of peak frequency of spectrum to dominant frequency of source wavelet:

$$Q = \frac{\pi t f_p f_m^2}{2(f_m^2 - f_p^2)}$$



Zhang, C., Ulrych, T.J., 2002. Estimation of quality factors from CMP records. *Geophysics* 67, 1542. doi:10.1190/1.1512799

Centroid Frequency Shift Method



As the name implies, this method finds Q by comparing centroid of output spectrum to that of input spectrum:

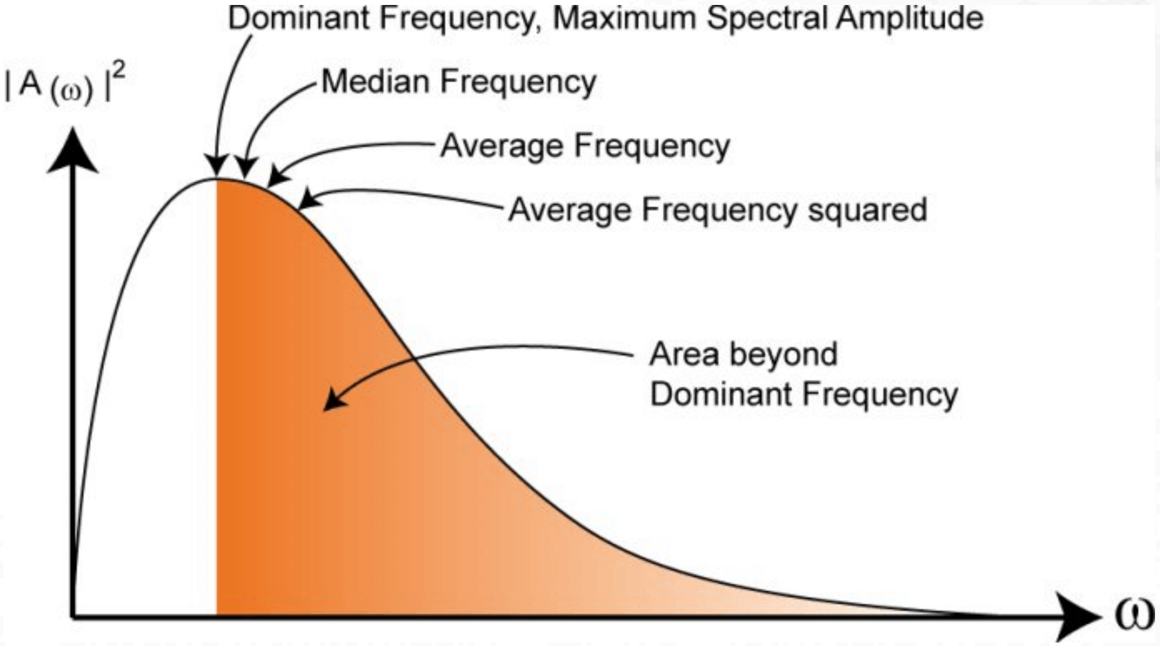
$$Q = \frac{\pi(t_r - t_s)\sigma_s^2}{f_{c,s} - f_{c,r}}$$

where

$$f_c = \frac{\int f \cdot |S(f)| df}{\int |S(f)| df} \qquad \sigma_s^2 = \frac{\int (f - f_{c,s})^2 \cdot |S(f)| df}{\int |S(f)| df}$$

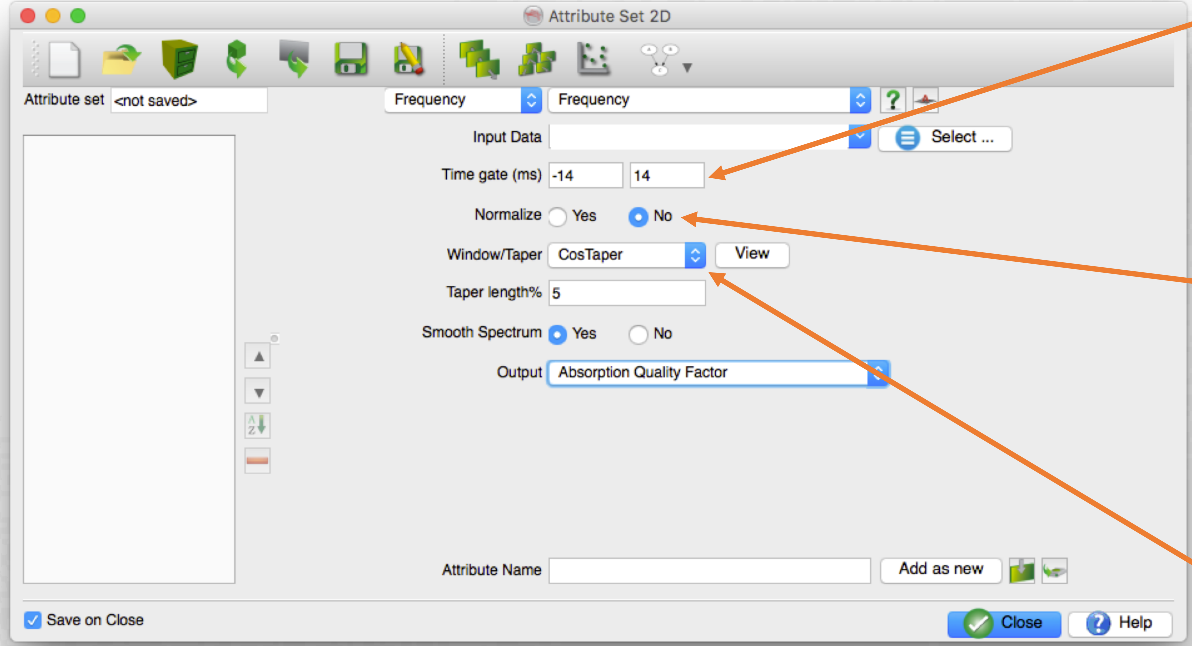
Quan, Y., & Harris, J. M. (1997). Seismic attenuation tomography using the frequency shift method. *Geophysics*, *62*(3), 895–905. http://doi.org/10.1190/1.1444197

Measuring Attenuation in OpendTect



$$Q = \int_{dom.freq.}^{\infty} \omega \cdot |A(\omega)|^2 \, d\omega$$

Measuring Attenuation in OpendTect



Attribute set <not saved>

Frequency | Frequency

Input Data

Time gate (ms) -14 14

Normalize ○ Yes ● No

Window/Taper CosTaper

Taper length% 5

Smooth Spectrum ● Yes ○ No

Output Absorption Quality Factor

Attribute Name

☑ Save on Close

Time gate: what range of data to input into Fourier transform

Normalize all spectra with respect to area?

Time gate is tapered according to these parameters (applies weights to data)

- Petrel makes similar simplification to estimating Q

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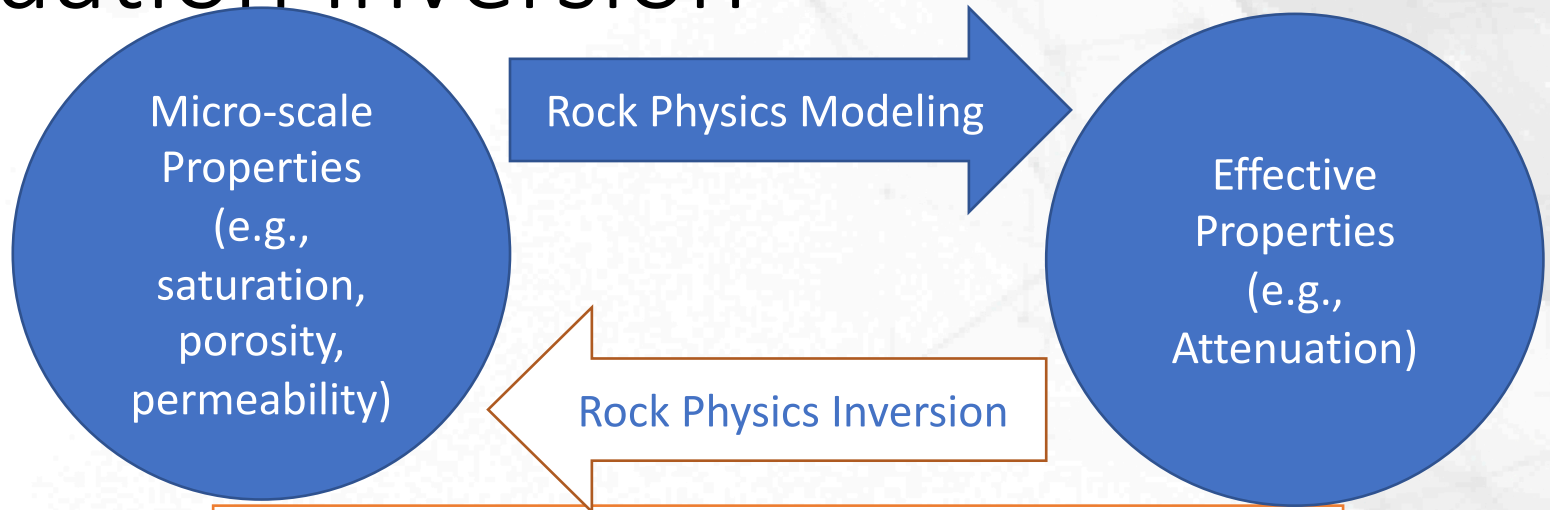
Attenuation Inversion

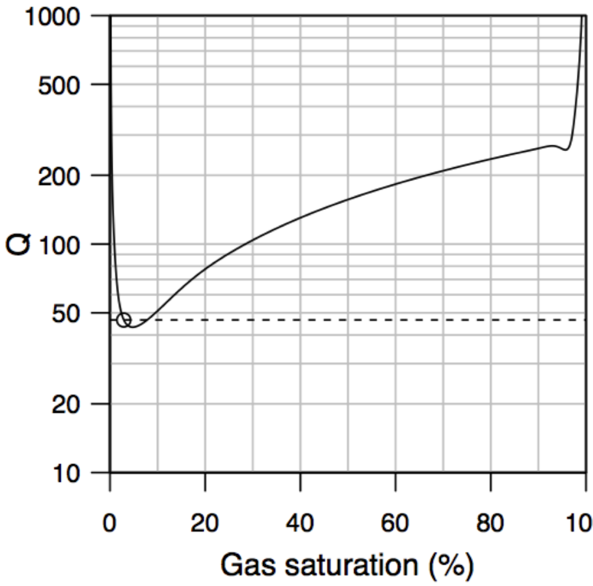


Micro-scale Properties (e.g., saturation, porosity, permeability)

Rock Physics Modeling

Effective Properties (e.g., Attenuation)

Rock Physics Inversion



Bayesian Inversion

Let x be a vector of parameter values (rock and fluid properties) and $Q(x)$ be the modeled quality factor (output from rock physics model). The measured Q values from the seismic survey are the model outputs plus some error:

$$\hat{Q} = Q(x) + e$$

The goal of Bayesian inversion is to estimate the posterior probability distribution of x, which is proportional to the product of a likelihood function and a prior distribution:

$$p\left(x \middle| \hat{Q}\right) \propto L\left(\hat{Q} \middle| Q(x)\right) \times \pi(x)$$

The likelihood function describes the chances of observing $\hat{Q}$ given a proposed x. Here a lognormal distribution is appropriate:

$$L\left(\hat{Q} \middle| Q(x)\right) = \mathit{lognormal}(\hat{Q}; Q(x), \sigma_Q)$$

The prior distribution gives the relative likelihood of observing a given set of rock and fluid property values, x. The logit-normal distribution is convenient because it allows us to bound the values (since we know ranges of likely values for these geologic conditions) while still having mean and covariance parameters.

$$\pi(\mathrm{x}) = logitnormal(x; \mu_{\mathrm{x}}, \Sigma_{\mathrm{x}}, a, b)$$

Where *a* and *b* are vectors of lower and upper bounds. However, many alternatives to this prior are equally as valid, it is just a matter of how you want to describe your prior knowledge!

Bayesian Inversion: Finding the Posterior

1. Conjugate priors
   - Analytical posterior distribution is known for certain pairings of likelihood functions and prior distributions (not helpful in this case)
2. Quadrature
   - Regularly sample *x* over grid and calculate product of likelihood and prior
   - Curse of dimensionality!
3. Markov Chain Monte Carlo (MCMC)
   - Effectively, a way to draw samples from the posterior distribution

Bayesian Inversion: MCMC

Example: Metropolis Algorithm Pseudo-code:

```
initialize $x$
for $i = 1 : niter$ do
    draw $x_i'$ from $J(x_i)$
    if $u < \frac{p(x_i' \mid \hat{Q})}{p(x_i \mid \hat{Q})}$, where $u$ is drawn from standard uniform distribution, then
            $x_{i+1} = x_i'$
        else
            $x_{i+1} = x_i$
    end if
end for
```

Save all x's and assess convergence and acceptance rate. After convergence, discard "burn-in" samples and "thin" samples as well.

Optimization Approach

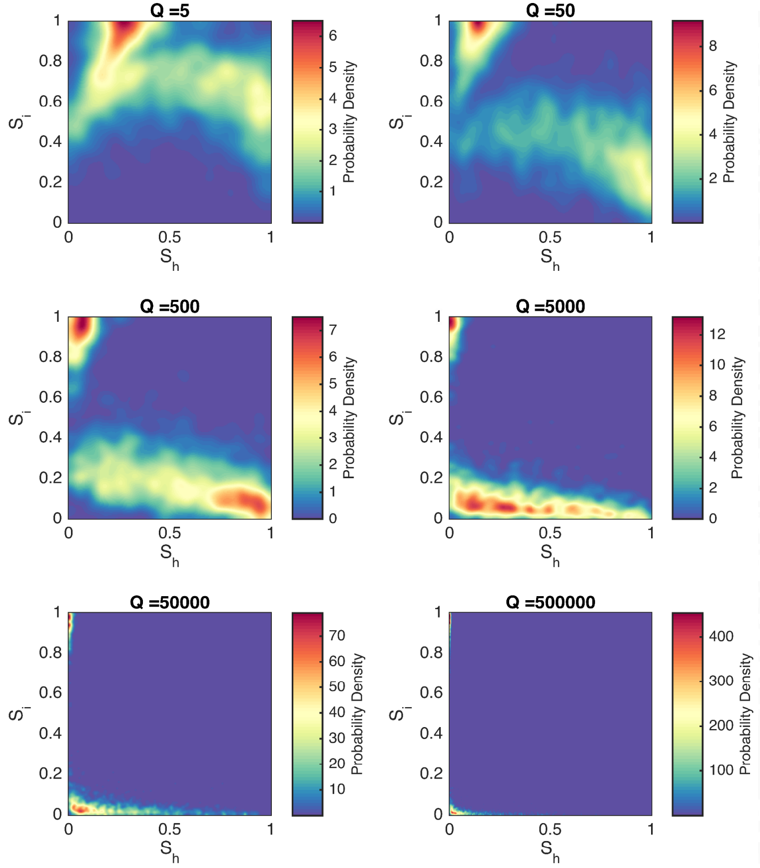
Solve:

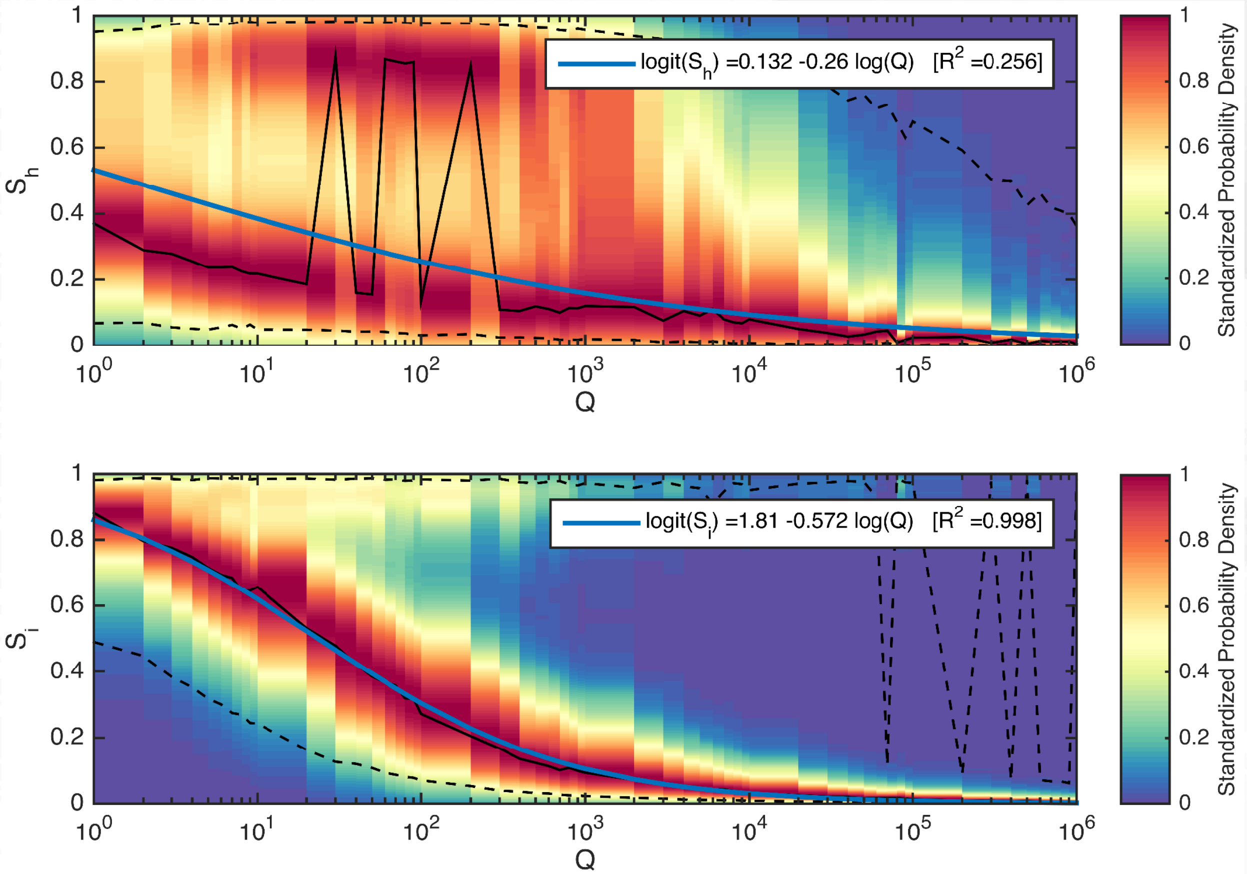
$$x^* = \arg\min\left(\hat{Q} - Q(x)\right)^2$$

Or, in words, find x that minimizes the error between the measured and modeled quality factors.

Problem: depending on the domain of x, $Q(x)$ may be highly nonlinear, so linear programming methods won't work well. Stochastic optimization methods (e.g. simulated annealing, genetic algorithm, or particle swarm algorithm) are more robust and don't require explicit calculation of the derivative of the optimization function.

Example of Posteriors from MCMC: Hydrate Effective Grains Model

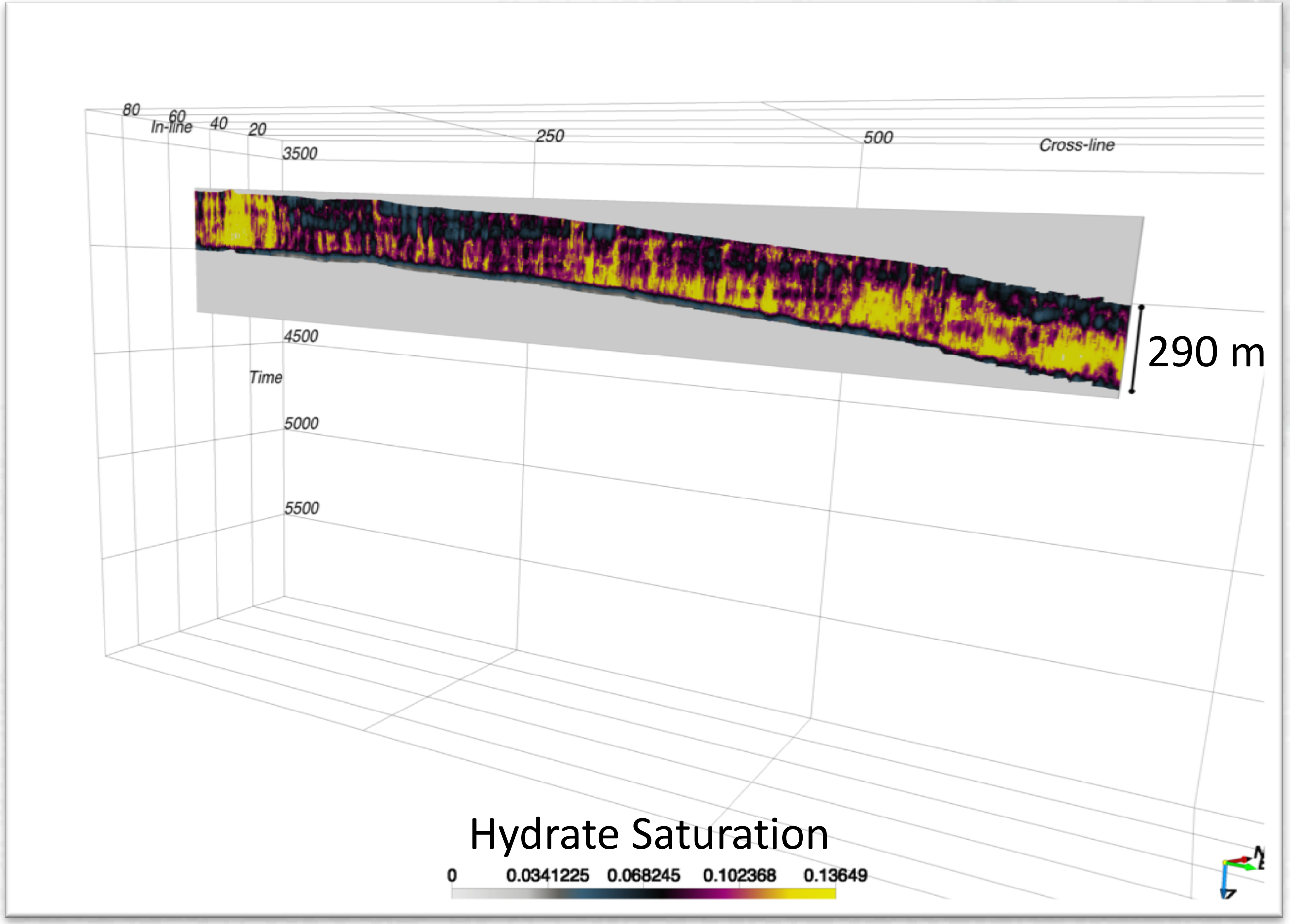




Braun, K.E. (2016) Inversion Scheme for Predicting Petrophysical Properties in the Blake Ridge Methane Hydrates Field from 3d Seismic Survey Data. *M.S. Thesis*, Penn State. https://etda.libraries.psu.edu/catalog/29000

Best, A. I., Priest, J. A., Clayton, C. R. I., & Rees, E. V. L. (2013). The effect of methane hydrate morphology and water saturation on seismic wave attenuation in sand under shallow sub-seafloor conditions. *Earth and Planetary Science Letters*, *368*, 78–87. http://doi.org/10.1016/j.epsl.2013.02.033

Application to Blake Ridge Hydrate Field



Braun, K.E. (2016) Inversion Scheme for Predicting Petrophysical Properties in the Blake Ridge Methane Hydrates Field from 3d Seismic Survey Data. *M.S. Thesis*, Penn State. https://etda.libraries.psu.edu/catalog/29000

Summary

- Seismic attenuation can be difficult to work with, but serve as a valuable metric for characterizing the subsurface
  - Intrinsic attenuation is strongly related to the hydraulic properties of porous media
  - But it’s difficult to separate intrinsic from scattering Q
  - And it’s difficult to accurately measure Q
- Inversion of rock physics models for attenuation is best done through stochastic methods
  - MCMC sampling efficiently gives the posterior distribution, which may show multiple modes
  - Stochastic optimization techniques (e.g., genetic algorithm, particle swarm optimization) may be more efficient, but may not discover other modes