Rock Physics Driven Seismic Modeling of CO_2 Injection in a Carbonate Reservoir from Canada*

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Abstract

Monitoring CO_2 injection for enhanced hydrocarbon recovery in carbonate reservoirs poses a technical challenge interpreting changes in pressure and fluid saturations away from wells. The present study focuses on quantitative rock physics modeling of time-lapse (4D) changes in reservoir pressure and multi-fluid saturations in a carbonate reservoir from southern Canada. The field is currently under WAG (Water Alternate Gas) injection, and both pressure and CO_2 saturation change during the CO_2 flooding process. The goal of the dynamic reservoir modeling is to understand and predict CO_2 saturations over the reservoir. To achieve this goal, we modeled reservoir properties at different fluid saturations with various effective pressure regimes. 4D rock physics analysis provides the link between dynamic reservoir properties and 4D seismic responses. We calculated elastic properties of fluid mixtures (brine, oil, and CO_2) at different pressures, based on a constant reservoir temperature of 600 deg C, as the WAG injection does not significantly alter temperatures in the reservoir. Initially, effective properties of the brine saturated reservoir are measured at the original pressure (15 MPa). Then we replace the brine fluid with a different mixture of fluids and calculate effective properties of the reservoir at different expected pressure values. These elastic properties (incompressibility and rigidity) are affected by changes in the pressure for the same fluid saturation. Modeling results show a significant change (around 30-40% decrease) in the impedance for fluid saturation when the reservoir is saturated with CO_2 compared to the brine-saturated case. 4D rock physics models demonstrated that, at reservoir level, Lambda-Rho highly correlate with changes in fluid saturation, with lowest values when the reservoir is saturated with CO_2. Likewise, Mu-Rho, highly correlated with reservoir pressure, is higher as the effective pressure increases. During WAG injection, it is expected that changes in CO_2 saturation are more prominent compared to changes in effective pressure away from injection wells.

Selected References

Churcher, P.L., and A.C. Edmunds, 1994, Reservoir characterization and geological study of the Weyburn Unit, southeastern Saskatchewan: Report Number 1, Proposed Miscible Flood, Horizontal Well, and Waterflood Optimization Areas: Internal report prepared for PanCanadian Petroleum Ltd., 28 p.

Dietrich, J.R., and D.H. Magnusson, 1998, Basement controls on Phanerozoic development of the Birdstail-Waskada salt dissolution zone, Williston Basin, southeast Manitoba: 8th Int. Williston Basin Symp., SGS Special Pub. No. 13, p. 166-174.

Wegelin, A., 1984, Geology and reservoir properties of the Weyburn Field, southeastern Saskatchewan, *in* J.A. Lorsong and M.A. Wilsons, eds., Oil and Gas in Saskatchewan: Saskatchewan Geological Society Spec. Pub No. 7, p. 71-82.

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Ikon Science Americas

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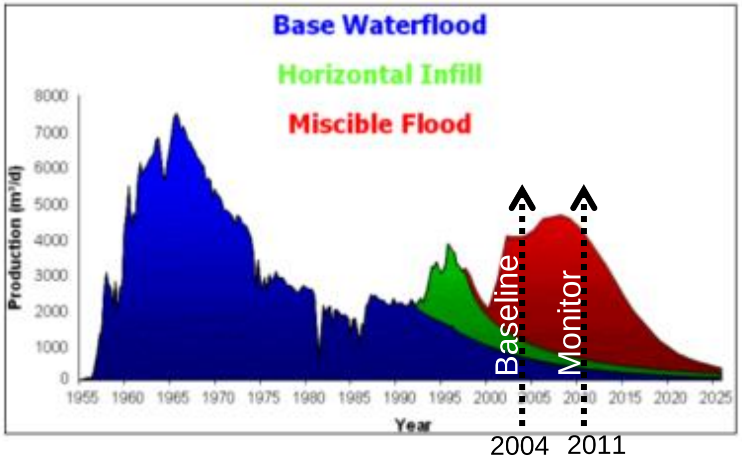
The Present And Future Of GeoPrediction

Outline

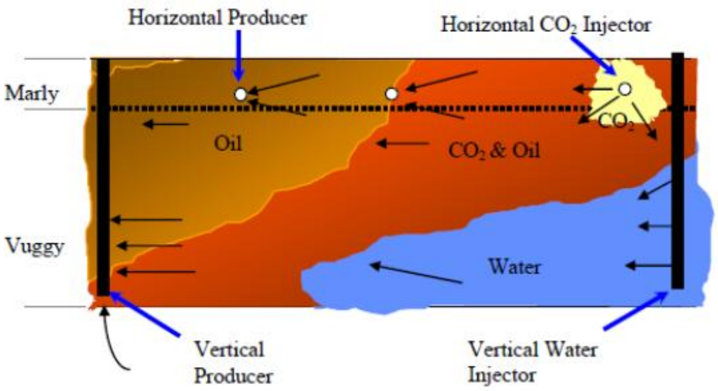
1. Introduction & Challenges
2. Rock Physics Modeling
3. Forward Seismic Modeling
4. Conclusions

1. Introduction & Challenges

Weyburn Field

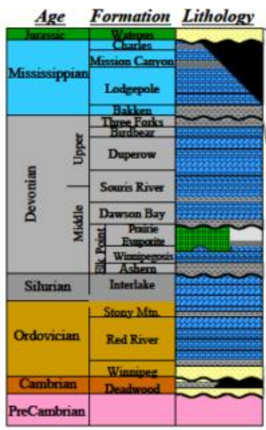


- Discovered in 1954
- Horizontal infill drilling started in 1991
- CO_2 injection started in 2000
- Seismic: Baseline (2004) & Monitor (2011)
- IOIP: 1.4 billion barrels

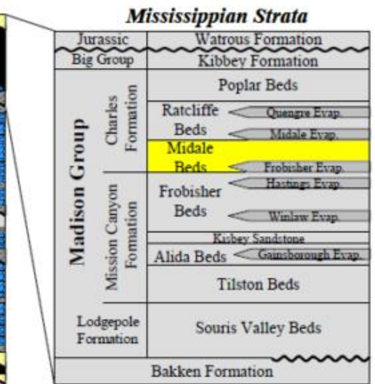


(Brown et al., 2004)

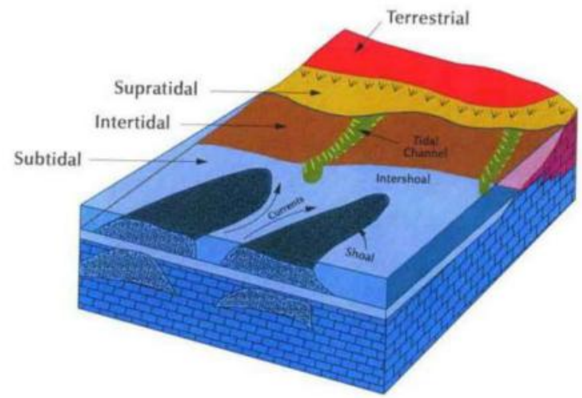
Weyburn Field – Petroleum System



(Dietrich and Magnusson, 1998)



(Wegelin, 1984)

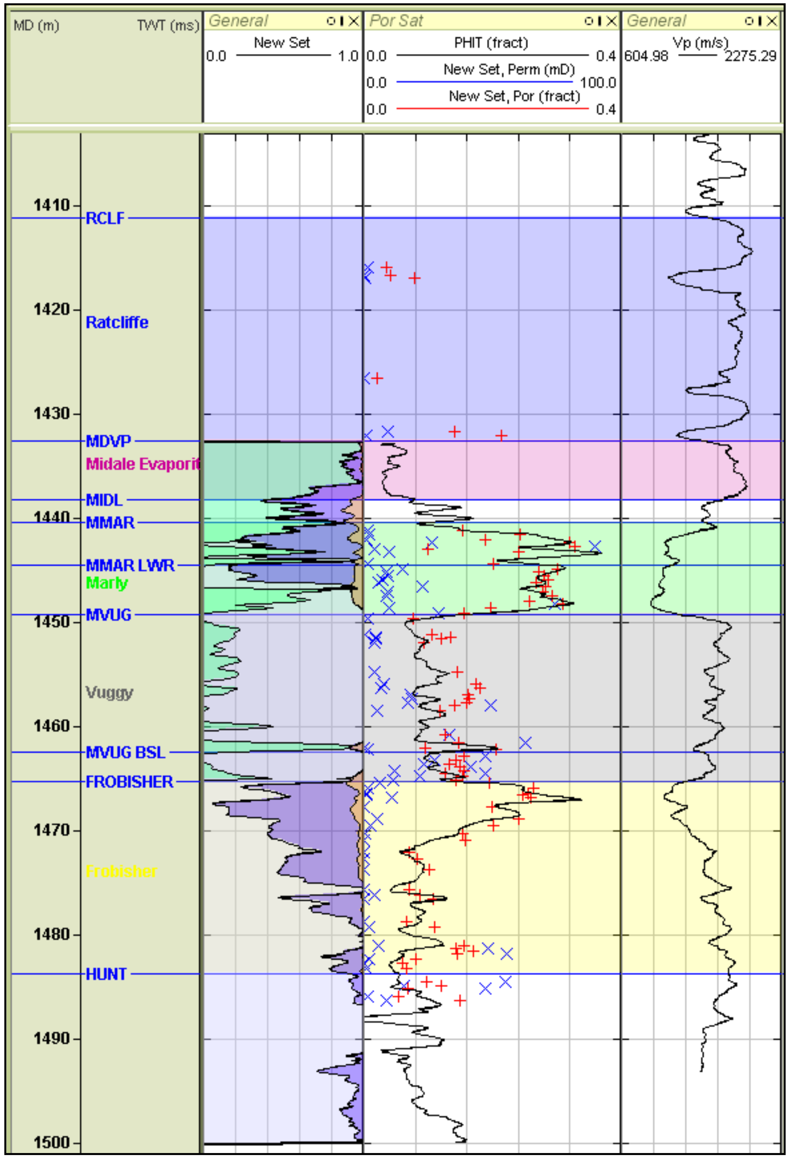


(Churcher and Edmunds, 1984)

Midale Depositional Environment

- Midale beds of the Mississippian Charles formation were formed during transgression-regression sequence.
- The Midale reservoir beds were deposited in a shallow carbonate shelf environment. The carbonate reservoir has been subdivided into the Marly dolostone and the Vuggy limestone.
- The Bakken shale is a possible source rock for the medium gravity crude oil at Weyburn field.
- The petroleum trap is both hydrodynamic and stratigraphic (Churcheer and Edmunds, 1994).

Log – Core porosity calibration



+ Core porosity
X Core permeability

Ratcliffe
(Dolomite+Evaporites)

Midale Evaporite

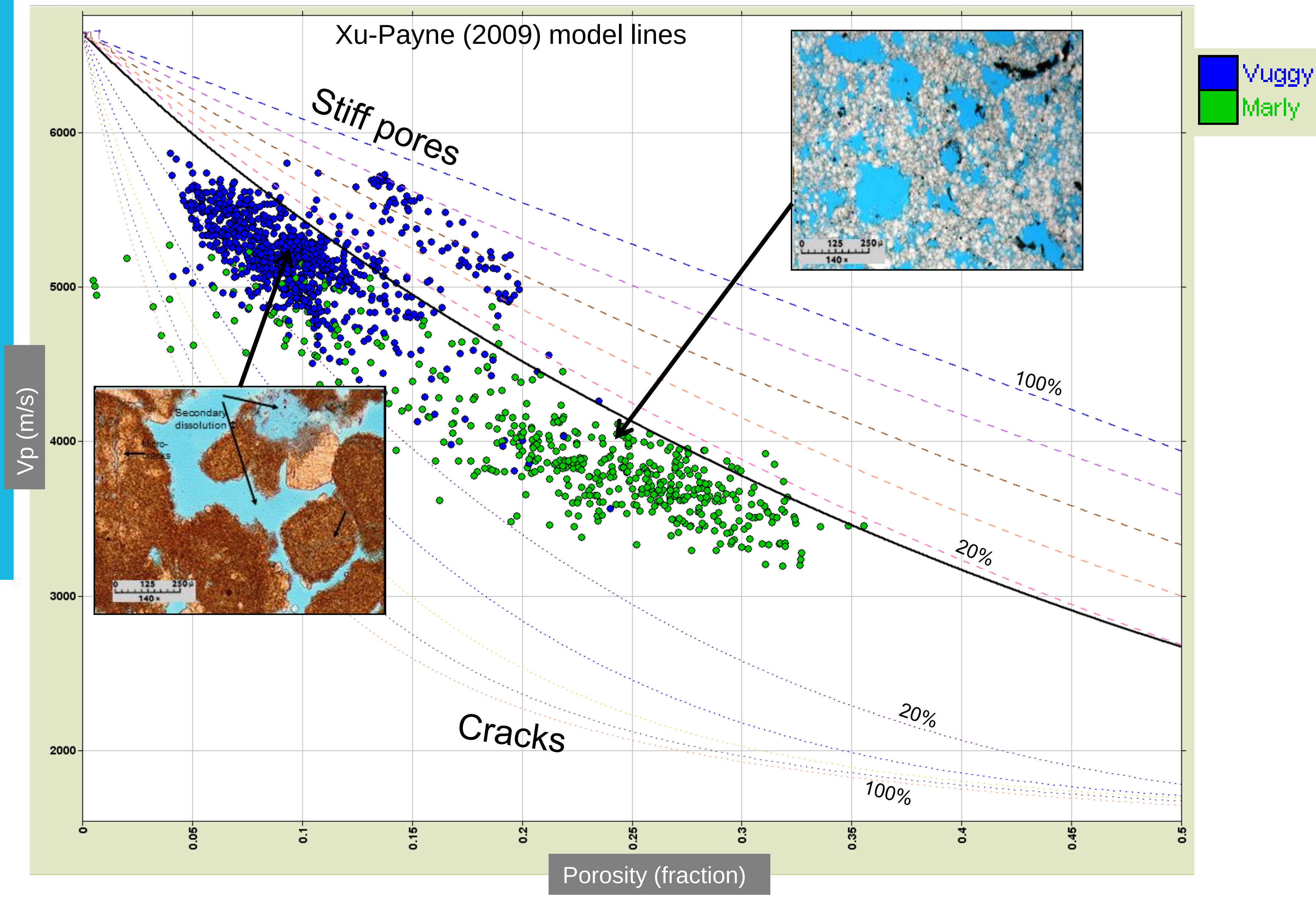
Midale Marly Dolomite
(Permeability: 1-50mD)

Midale Vuggy Limestone
(Permeability: 10-300mD)

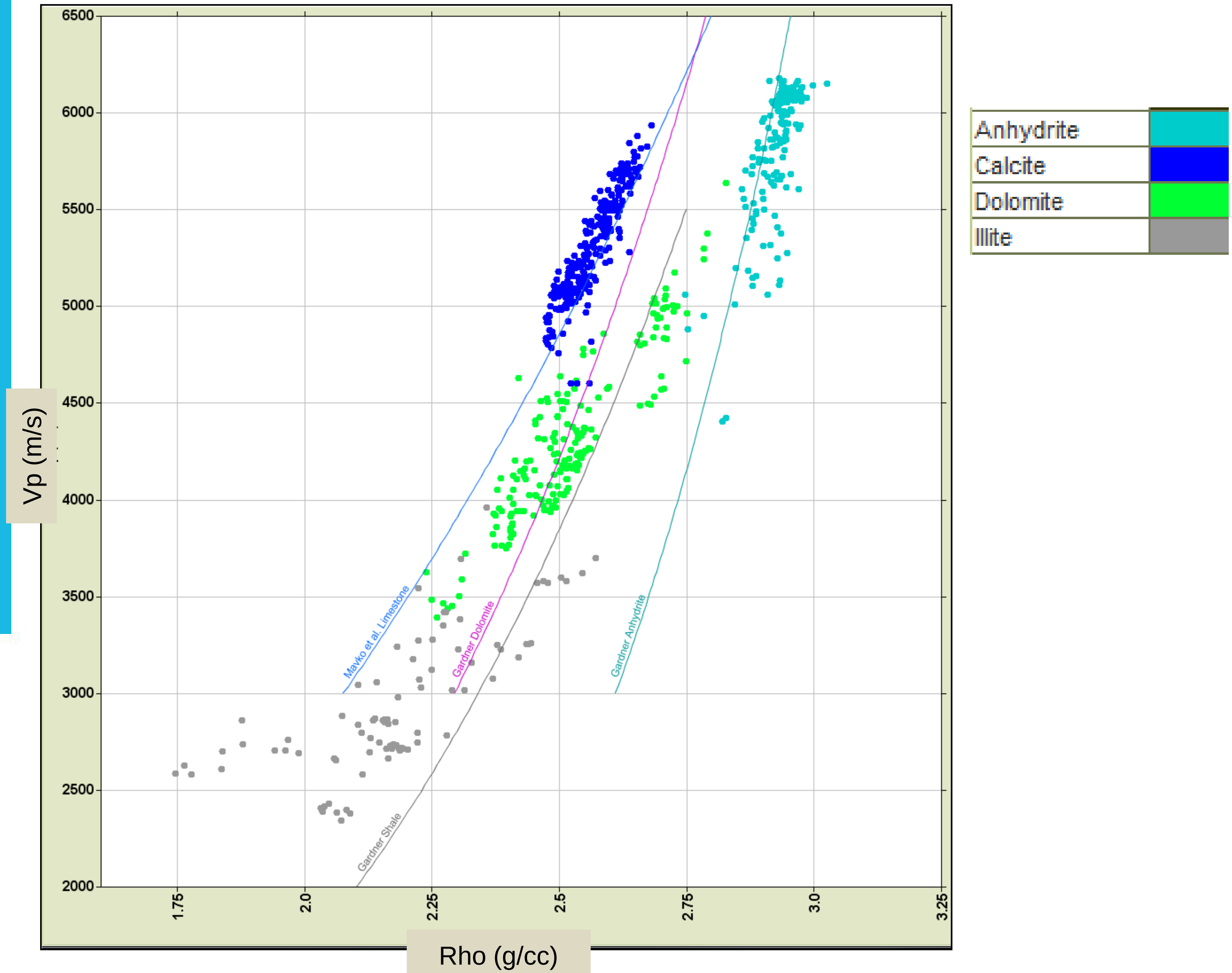
Frobisher

Good calibration between log and core porosities

Vp vs. Porosity



QC for lithofacies



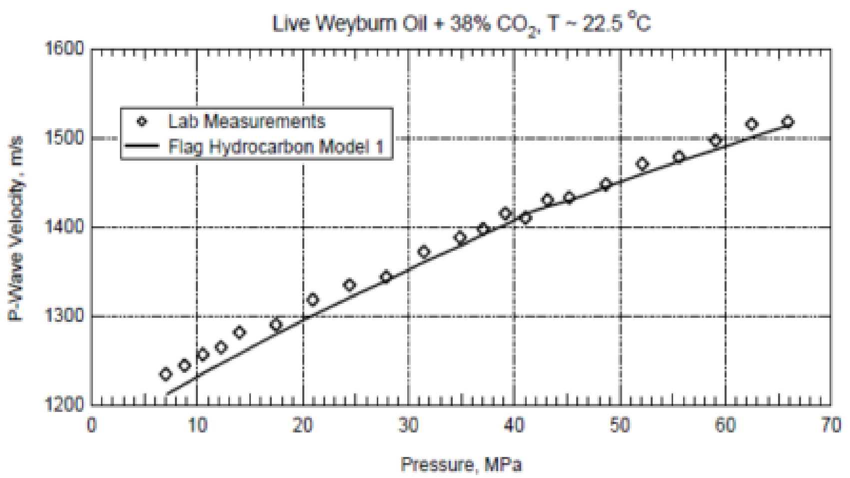
2. Rock Physics Modeling

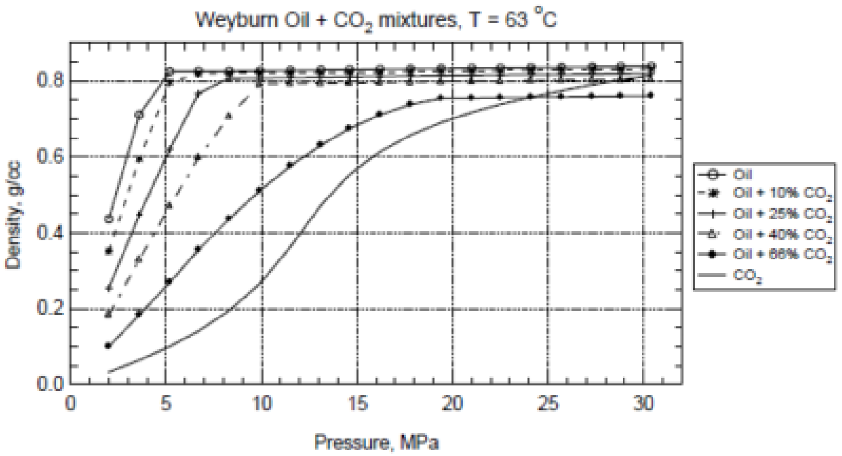
Fluid/Pressure Modeling Assumptions

Due to a lock of data, many assumptions needed to be made in order to perform the 4D fluid and pressure modelling. These are detailed below:

- That the baseline reservoir pressure was 15MPa. This assumption was based on a hydrostatic gradient with no overpressure effects.
- That baseline water salinity was 85000ppm while monitor salinity was 100000ppm.
- Baseline Oil API was 29API, Monitor was 27API
- Temperature was constant throughout at 60 degrees.
- The fluid properties for water, oil and CO_2 were calculated using FLAG
- Values for mixed miscible CO_2 in oil were calculated using Brown's Thesis.

Weyburn EOR reservoir properties





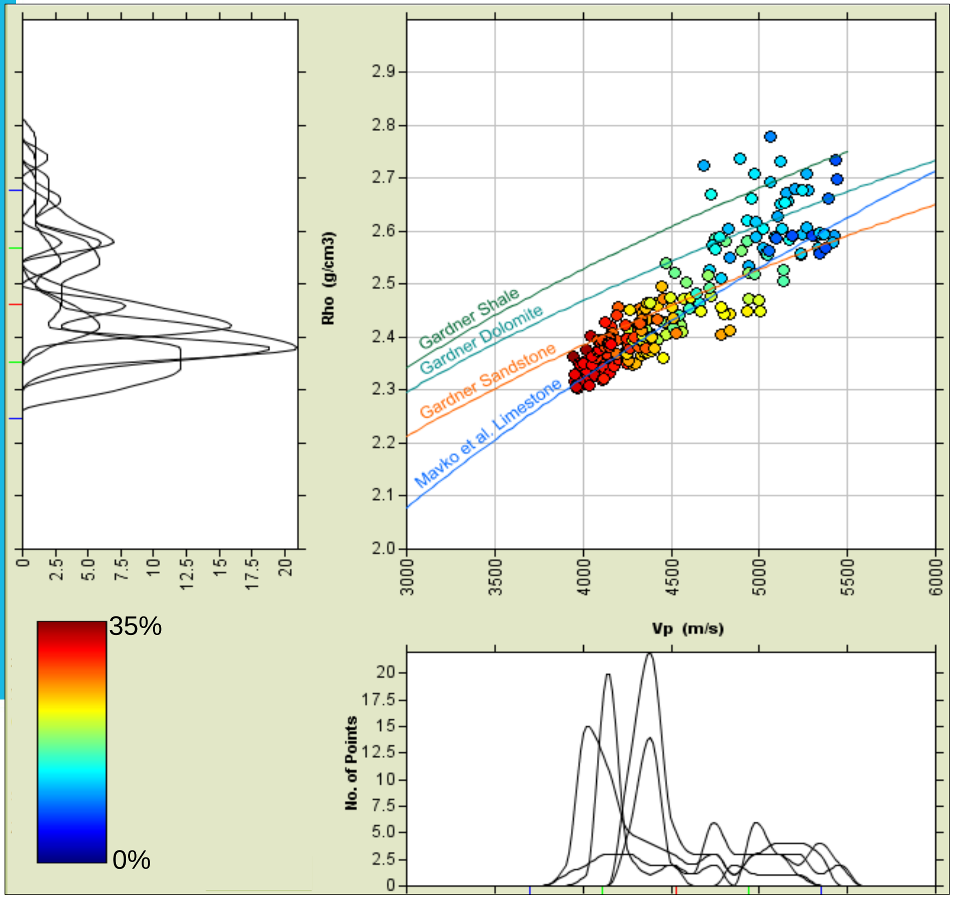
(Brown et al., 2004)

Oil and CO_2 mixture will attain miscibility at pressures of 14 to 17 MPa

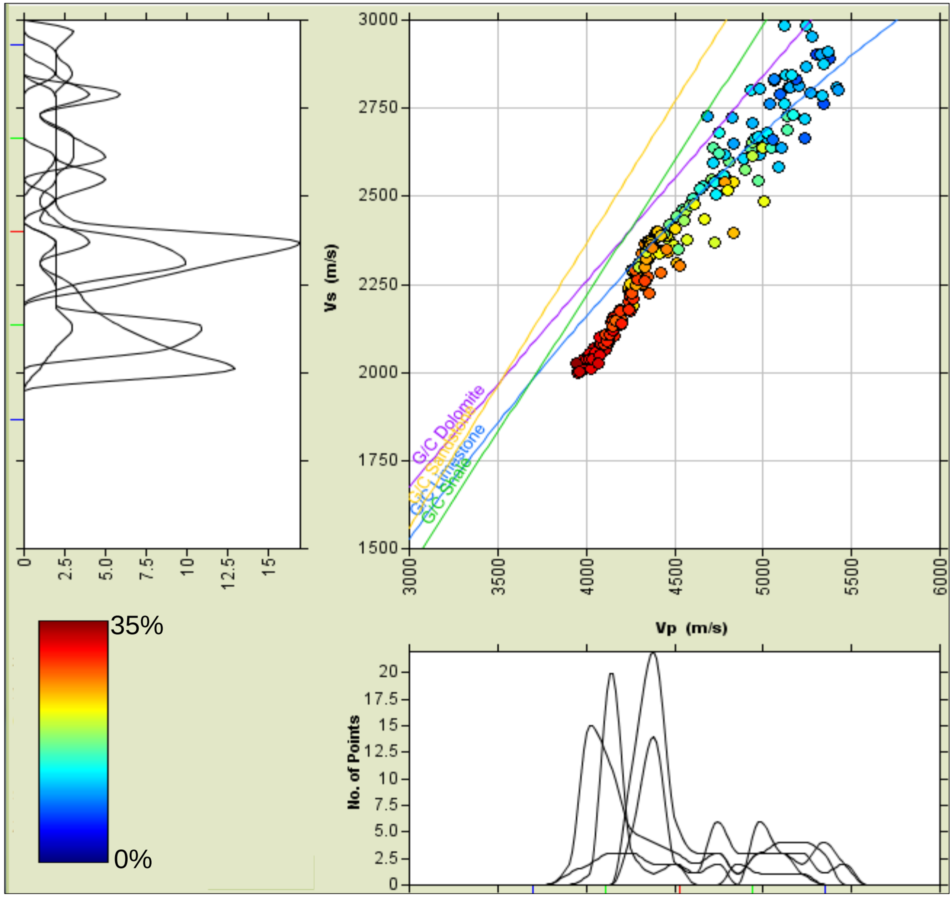
The fluid properties for various mixes of CO2 and oil were taken directly from Brown's thesis (Brown et al., 2004). The mixes on the graph above were modelled at 5, 10, 15, 20 and 25MPa.

5MPa (Marly)

Vp vs. Rho

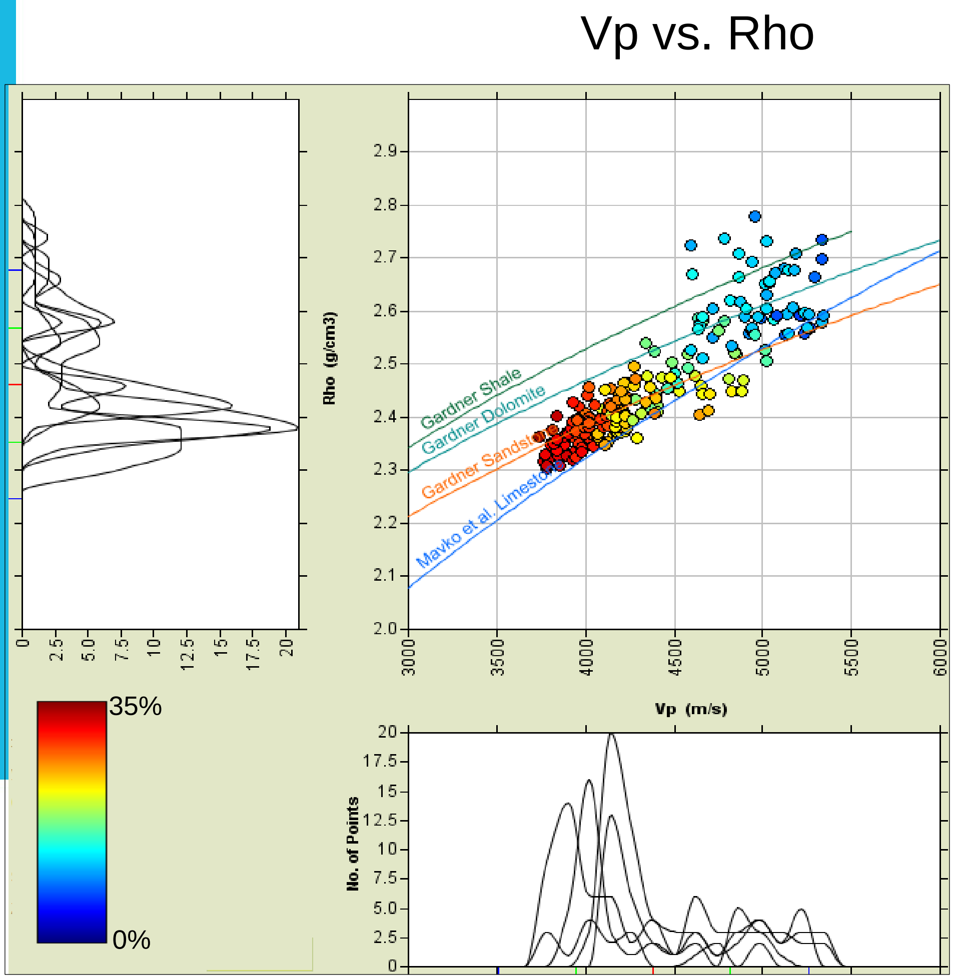


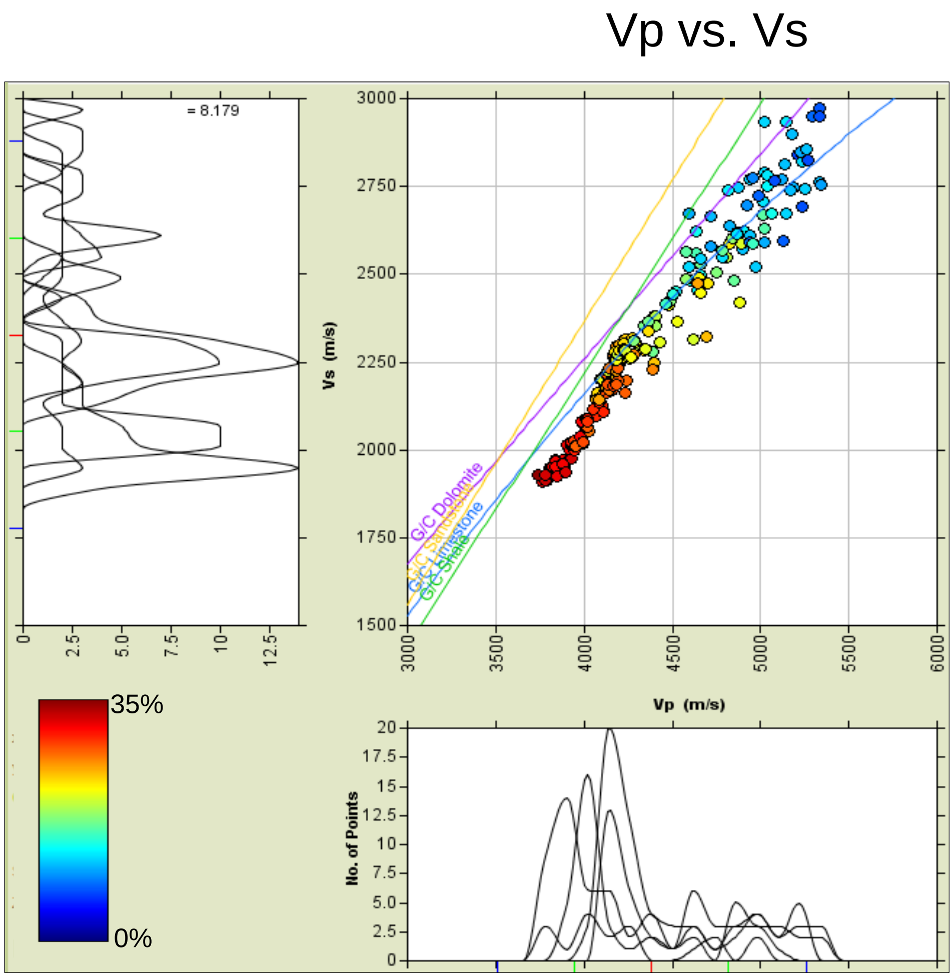
Vp vs. Vs



The plot above shows the Marly section data crossplot Vp vs. Rho and Vp vs. Vs. Both plots are coloured by Porosity. In these plots the data have been modulated from the initial in situ conditions to 100% Brine at 5MPa using the monitor fluid properties.

10MPa (Marly)



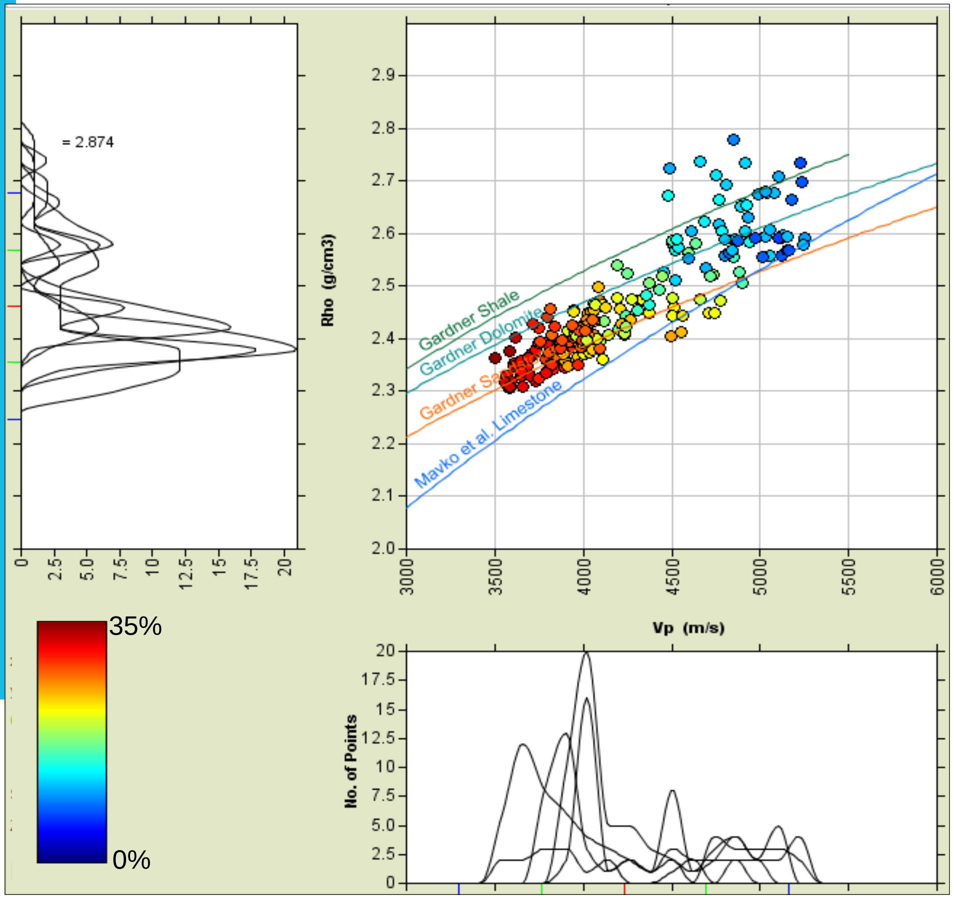


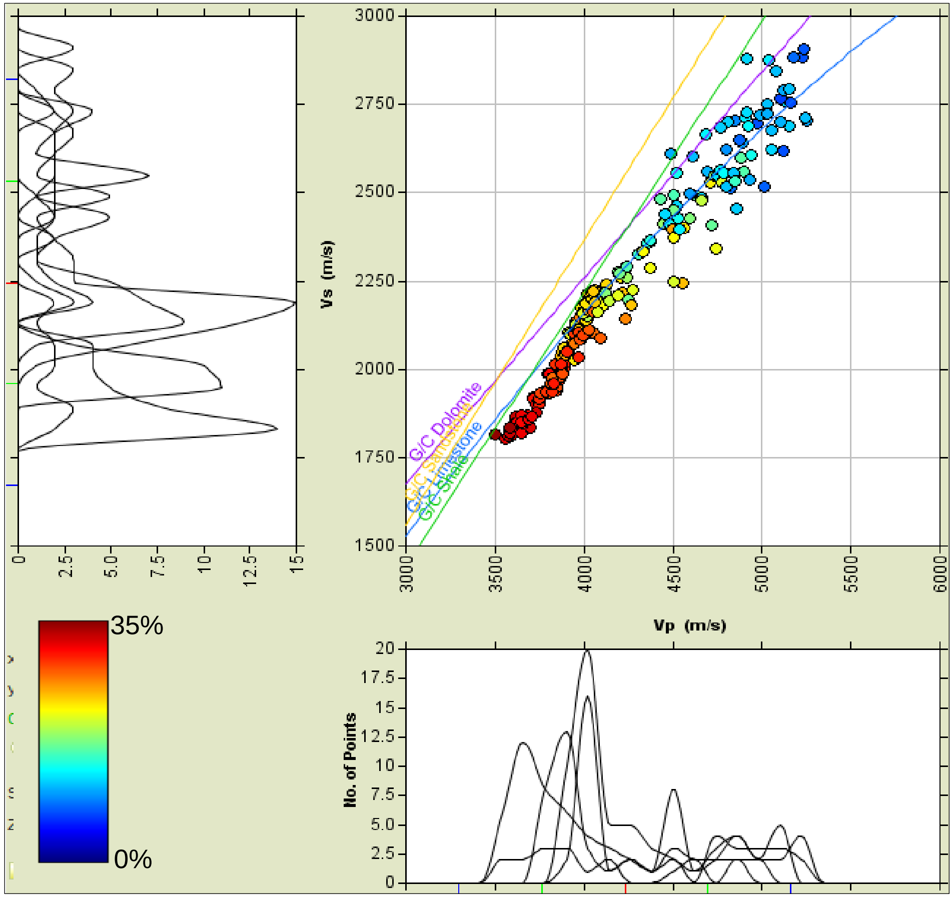
The plot above shows the Marly section data crossplot Vp vs. Rho and Vp vs. Vs. Both plots are coloured by Porosity. In these plots the data have been modulated from the initial in situ conditions to 100% Brine at 10MPa using the monitor fluid properties.

15MPa (Marly)

Vp vs. Rho

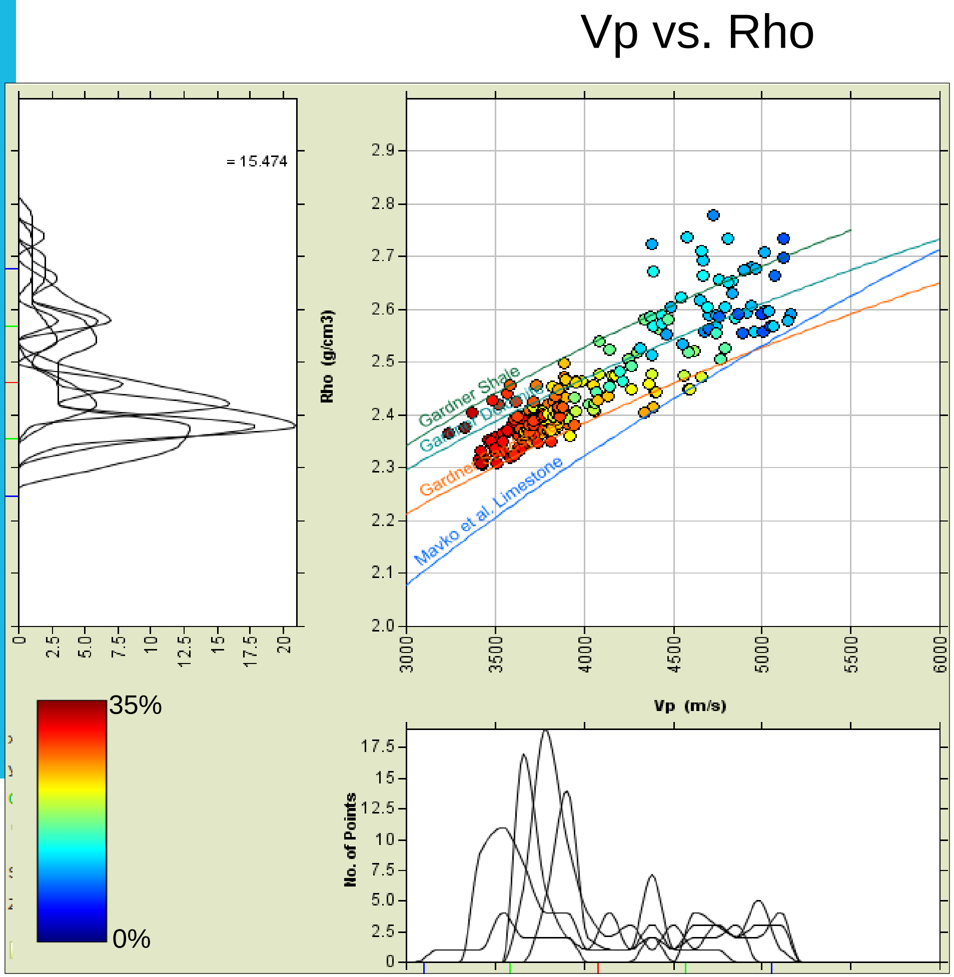
Vp vs. Vs

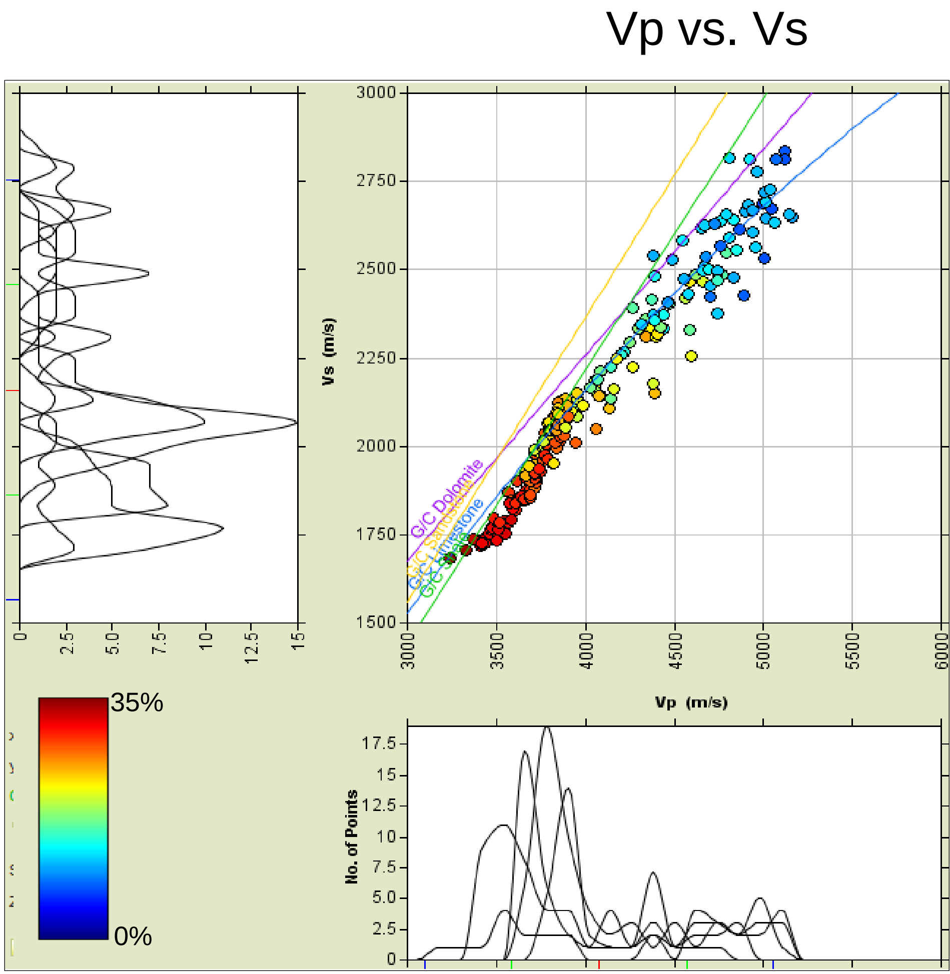




The plot above shows the Marly section data crossplot Vp vs. Rho and Vp vs. Vs. Both plots are coloured by Porosity. In these plots the data have been modulated from the initial in situ conditions to 100% Brine at 5MPa using the monitor fluid properties.

20MPa (Marly)

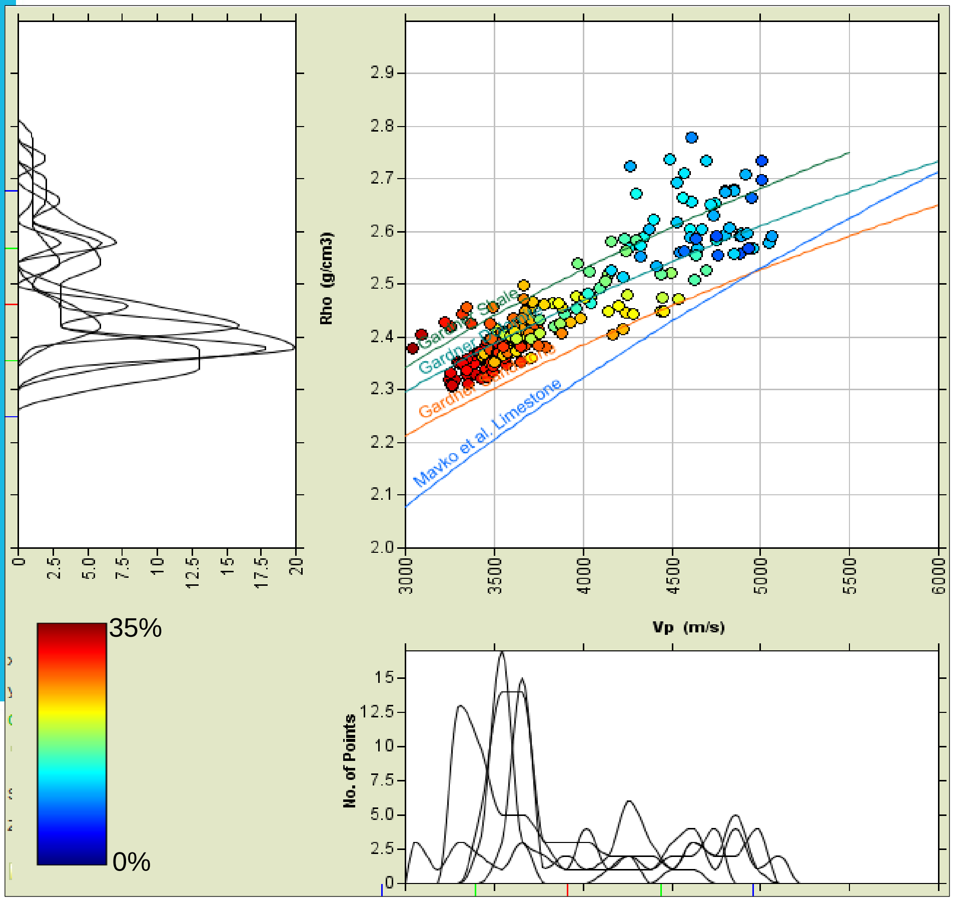




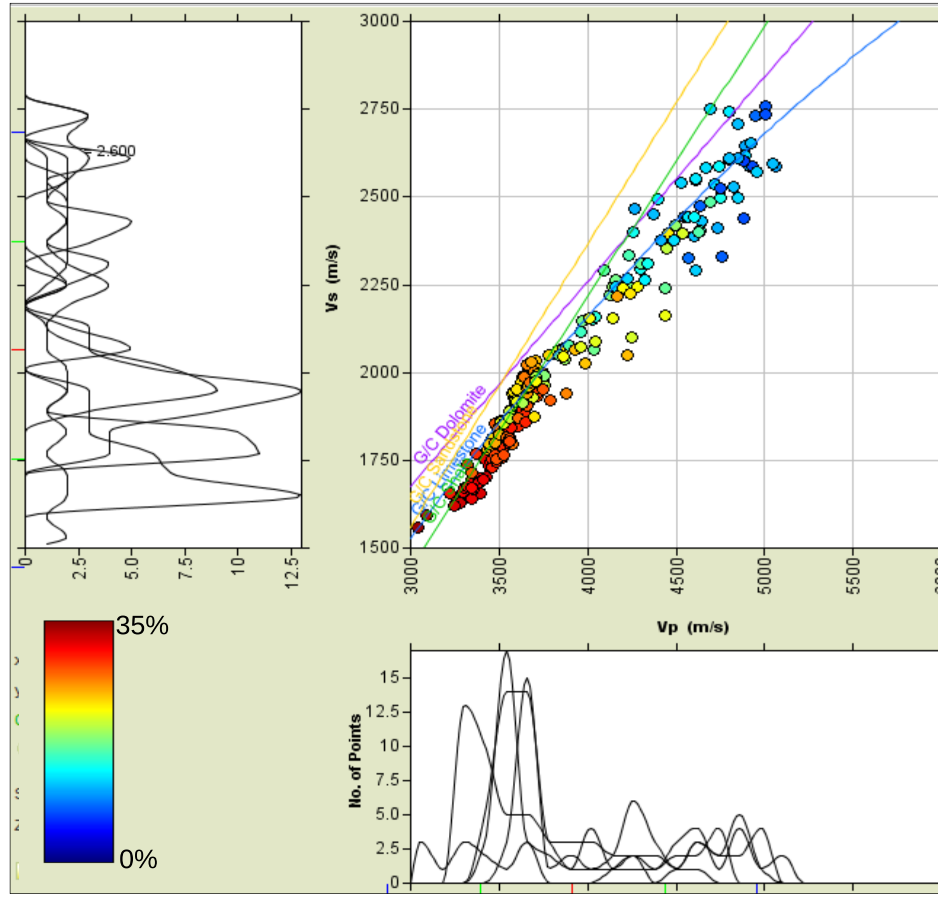
The plot above shows the Marly section data crossplot Vp vs. Rho and Vp vs. Vs. Both plots are coloured by Porosity. In these plots the data have been modulated from the initial in situ conditions to 100% Brine at 5MPa using the monitor fluid properties.

25MPa (Marly)

Vp vs. Rho

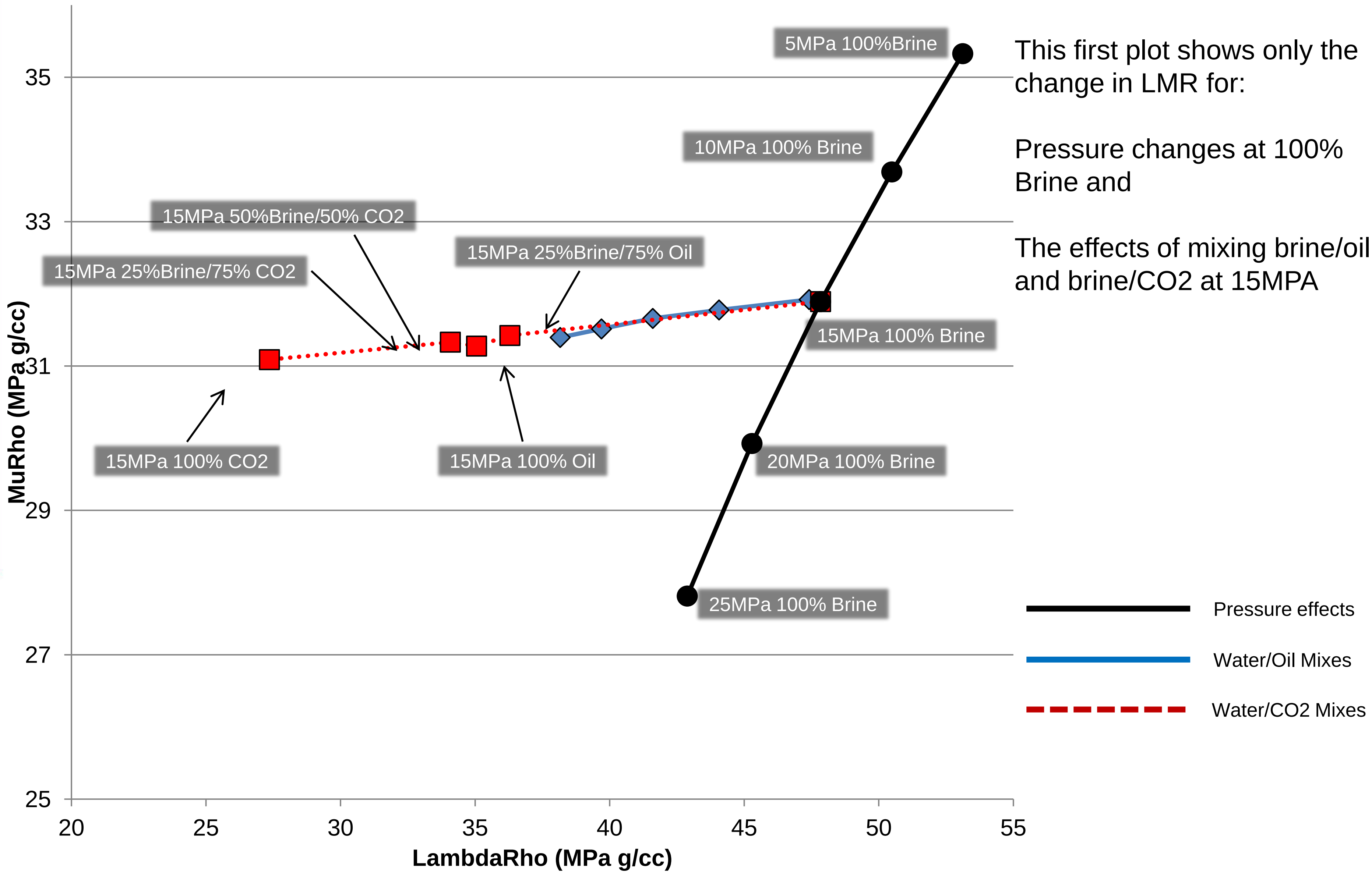


Vp vs. Vs



The plot above shows the Marly section data crossplot Vp vs. Rho and Vp vs. Vs. Both plots are coloured by Porosity. In these plots the data have been modulated from the initial in situ conditions to 100% Brine at 5MPa using the monitor fluid properties.

LambdaRho vs. MuRho (Marly)

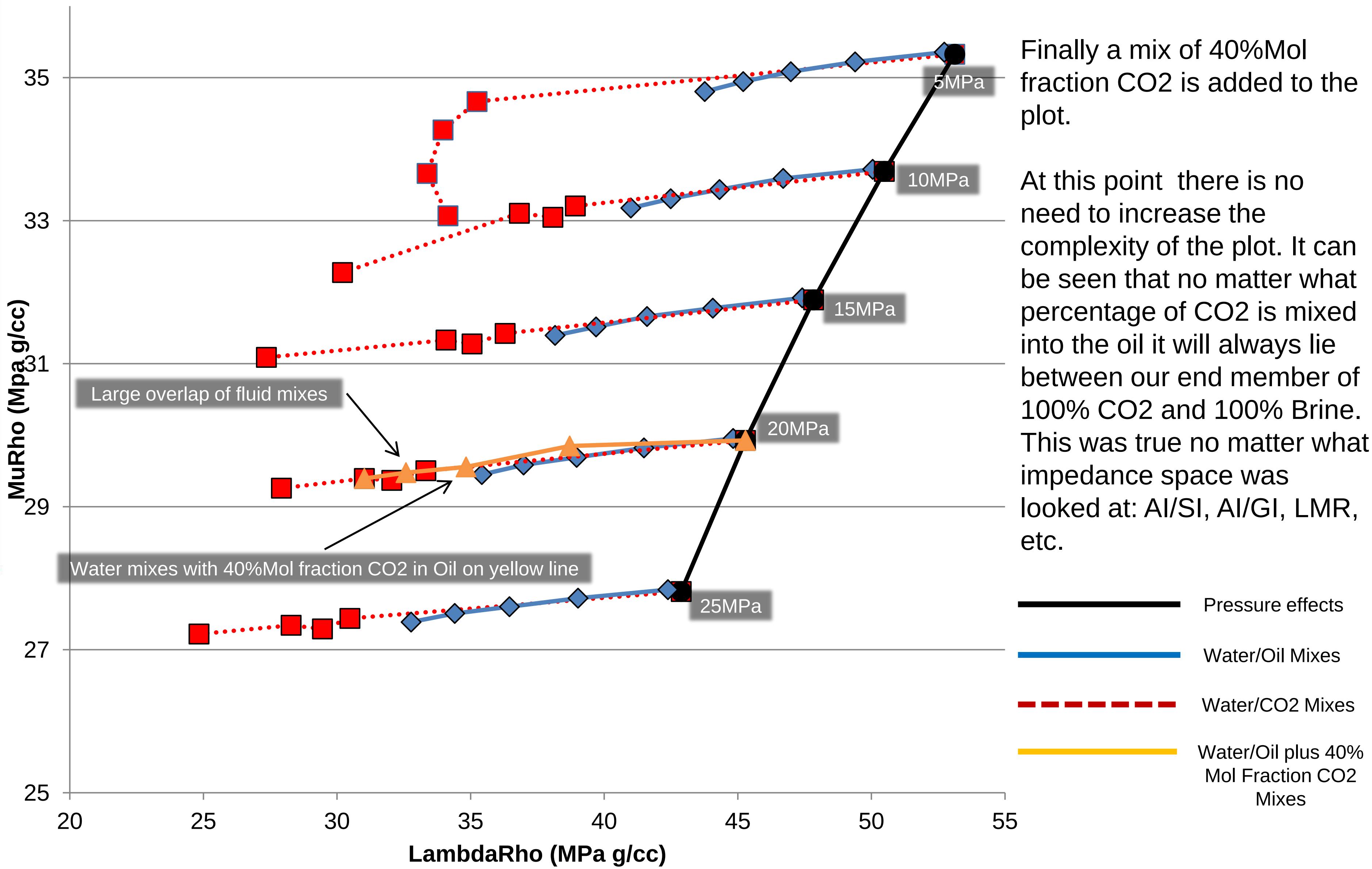


This first plot shows only the change in LMR for:

Pressure changes at 100% Brine and

The effects of mixing brine/oil and brine/CO2 at 15MPA

LambdaRho vs. MuRho (Marly)



Finally a mix of 40%Mol fraction CO_2 is added to the plot.

At this point there is no need to increase the complexity of the plot. It can be seen that no matter what percentage of CO_2 is mixed into the oil it will always lie between our end member of 100% CO_2 and 100% Brine. This was true no matter what impedance space was looked at: AI/SI, AI/GI, LMR, etc.

3. Forward Seismic Modeling

Reflectivity Analysis

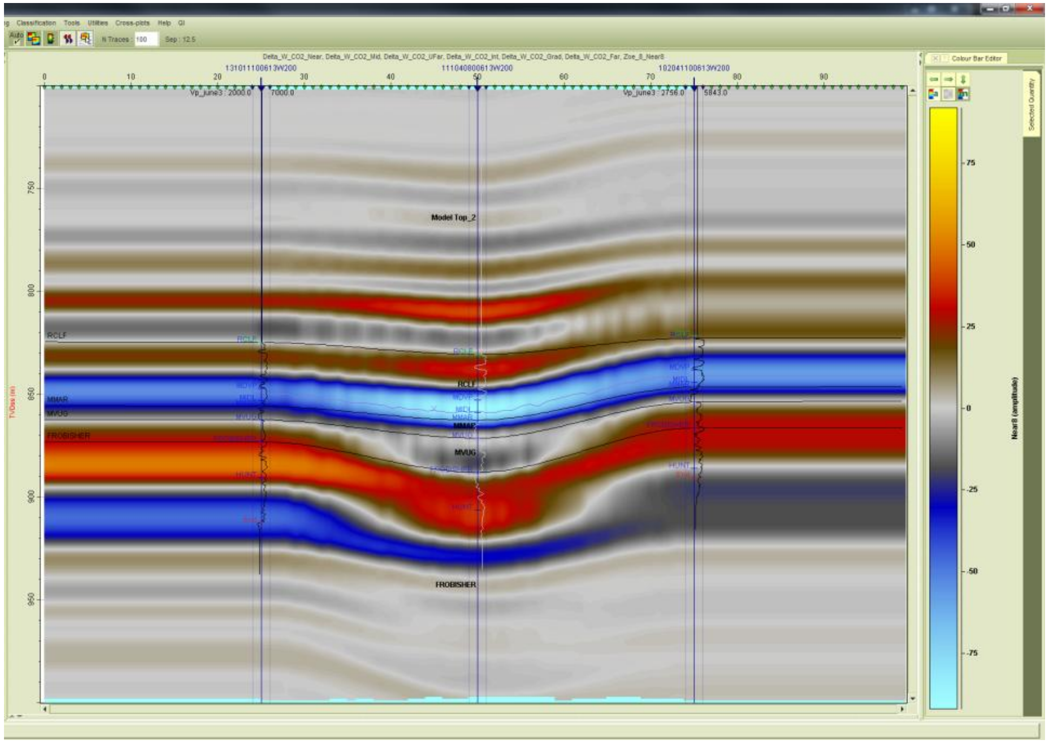
- With the nine fluid-pressure cases, three substitution target scenarios were modeled (3 wells):
  - Marly
  - Vuggy
  - Marly and Vuggy
- Synthetic seismic was produced from these 27 cases (9 cases for each target scenario) using the mid-stack wavelet extracted from the baseline survey
- Measurement events were picked at the maximum negative reflection at the Marly-Overburden interface and at the maximum positive reflection at the Vuggy-Frobisher interface
- The average intercept and gradient as well as percent change (from scenario 4) along these measurement horizons was then cross plotted

Construction of Fluid Mixes

Oil/Water/CO_2 mixes:
background 35% oil and 65% water

Pp (MPa)	Saturation	Cases 1,4,7 0.0 % CO_2	Cases 2,5,8 max miscible CO_2	Cases 3,6,9 90% CO_2
8 (cases 1-3)	So	0.35	0.35	0.0
	Sw	0.65	0.65	0.1
	Sg	0.0	0.0	0.9
15 (cases 4-6)	So	0.35	0.35	0.0
	Sw	0.65	0.65	0.1
	Sg	0.0	0.0	0.9
20 (cases 7-9)	So	0.35	0.35	0.0
	Sw	0.65	0.65	0.1
	Sg	0.0	0.0	0.9

General Workflow



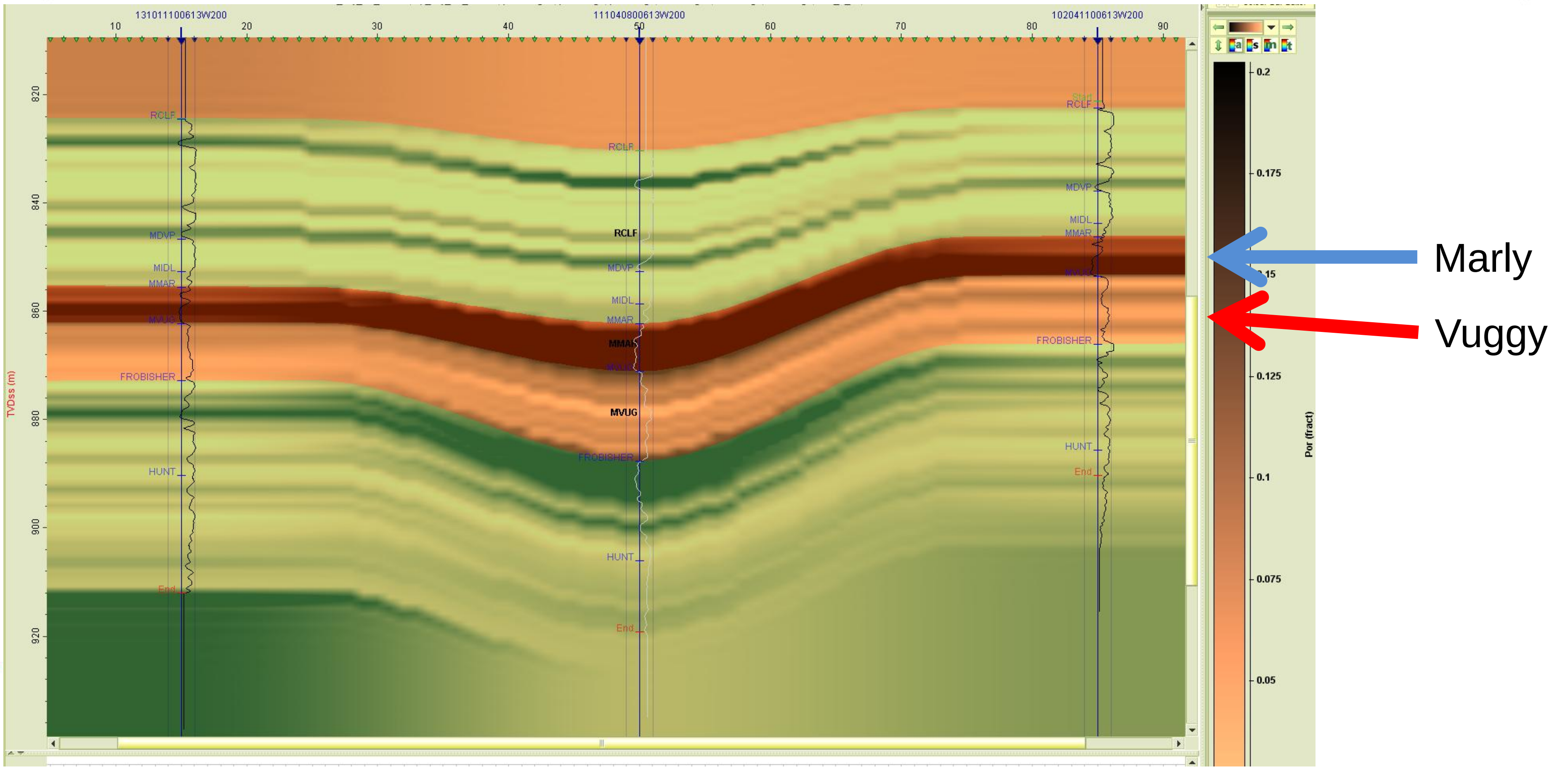
Baseline 2D Model

Pressure Perturbation
Pressure Dependent Fluid Subs

Reservoir rock and fluids at effective pressures related to injection/production

Computed % and absolute difference between Monitor and Baseline

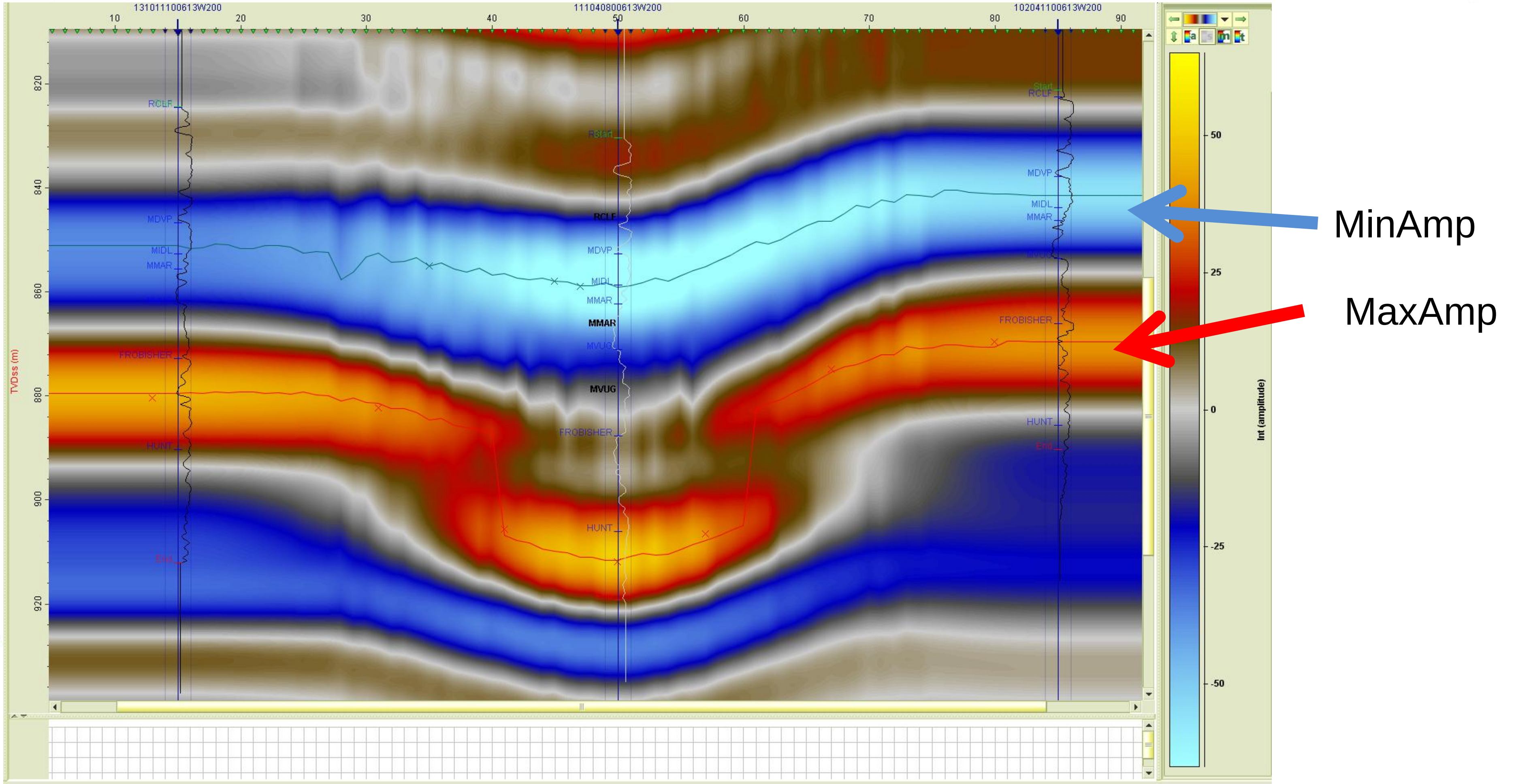
2D Model – Pressure perturbation and Fluid Substitutions applied to Marly and Vuggy bodies



In order to understand subtle seismic amplitude changes on the thinly bedded reservoir units, Fluid and Pressure perturbations made on:

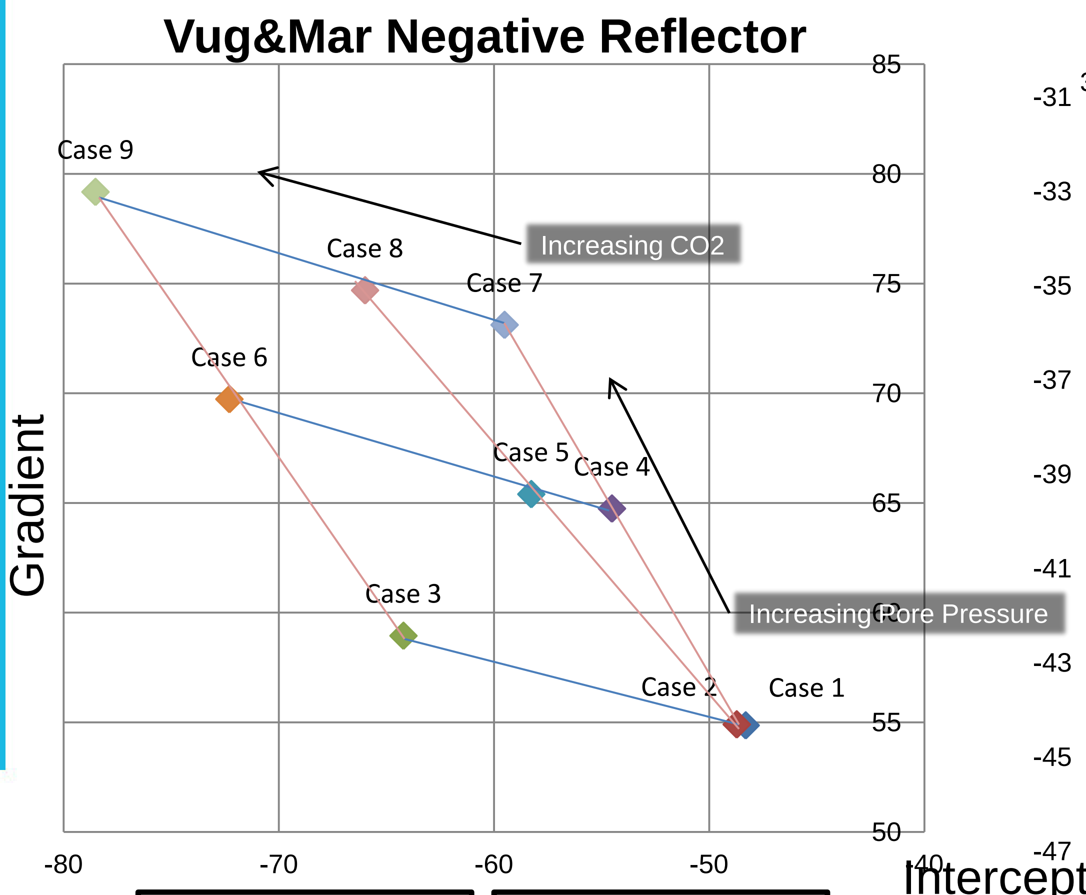
- Marly only
- Vuggy only
- Both Marly and Vuggy

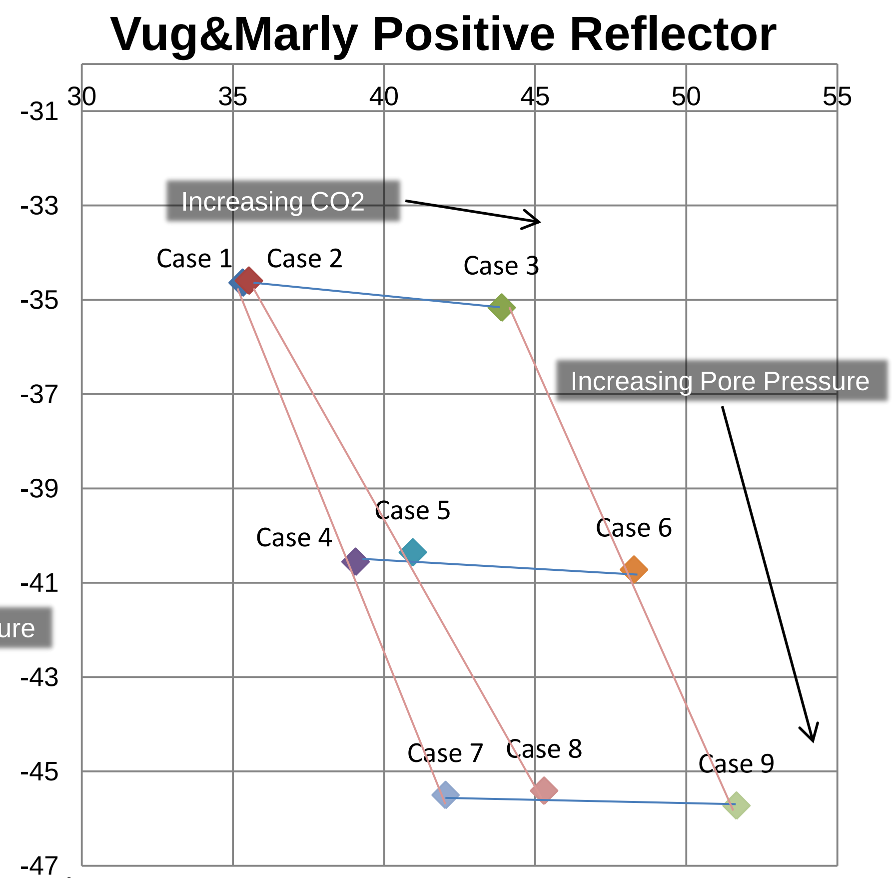
Measurement events at minimum and maximum amplitudes at reservoir.

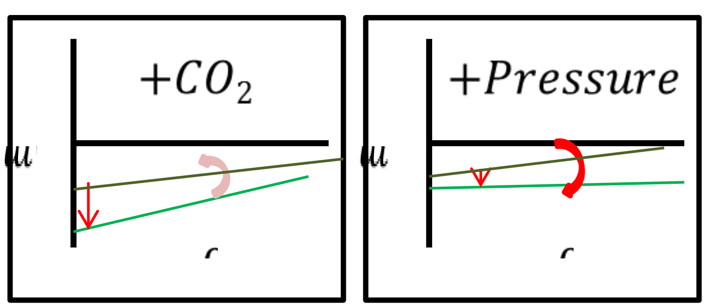


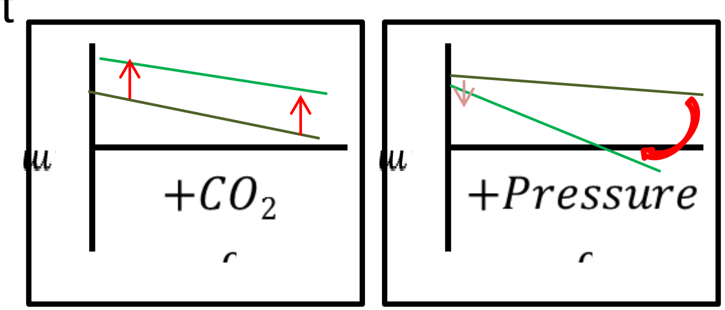
Intercept and gradient amplitude values for the various fluid cases were extracted along these max +/- reflectors. The extracted values are averaged and cross plotted on the following slides. The relative AVO effects are visualized at the bottom of the absolute amplitude plot slides. The following three slides show percent changes.

Marly & Vuggy Substitutions Int vs Grad

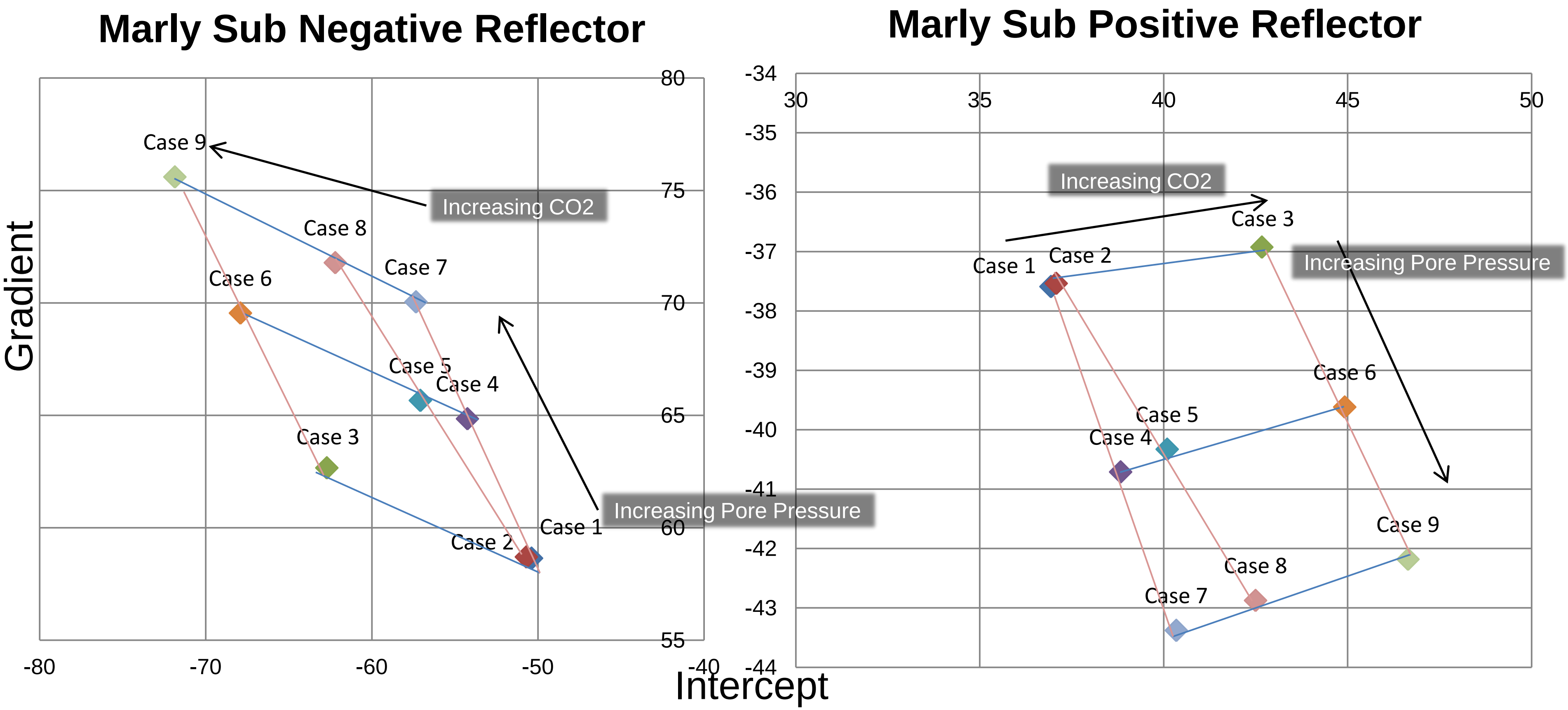


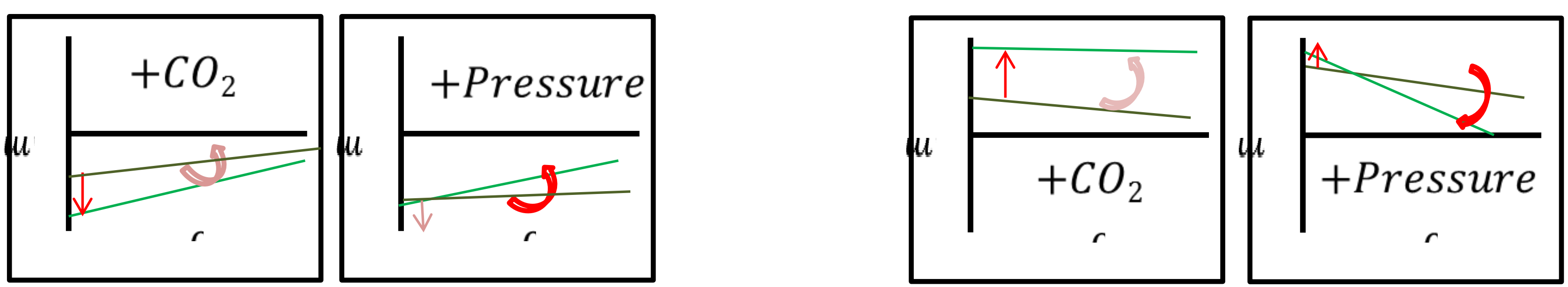




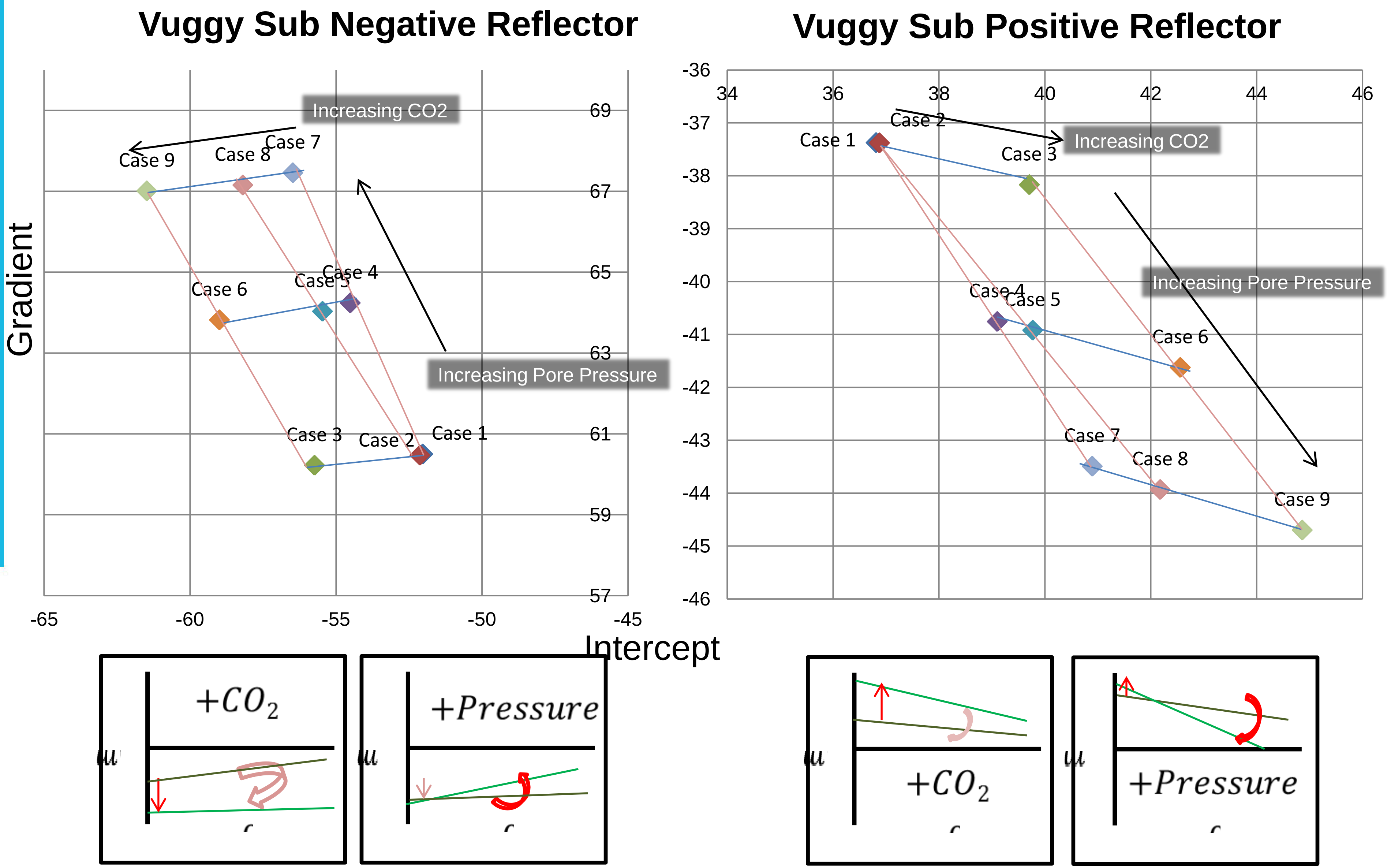


Marly Substitutions Int vs Grad

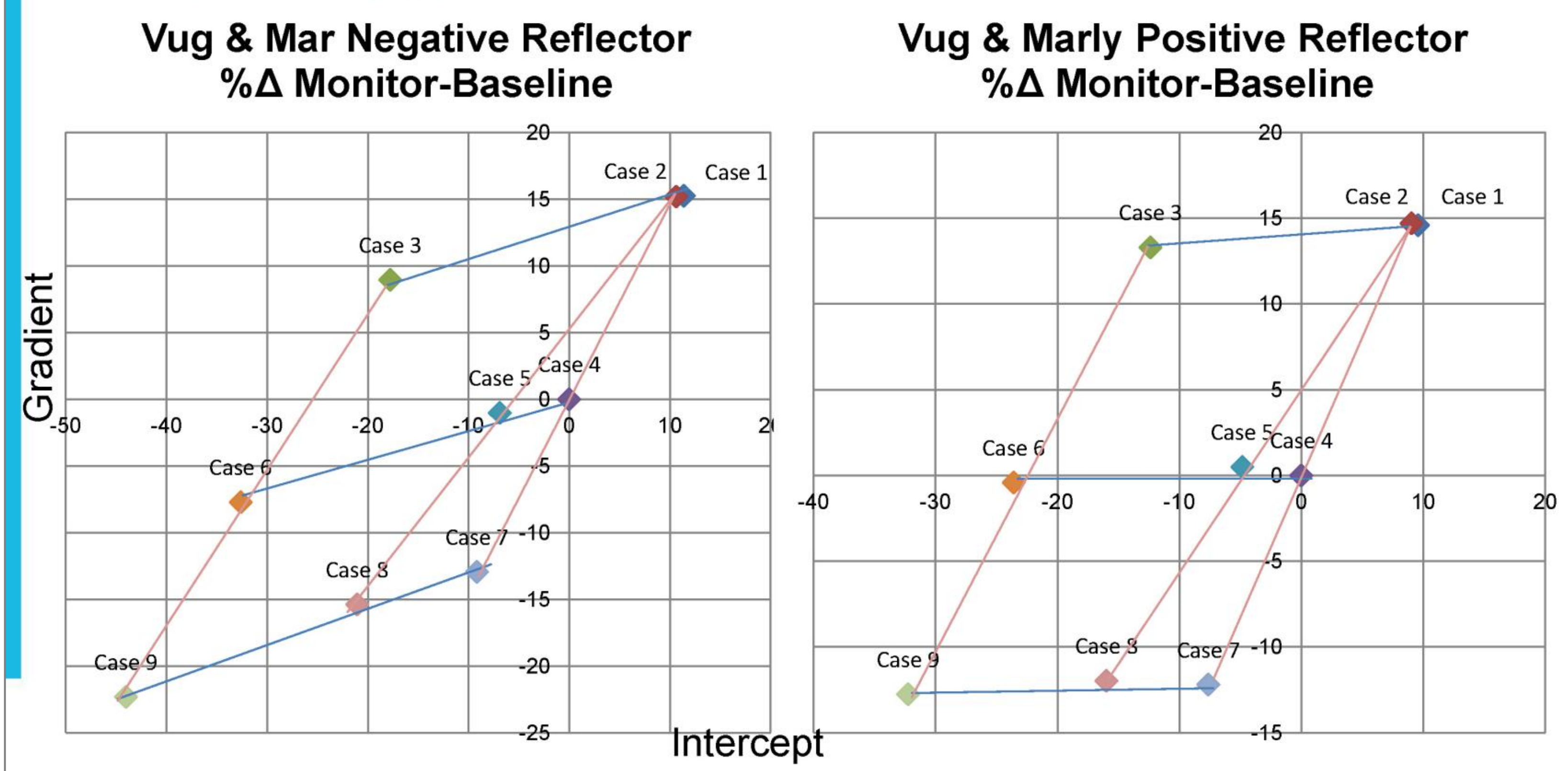




Vuggy Substitutions Int vs Grad



Marly & Vuggy Substitutions %Δ Int vs Grad

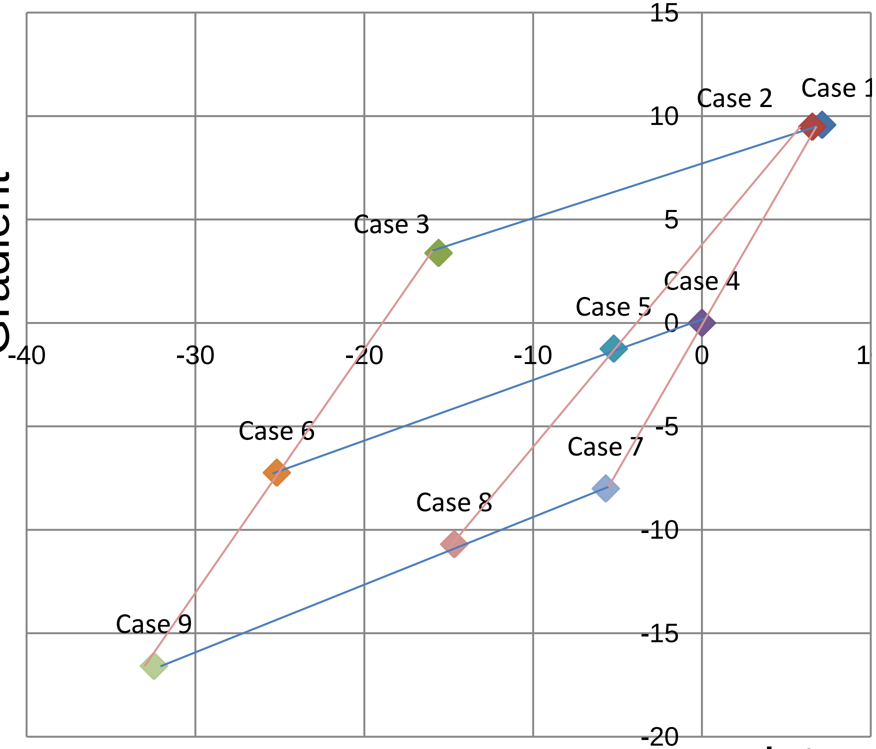


Presenter's notes: With CO_2 flooding in both units, the effect on the gradient to fluid (not pressure) seems to be minimized – slope of line decreases when both units are flooded – the sign of fluid effects on gradient in Marly and Vuggy are opposite. See Vuggy only vs Marly only vs Both. If we are sure both units are flooded, gradient changes are even more likely to be due to pressure!

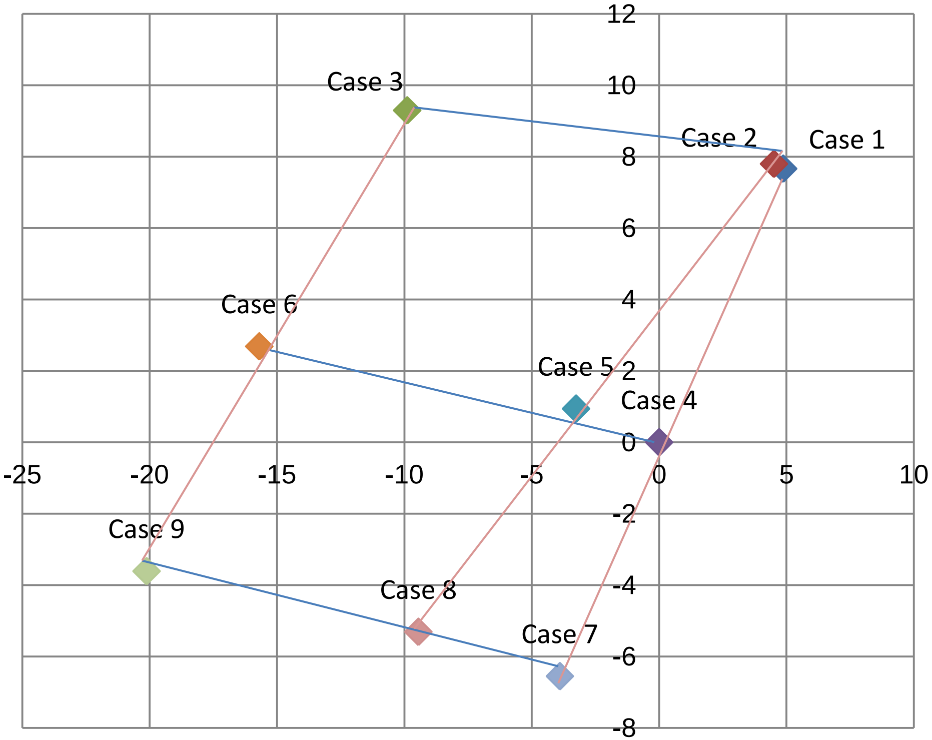
Red lines link similar fluid cases between pressure cases – they are all similar in slope

Marly Substitutions %Δ Int vs Grad

Marly Sub Negative Reflector %Δ Monitor-Baseline



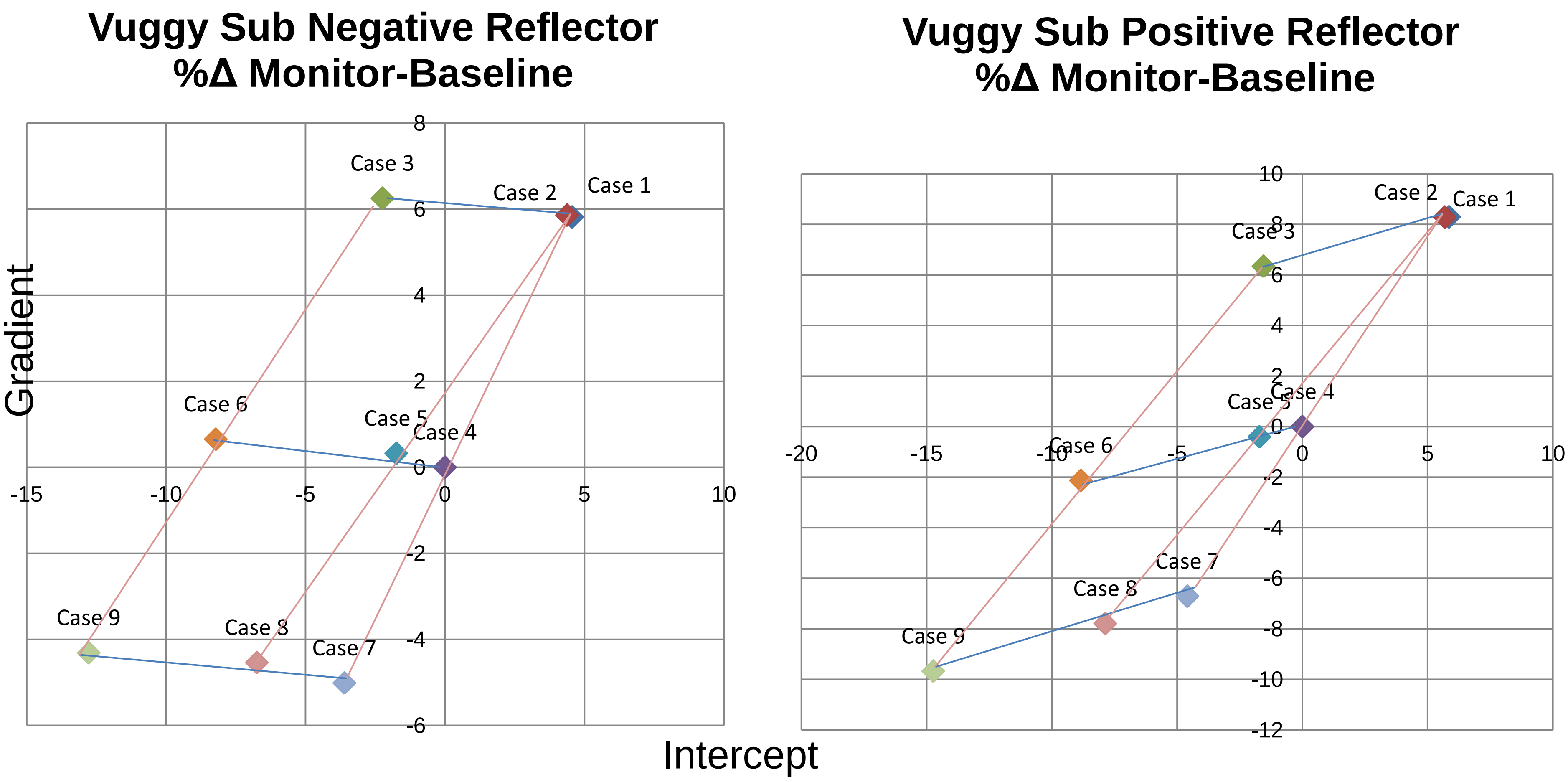
Marly Sub Positive Reflector %Δ Monitor-Baseline



Gradient

Intercept

Vuggy Substitutions %Δ Int vs Grad



4. Conclusions

Conclusions

- Our Rock Physics modeling approach is useful to understand both pressure and saturation effects.
- Fluid saturation effects are visible in Lambda-Rho domain.
- Pressure changes are visible in Mu-Rho domain.
- Forward seismic modeling results show that both Intercept and Gradient are affected by fluid and pressure changes in Marly & Vuggy intervals during CO_2 injection.