From Mineralogy to Mechanical Properties: integrating core data and rock physics simulations for stiffness tensor estimation in Vaca Muerta organic-rich mudrock

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Characterization of ultra-low permeability, organic-rich mudrock reservoirs. I

- This work presents a methodology to characterize and analyze the lower section of the Vaca Muerta Formation (VMF) in the Neuquén Basin, Argentina.
- A core sample extracted at depth 3100 m was dried under laboratory conditions.
- Ultrasonic phase velocity measurements conducted at a frequency of 1 MHz, exhibited a clear **vertical transverse anisotropy (VTI)** behavior in the formation.
- VMF has a stratified microstructure, with clay platelets and **organic matter (mostly kerogen)** parallel or sub-parallel to bedding.

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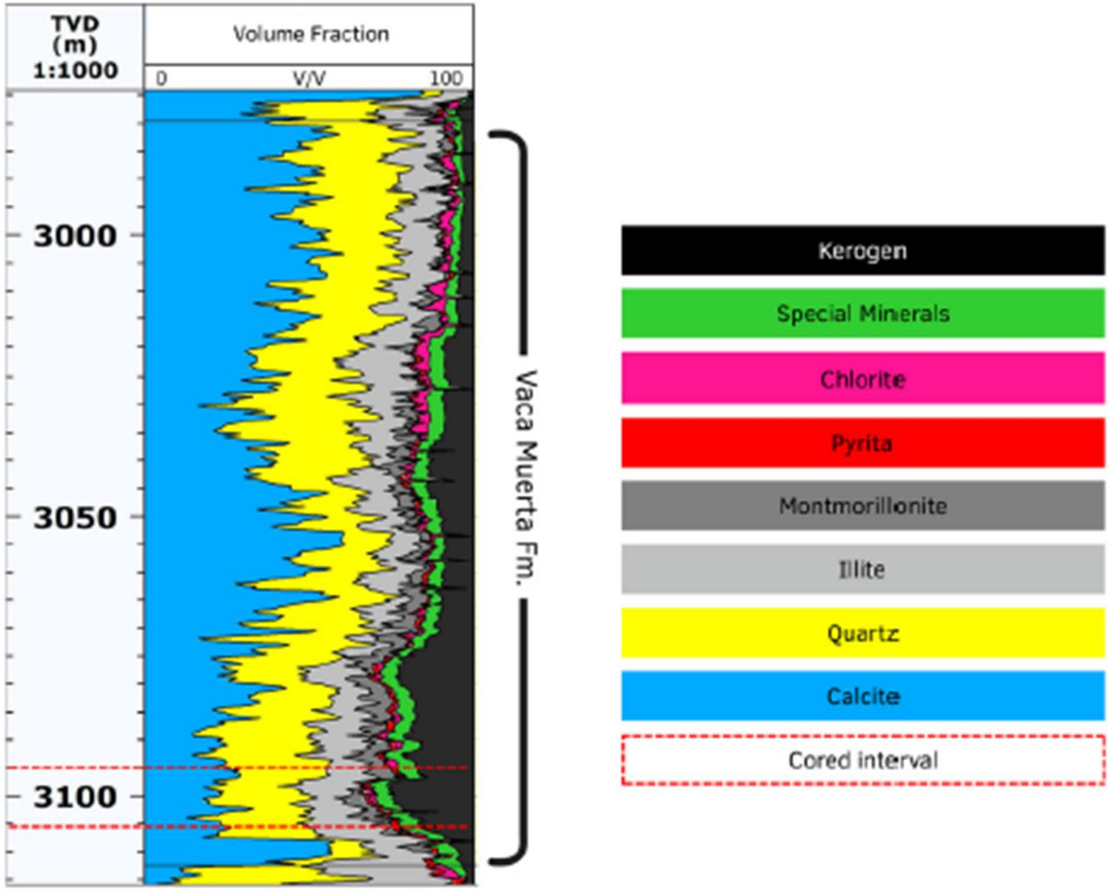
Well in the VMF from where the core sample was extracted

Measured data: rock mineralogy and phase velocities, vp11, vp33, vp55 and vp66.

This core corresponds to the window of maximum oil generation (location marked with a red rectangle).

Green region corresponds to the the oil-generating window in the VMF.



Characterization of ultra-low permeability, organic-rich mudrock reservoirs. II

- VMF is assumed to consist of a periodic sequence of very thin horizontal layers where **Biot's theory in the diffusive frequency range** is applicable.
- To characterize the VTI stiffness coefficients pij of the equivalent VTI medium, numerical harmonic simulations—both compressional and shear—were performed on a representative synthetic rock model.
- The model **consists of a periodic sequence of two porous materials**, both of 6 percent porosity and permeability 2.75 10^{-18} m^2.

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Characterization of ultra-low permeability, organic-rich mudrock reservoirs. III

- Material 1 is a complex, multimineral assemblage composed of seven solid phases, including 23 percent of kerogen, which is treated as a solid mineral constituent.
- After estimating the bulk and shear moduli of the individual solid phases **using a generalized Krief's model**, and taking into account their volume fractions, **for Material 1 we get a frame bulk modulus of 29.19 GPa and a shear modulus of 17.78 GPa**, values that lie within the Hashin–Shtrikman bounds.
- Material 2 is composed entirely of pure kerogen with grain modulus 7 GPa, density 1400 kg/m^3, frame modulus 1.29 GPa and shear modulus 0.36 GPa.

Fluid and minerals properties

Table 1. Fluid properties.

fluid	Bulk modulus (Pa)	Density (kg/m^3)	Viscosity (Pa . s)
Air	1.01325d5	1.225d0	1.805d-5
Water	2.25d9	1000	0.001
Oil	0.57d9	700	0.01
Gas	0.022d9	78	0.000015

Table 2. Mineralogical properties obtained from X-ray diffraction (XRD) analysis of core sample, used for Material 1 at an effective pressure of 17.23 MPa

mineral	Bulk modulus (GPa)	shear modulus (GPa)	Density (kg/m^3)	Proportions (%)
kerogen	7.0	2.	1400	23
Clay	25	9	2700	0.3727
Quartz	45	55	2700	0.1461
Calcite	80	40	2800	0.1068
Plagioclase	80	40	2800	0.0257
Dolomite	100	50	2900	0.0237
Pyrite	170	110	5000	0.035

Computed VTI velocities using dry-core data

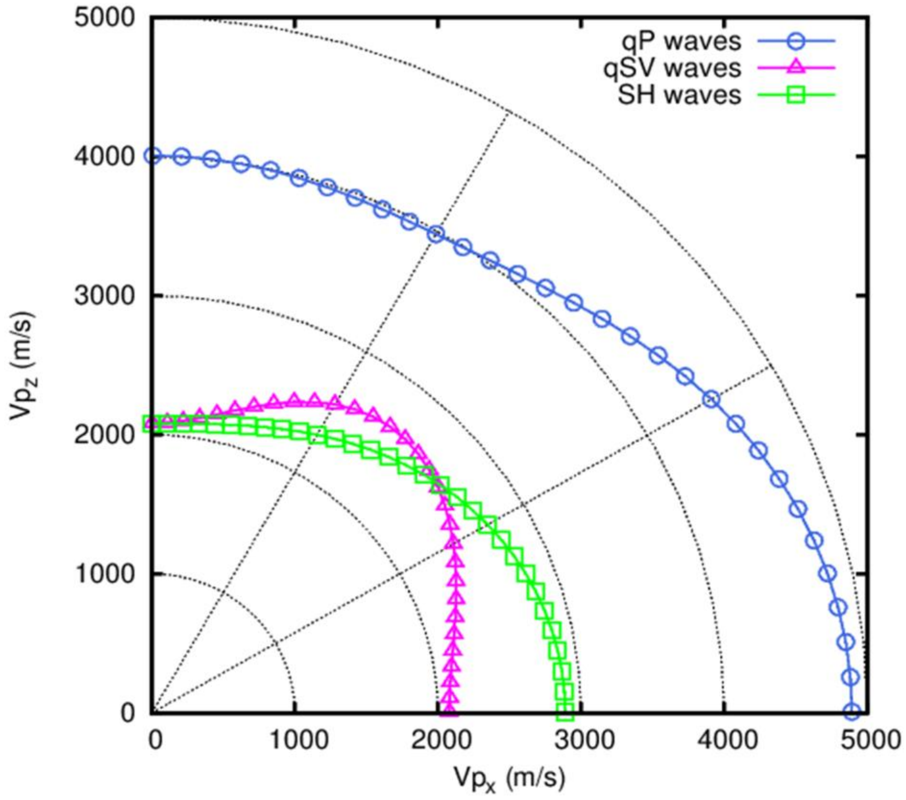
The harmonic experiments were performed on a dry square sample with a side length of 2 mm, consisting of four repetitions of **a periodic sequence composed of 49 layers of Material 1 and one layer of Material 2** per period. Each layer has a uniform thickness of 10^{-5} m. The domain was discretized using a 200×200 mesh.

Table 2 summarizes the results of the VTI experiments at 1 MHz

Phase velocity vp (m/s)	Computed	Measured	Percentage error
v11	4644.37	4331	7.2 %
v33	3804.51	4217.47	9.8 %
v55	1974.76	2193.61	9.9 %
v66	2742.64	2581	6.2 %

Polar representation of qP, qSV and SH phase velocities at 1 MHz. Dry sample.

Figure 2: phase velocities



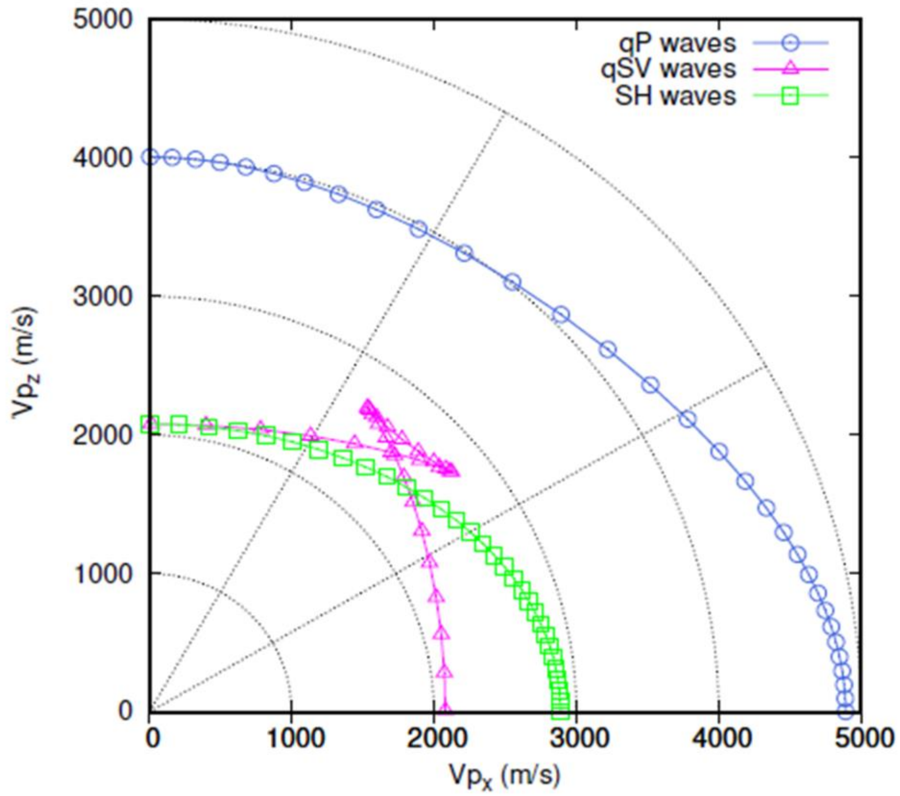


Figure 3: energy velocities

Anisotropy is clearly observed

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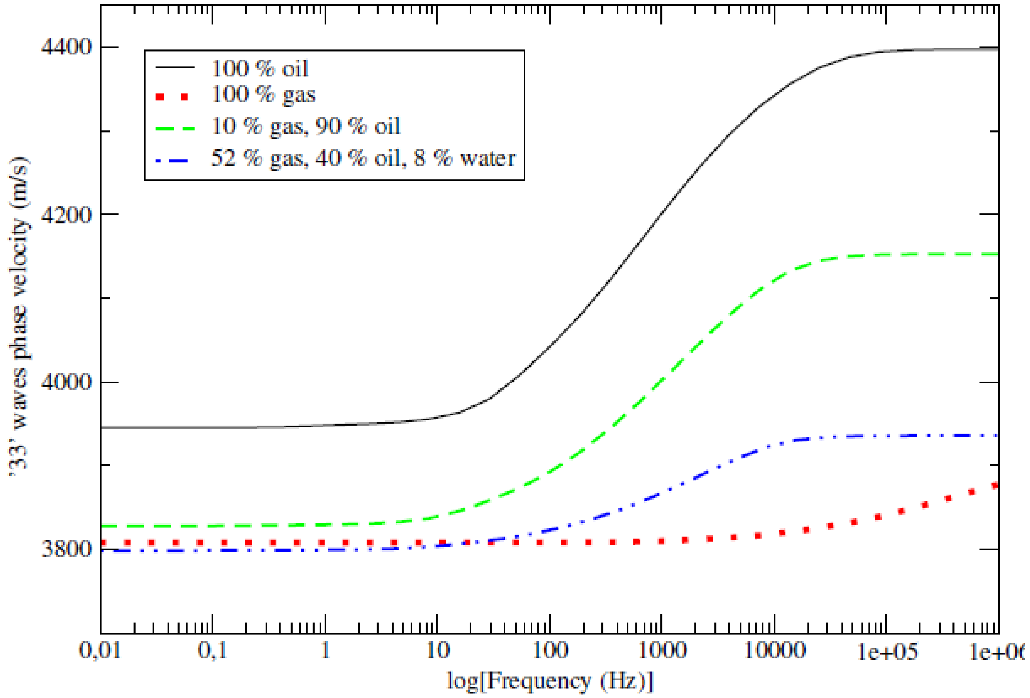
Analysis of fluid saturated VMF

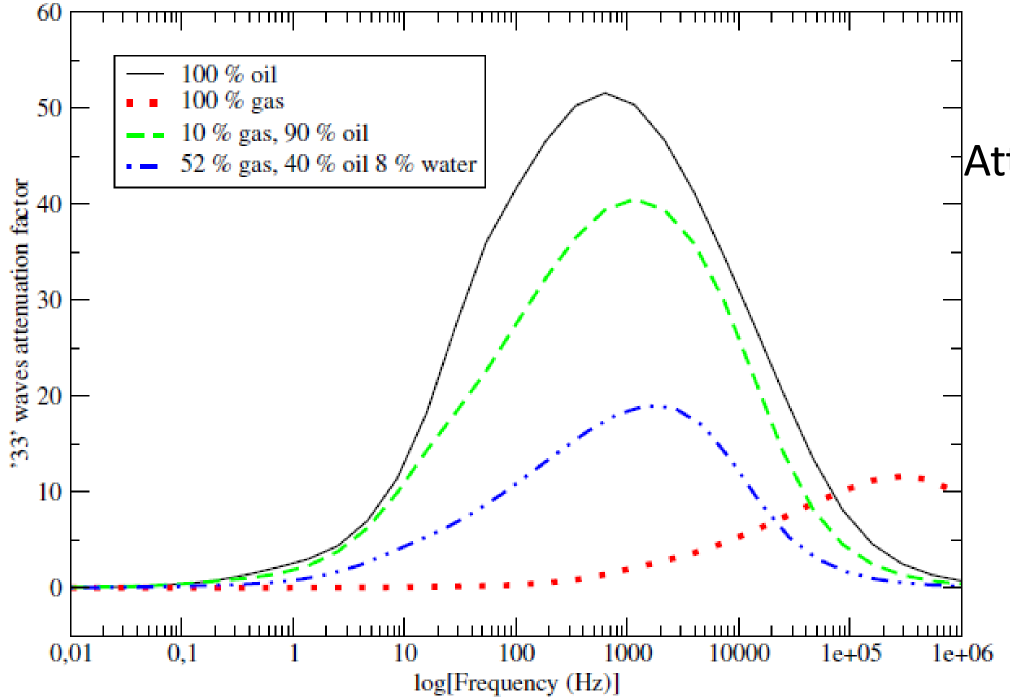
- Four fluid saturation scenarios are analyzed : 100 percent oil, 100 percent gas, 10 percent gas plus 90 percent oil and a ternary fluid mixture consisting of 40 percent gas, 52 percent oil, and 8 percent water, obtained from the well's fluid saturation log.
- Next Figures display phase velocities and attenuation factor 1000/Q, with Q denoting the quality factor. We consider waves traveling normaly to the layering plane ('33' waves).
- For brevity, waves traveling parallel to the layering plane are not shown.
- While phase velocities allows to analyze velocity dispersion for the four saturation scenarios, the attenuation figure allows to study the WIFF.

Phase velocities and attenuation of ´33´waves

Four fluid saturation scenarios: 100 % oil, 100 % gas, 10 % gas plus 90 % oil, and a ternary fluid mixture of 40 % gas, 52 % oil, 8 % water, obtained from the well's fluid saturation log at the depth corresponding to the core sample.

phase velocity.





Attenuation factor

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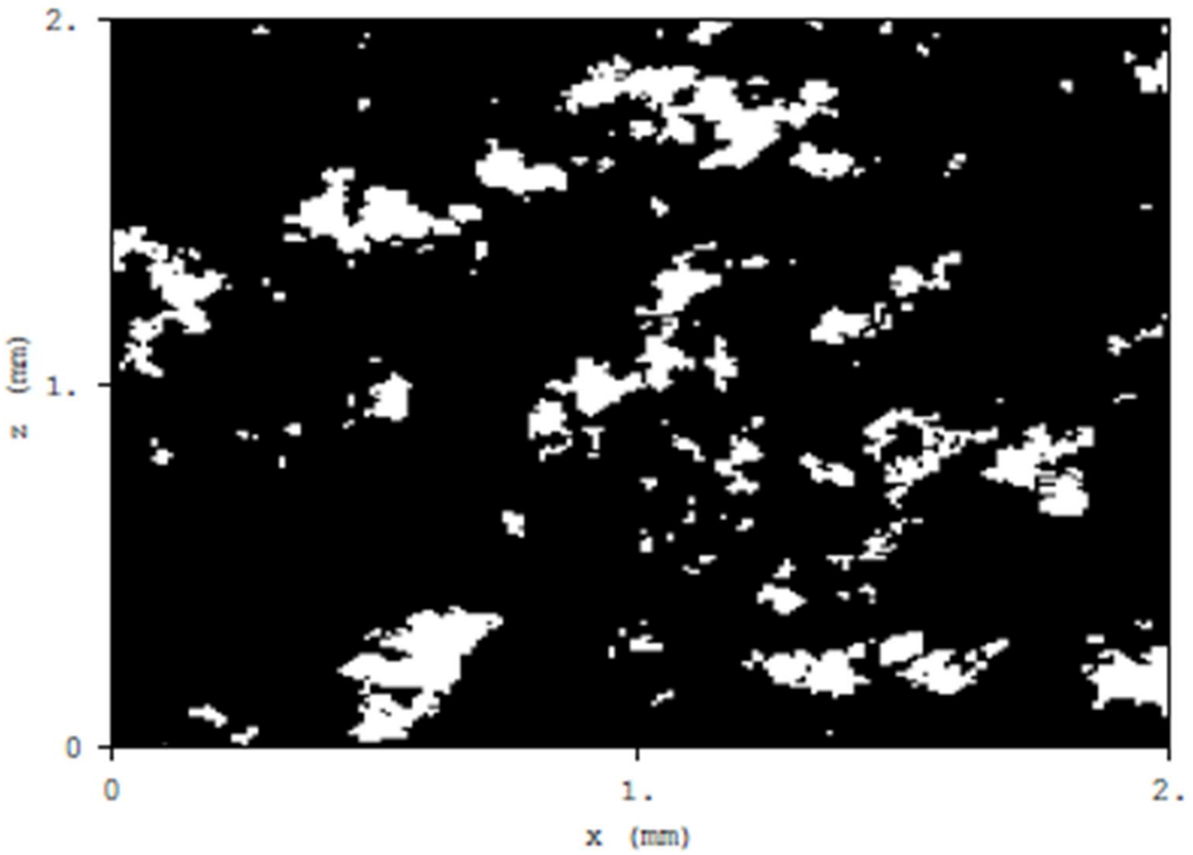
Patchy Saturation



The von Karman self-similar correlation function was used to generate patchy saturation patterns. White zones correspond to full gas saturation and black regions to full oil saturation. Overall gas saturation is 10 percent.

Phase velocity of ’33’ waves for uniform and patchy saturation

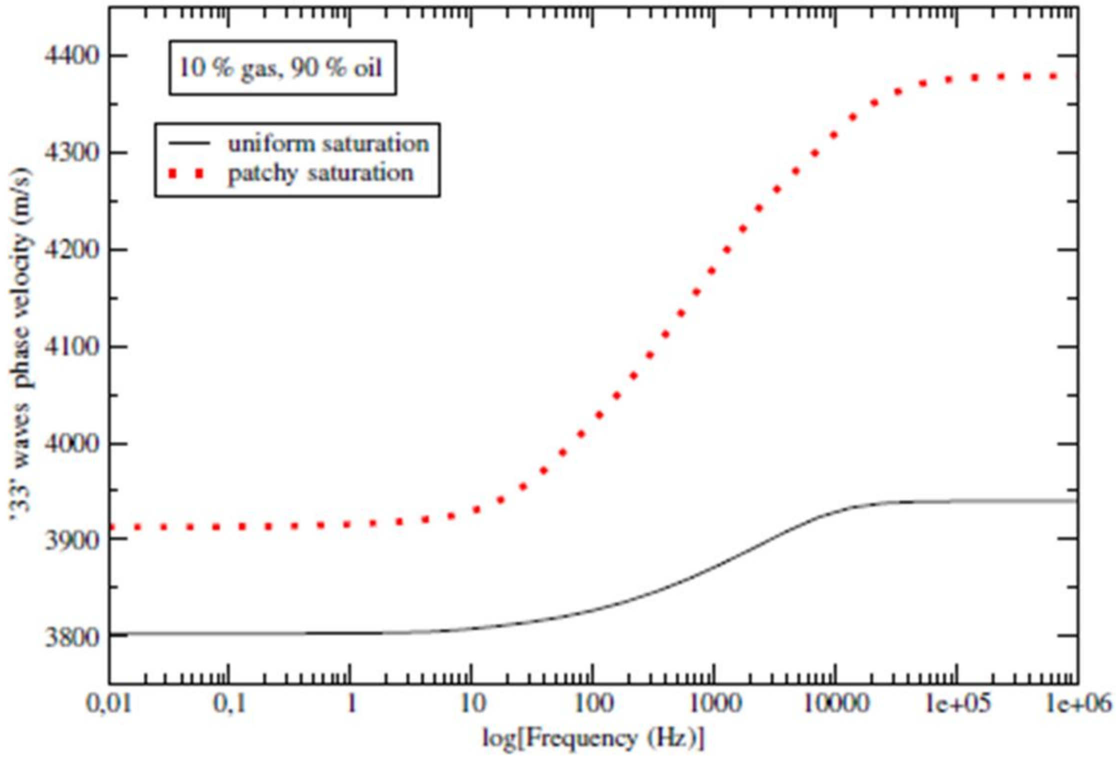


Figure 7: Phase velocity of ’33’ waves as function of frequency for 10 % gas, 90 % oil and uniform and patchy saturation

Uniform case: perfect mixing, producing a single-phase effective fluid, resulting in lower velocities.

Patchy case: wave propagation is governed by the stiffer oil-saturated zones, leading to higher velocities

The difference becomes particularly evident above 100 Hz, consistent with mesoscopic WIFF activation.

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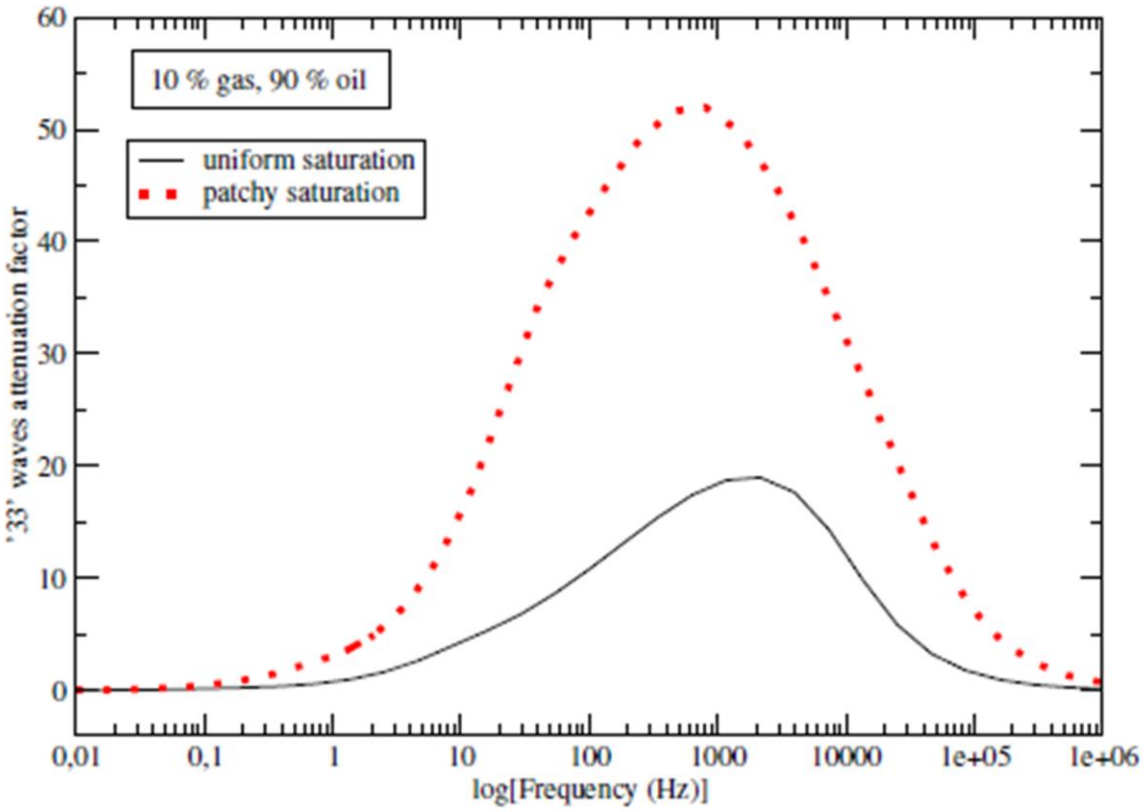
Attenuation factor of ’33’ waves for uniform and patchy



Patchy case: markedly higher attenuation due to enhanced WIFF at gas–oil interfaces. The attenuation peak is shifted to lower frequencies reflecting the longer diffusion times associated with larger- scale heterogeneities and limited pressure communication between fluid patches.

Figure 8: Attenuation factor of ’33’ waves as function of frequency for 10 % gas, 90 % oil and uniform and patchy saturation.

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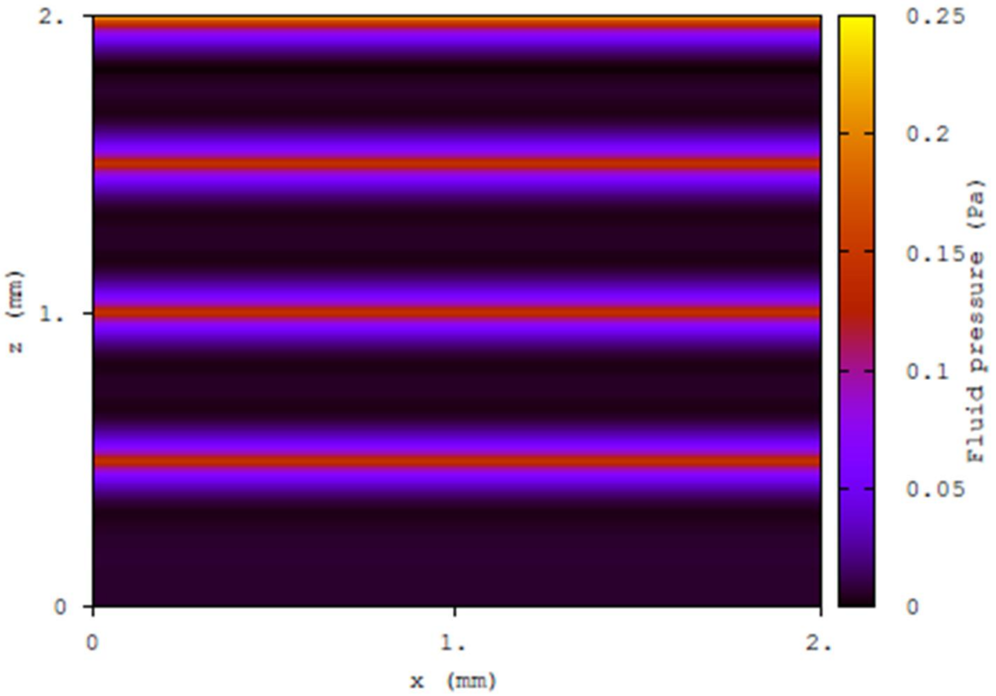
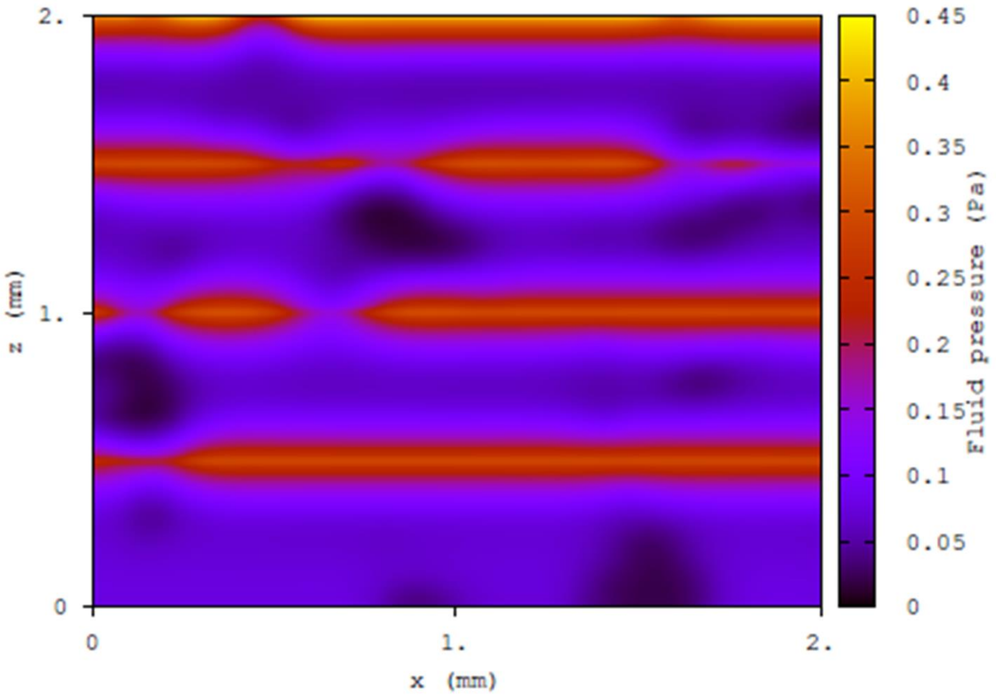
Fluid pressure of ’33’ waves for uniform and patchy saturation.

Figure 9: Fluid pressure for the case of 10 % gas, 90 % oil and uniform saturation (left) and patchy saturation (right).





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Conclusions

- This study presented a physically grounded, non-phenomenological methodology for estimating the effective anisotropic behavior of the organic-rich mudrock reservoirs.
- The simulations were performed on a finely layered synthetic medium representative of a core sample from the Vaca Muerta Formation.

Conclusions

- The computed stiffness tensors showed very good agreement with laboratory-measured phase velocities and well-log data, capturing the strong VTI anisotropy of the formation.
- The inclusion of both patchy and uniformly mixed fluid saturation scenarios emphasized the critical influence of mesoscale fluid heterogeneities on seismic wave dispersion and attenuation.

Thanks for your attention !!!!