Implication of Non-Gassmann Effects for CO2 Monitoring

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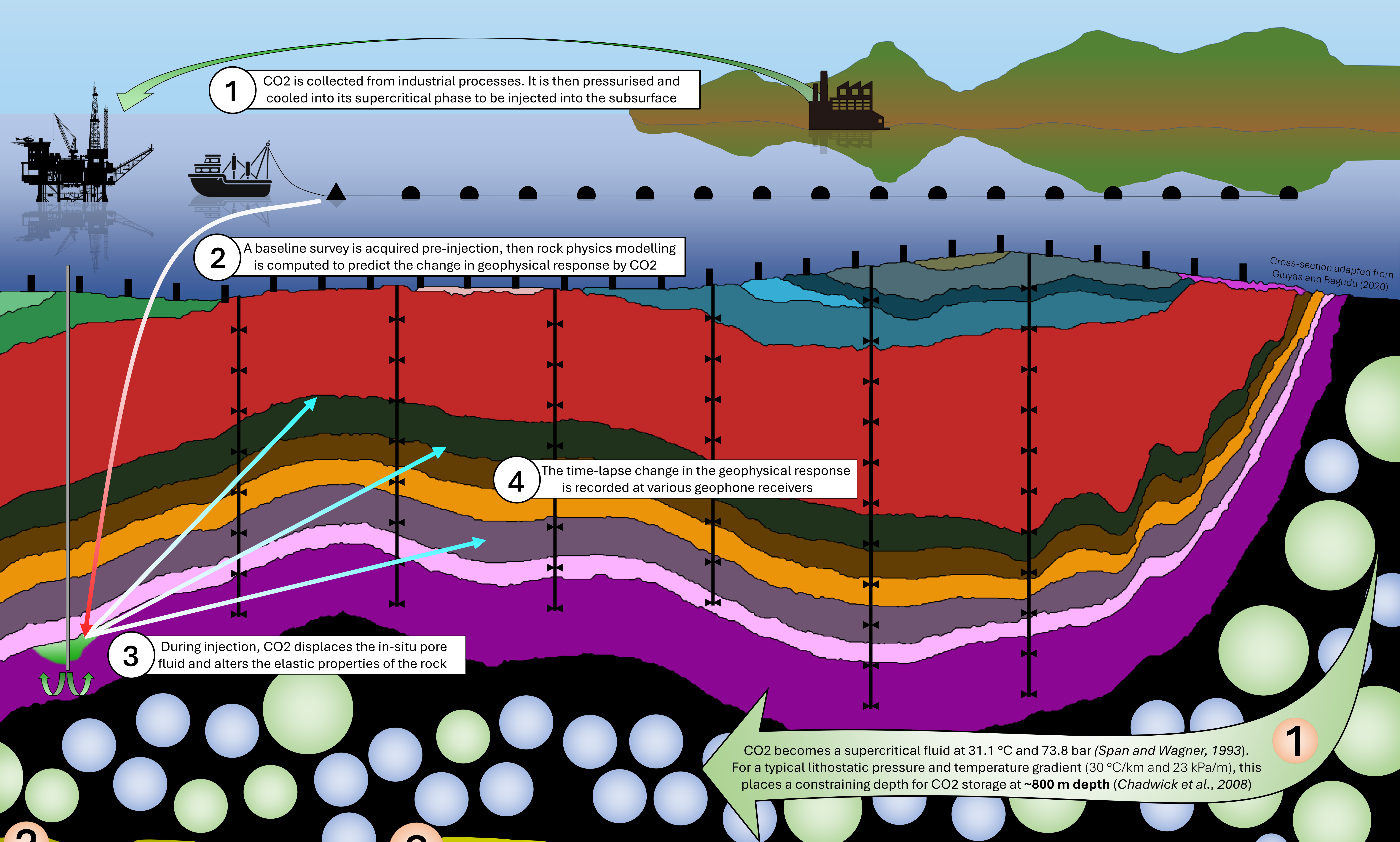

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- A **baseline** survey is the initial survey acquired before CO2 injection to create a static reservoir model on which simulations are performed
- The **baseline** survey generally consists of a 3D seismic survey and one or more appraisal wells
- The **geophysical response** for this study is considered the seismic attributes relating to seismic travel-time, phase, amplitude and attenuation

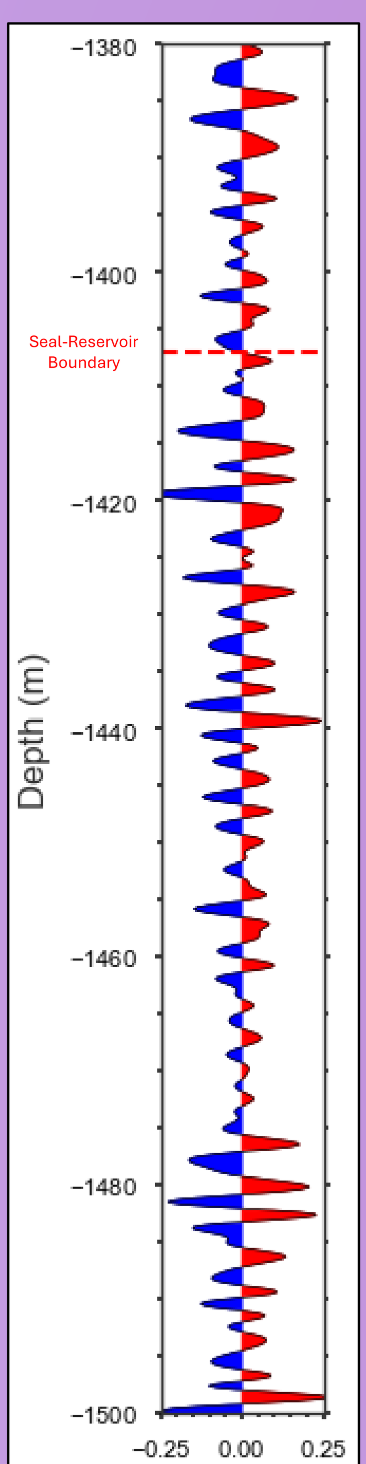

Figure 1: *Synthetic seismogram, convolved from well 42/25d-3 derived reflection coefficients with added noise with a 50 Hz Ricker wavelet*

- **Rock Physics Modelling** links the geophysical observables, such as velocity, impedance or reflectivity (Figure 1), to the rock properties, such as porosity, fluid saturation and elastic attributes
- Typically, for rock physics studies the **Gassmann equations** are used to model the change in elastic properties of a rock due to the replacement of the in-situ pore fluid (*Prasad et al., 2021*)
- Effective Medium Theory's are utilised to account for the more complex influences of anisotropy, fractures, partial saturation and frequency-dependent effects

- For this study, the reference model is parametrised from available data for well log *42/25d-3* in the Endurance field, located in the Southern North Sea
- The storage reservoir is the Bunter sandstone (~1407 m depth) which is sealed by the Röt clay and Röt halite members

Full reference list and acknowledgements available via the QR code.

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- Classically, we model the change in the geophysical response using the **Gassmann equations**
- The **Gassmann equations** assume a homogenous, isotropic, linearly elastic, low-frequency rock
- In reality, rocks can be layered, fractured, heterogeneous, non-linearly elastic and multi-frequency

$$K_{dry} = \frac{K_{sat}(\Phi K_m/K_{fl} + 1 - \Phi) - K_m}{\Phi K_m/K_{fl} + K_{sat}/K_m - 1 - \Phi}$$

$$\mu_{sat} = \mu_{dry}$$

- We propose the use of the **frequency-dependent anisotropic partial saturation model** (*Jin et al., 2018*), which is an extension of the **Chapman model** (*Chapman et al., 2002*)

$$C_{ijkl}(\omega) = C^0_{ijkl}(\Lambda, \Upsilon) - \Phi_P C^1_{ijkl;}(\lambda^0, \mu^0, \omega) - \varepsilon_c C^2_{ijkl}(\lambda^0, \mu^0, \omega) - \varepsilon_f C^3_{ijkl}(\lambda^0, \mu^0, \omega)$$

- This model addresses the limitations of the Gassmann equations (Figures 2 and 3), accounting for the effects of anisotropy (*e.g., Hudson, 1980*), attenuation (*e.g. Ursin and Toverud, 2002*), partial saturation (*e.g. Papageorgiou and Chapman, 2017*) and is consistent with the Gassmann equations in the seismic broadband (10 – 100 Hz) (*Mavko et al., 2009*) but also consistent with experimental observations in the ultrasonic frequency range (>1 kHz)(*e.g. Falcon-Suarez et al., 2020*)

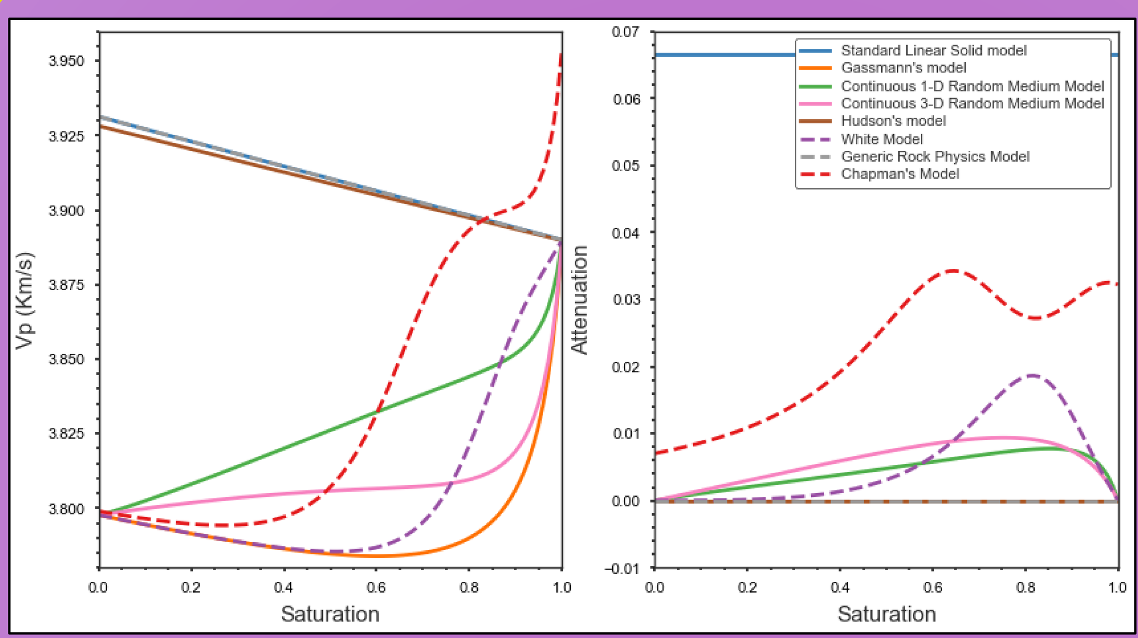

Figure 2: *Comparative P-wave velocity (left) and attenuation (right) plots for different rock physics models which account for the effects of saturation, frequency-dependence and anisotropy. The model is defined from the Endurance well 42/25d-3, with the in-situ values of Vp = 3.89 km/s, Vs = 2.18 km/s, Rho = 2.31 g/cm³, and fluid parameters of 0% CO2 saturation, q = 1, T = 40 °C, P = 14 bar and Salinity = 2.6 x10⁵ ppm (NaCl) . Attenuation (right) is calculated by* $Im(C_{1,1})/Re(C_{1,1})$.

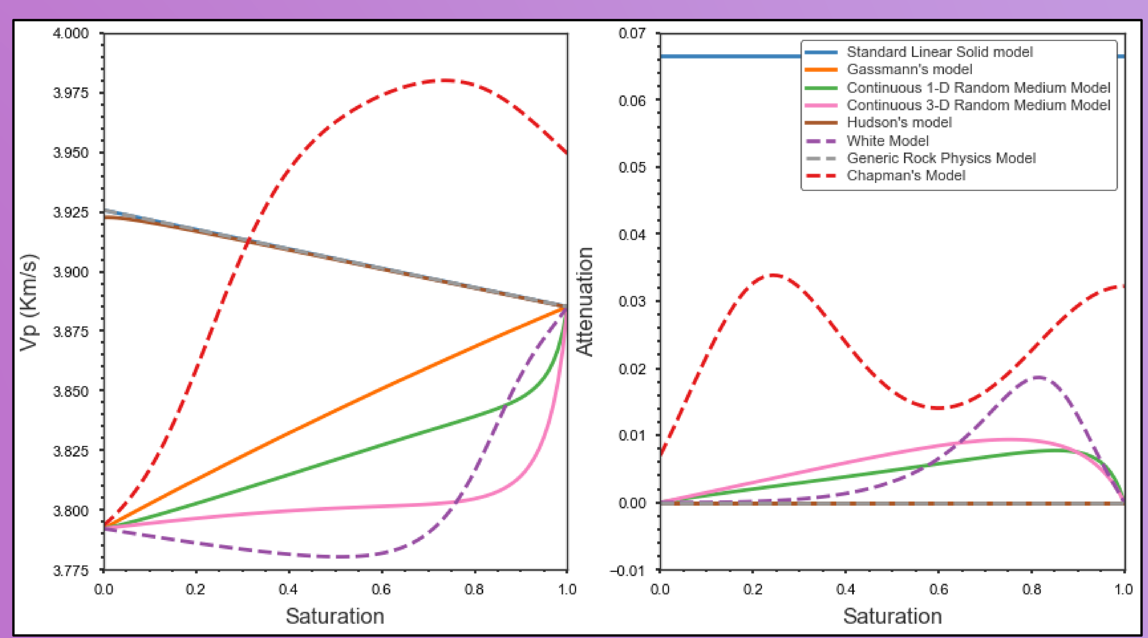

Figure 3: *Comparative P-wave velocity (left) and attenuation (right) plots for different rock physics models which account for the effects of saturation, frequency-dependence and anisotropy. The model is similarly parametrised as Figure 2, except with the fluid parameters of 12% CO2 saturation and q = q0.*

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- For monitoring, repeat acquisitions with the same survey geometry are conducted to image the **time-lapse** change to the geophysical response
- For an anisotropic model case (Figure 4), we show that dependent upon the fracture orientation, the observed response will change dependent upon the observational azimuth
- We additionally show that for an attenuative (viscoelastic) Earth model (Figure 5), we observe non-amplitude changes to the geophysical response

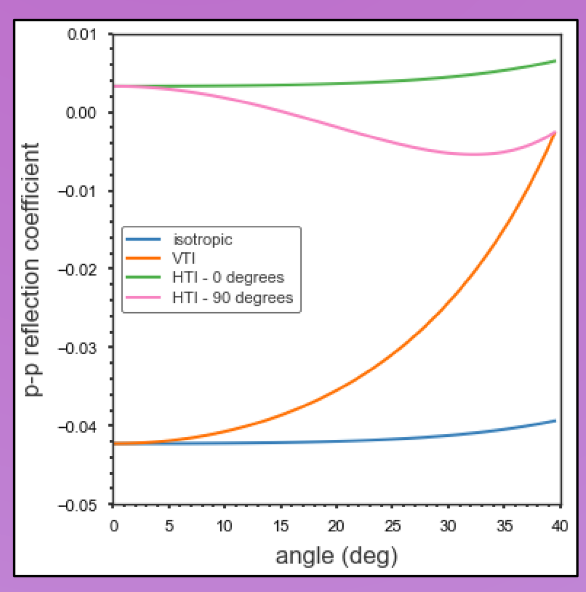

Figure 4: *Amplitude Versus Offset (AVO) response using the Schoenberg and Protazio (1990) formulation for different anisotropic media rotations for a model parametrised from Endurance well 42/25d-3*

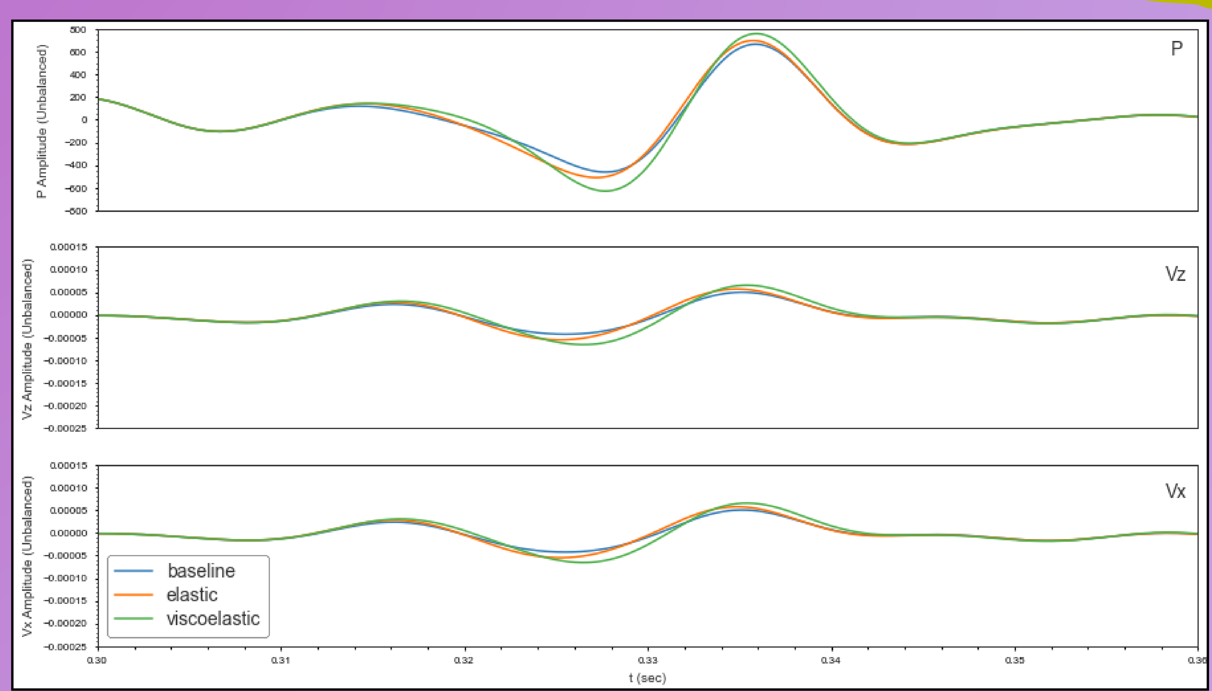

Figure 5: *Pressure (top), vertical motion (middle) and horizontal motion (bottom) synthetic Vertical Seismic Profile (VSP) traces generated by staggered-grid, 2D anisotropic viscoelastic finite-difference seismic wavefield simulation. Model is parametrised from Endurance well 42/25d-3 and averaged per lithological formation.*