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Quantitative Interpretation (QI) - Four well Rock Physics and Inversion Study in the Balmoral Field UK Central North Sea

- *UKCS Quad 15 Pilot Study*

Available data

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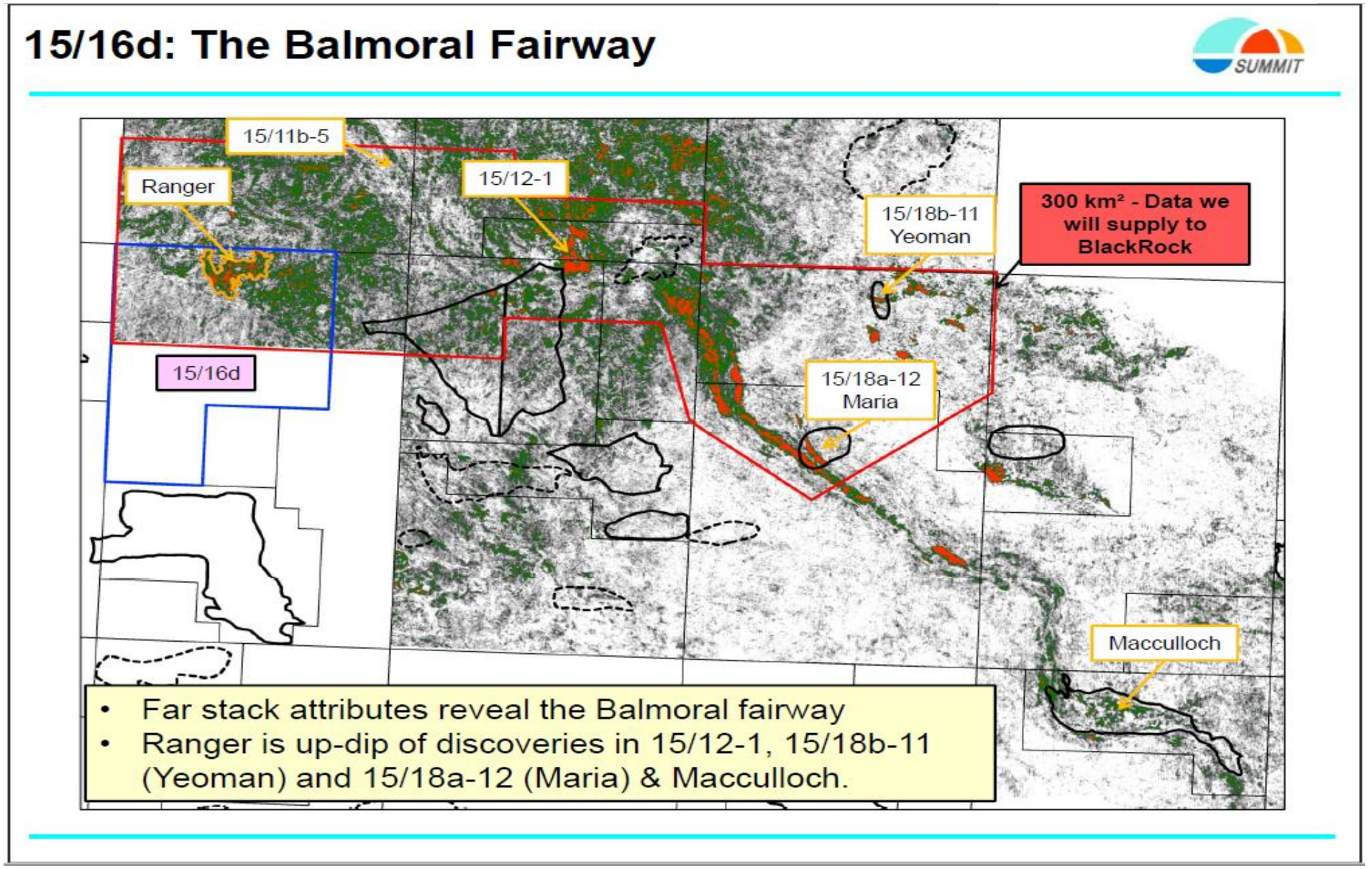
Balmoral Fairway with Ranger prospect.



Data courtesy of Summit Exploration and Production

Available data

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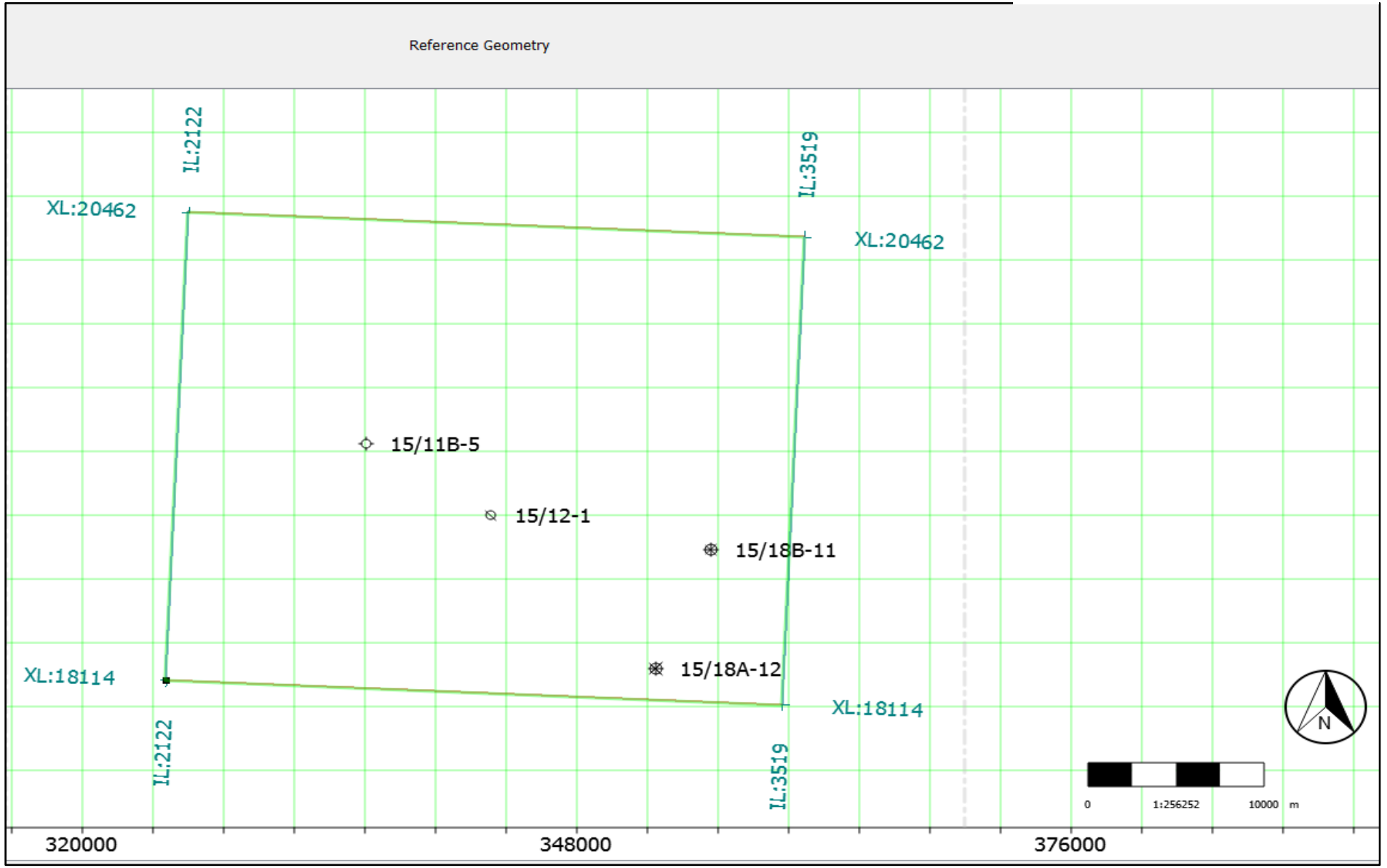
This study investigates four wells and seismic data available in the Central North Sea in Quad 15.

The input data includes: Petrophysical curves, formation tops, deviation surveys, check-shot surveys and well reports for this study.



Aims and objectives

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The four wells in this study are Well 15/11B-5, Well 15/12-1, Well 15/18A-12 and Well 15/18B-11.

The target reservoir interval is the Forties Formation and the Balmoral fairway. There have been hydrocarbon discoveries made at Well 15/18B-11 (Yeoman; oil and gas), Well 15/18A-12 (Maria; oil column with a gas cap) and Well 15/12-1 (oil). Well 15/11B-5 is a dry hole.

The aim of the study is to condition the well log data and review the Rock Physics analysis at the wells before proceeding on to an Inversion workflow to try to discriminate hydrocarbon bearing intervals in the seismic data.

The Rock Physics workflow will be carried out in three sections; Single Well Rock Physics – Part 1, Multi-well analysis and Single Well Rock Physics – Part 2. The contents of these sections will be explained during the course of the project.

Single Well Rock Physics – Part 1

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Single Well Rock Physics - Part 1 is the name given to the section of the workflow containing the initial set up work for the Rock Physics project.

The aim of this section is work is to output conditioned well logs at 100% Brine conditions for trend analysis in the multi-well analysis section.

The following steps are typically carried out;

- Data loading (logs, tops, deviation surveys, check-shots)
- Visual overview at each well
- QC cross-plots of Vp-Vs and Vp-Rho log data
- Log edits of erroneous log data
- Deriving fluid properties using FLAG fluid calculator
- Deriving elastic properties (bulk modulus, shear modulus) for clean shale points
- Gassmann fluid substitution from INSITU conditions to ensure that all log data is at 100% Brine conditions.

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Single Well Rock Physics – Part 1
Selected slides from Well 15/18B-11

- *Quad 15 Pilot Study*

Well 15/18B-11 – Vp-Rho cross-plot

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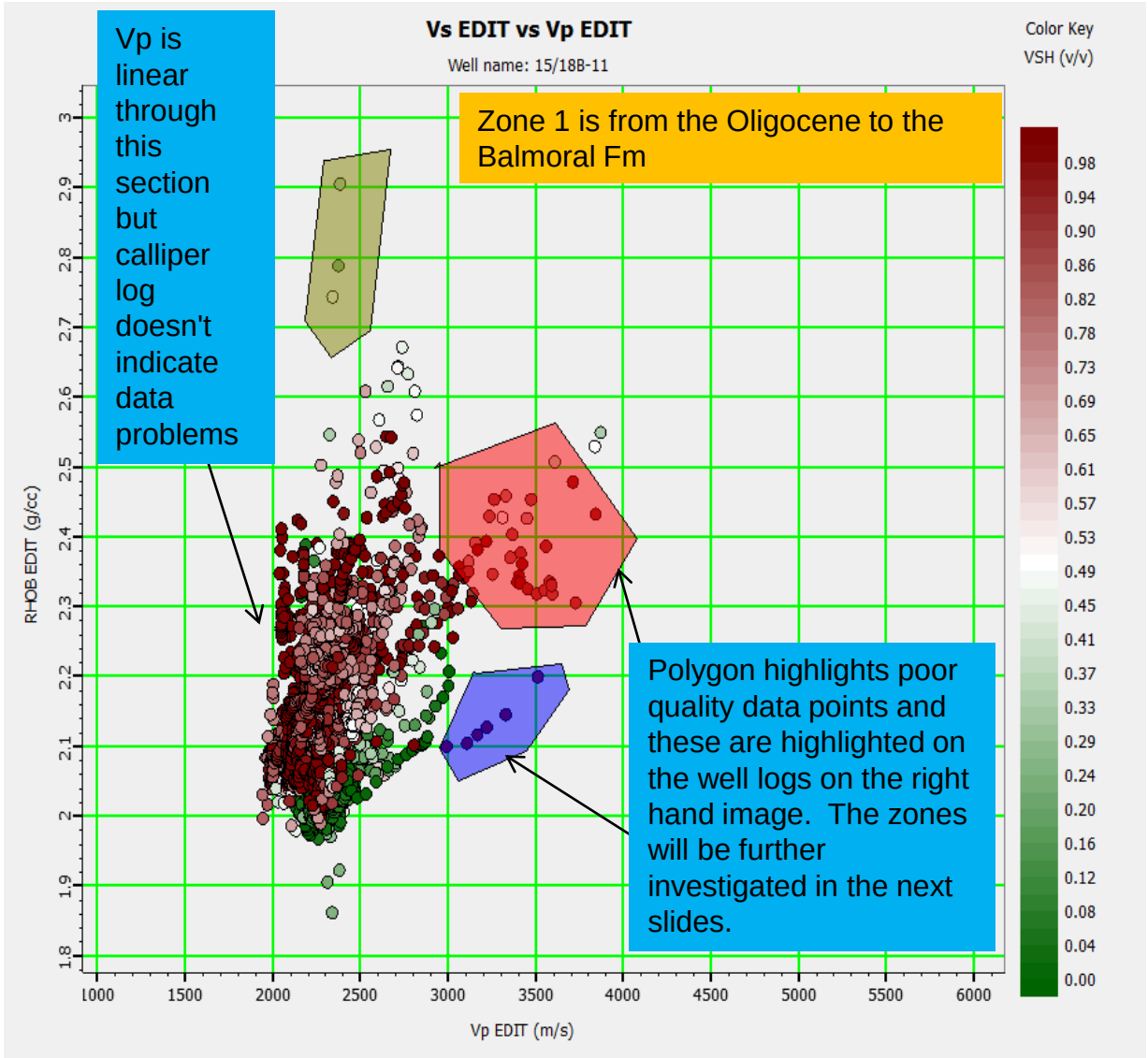
Vp – Rho cross-plot – Zone 1

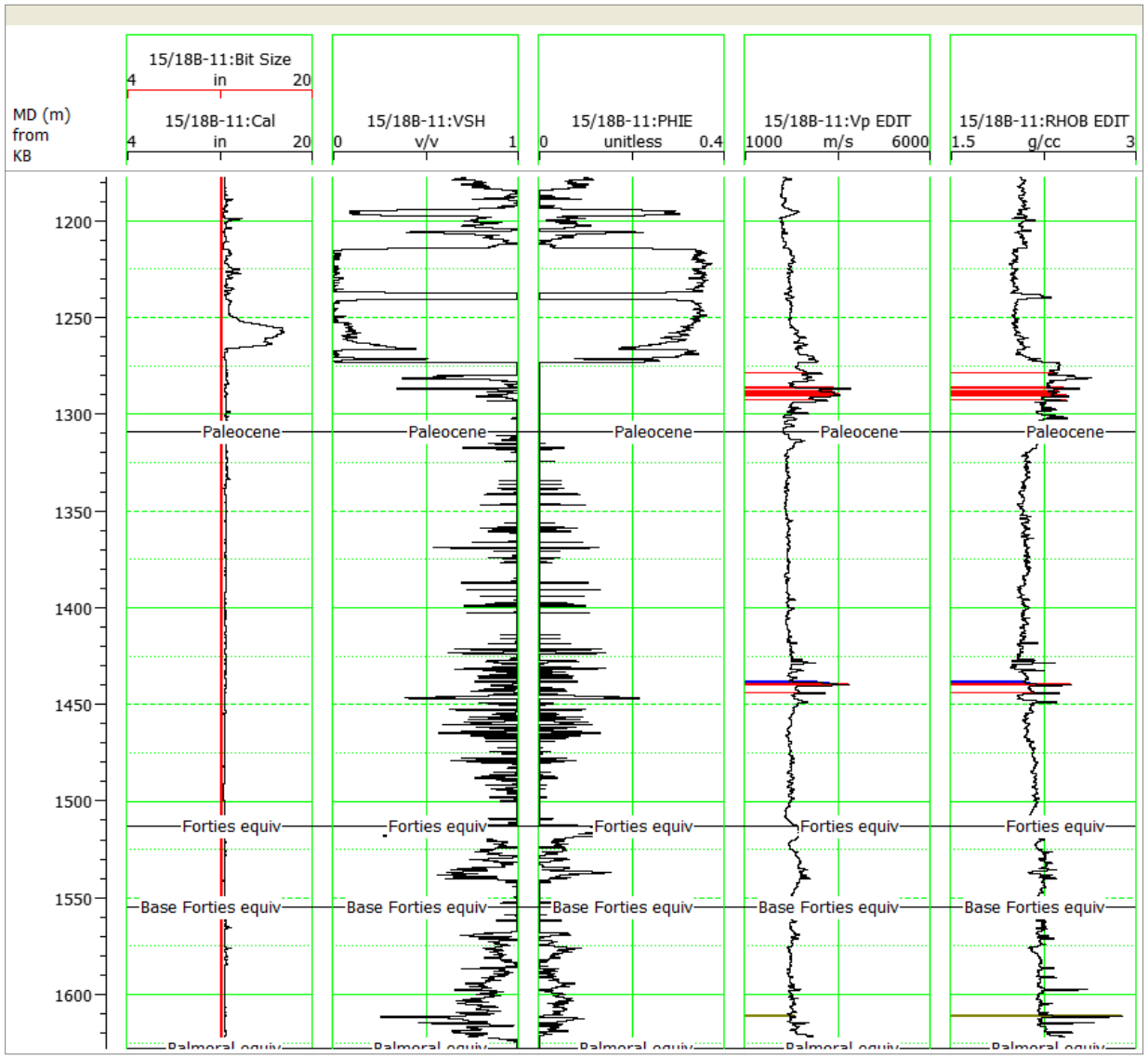


Vp is linear through this section but calliper log doesn't indicate data problems

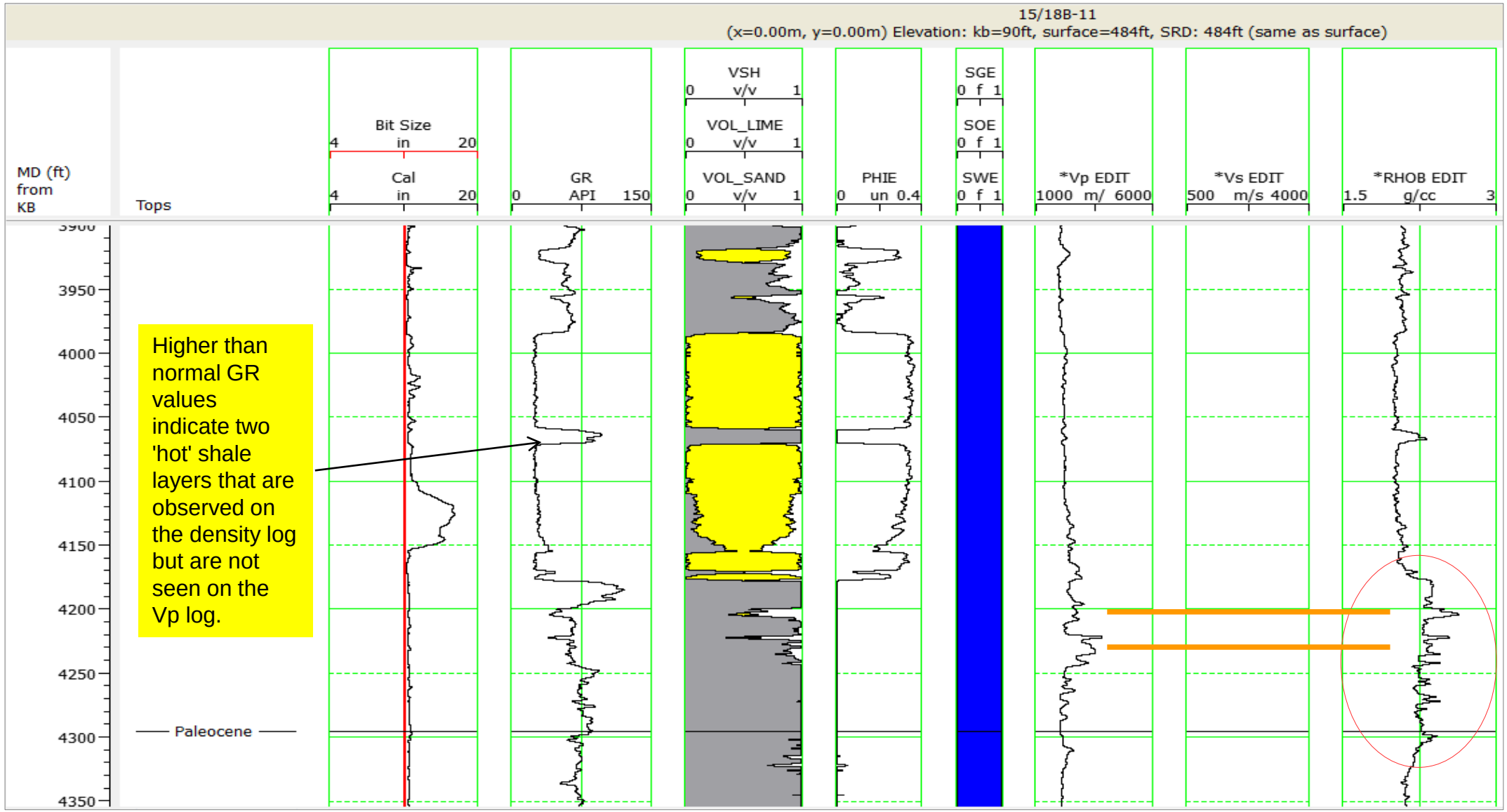
Zone 1 is from the Oligocene to the Balmoral Fm

Polygon highlights poor quality data points and these are highlighted on the well logs on the right hand image. The zones will be further investigated in the next slides.

Corresponding well data



Well 15/18B-11 – Areas of concern (red)



The cross-plot on the previous slide (red polygon) shows a mismatch between the Vp and Rho logs and the VSh and porosity logs between the orange lines.

The density log reads the hot shale layers but a spike a seen after that and it doesn't fit the expected trend so the density log will be clipped at this spike.

Well 15/18B-11 – Vp-Rho cross-plot

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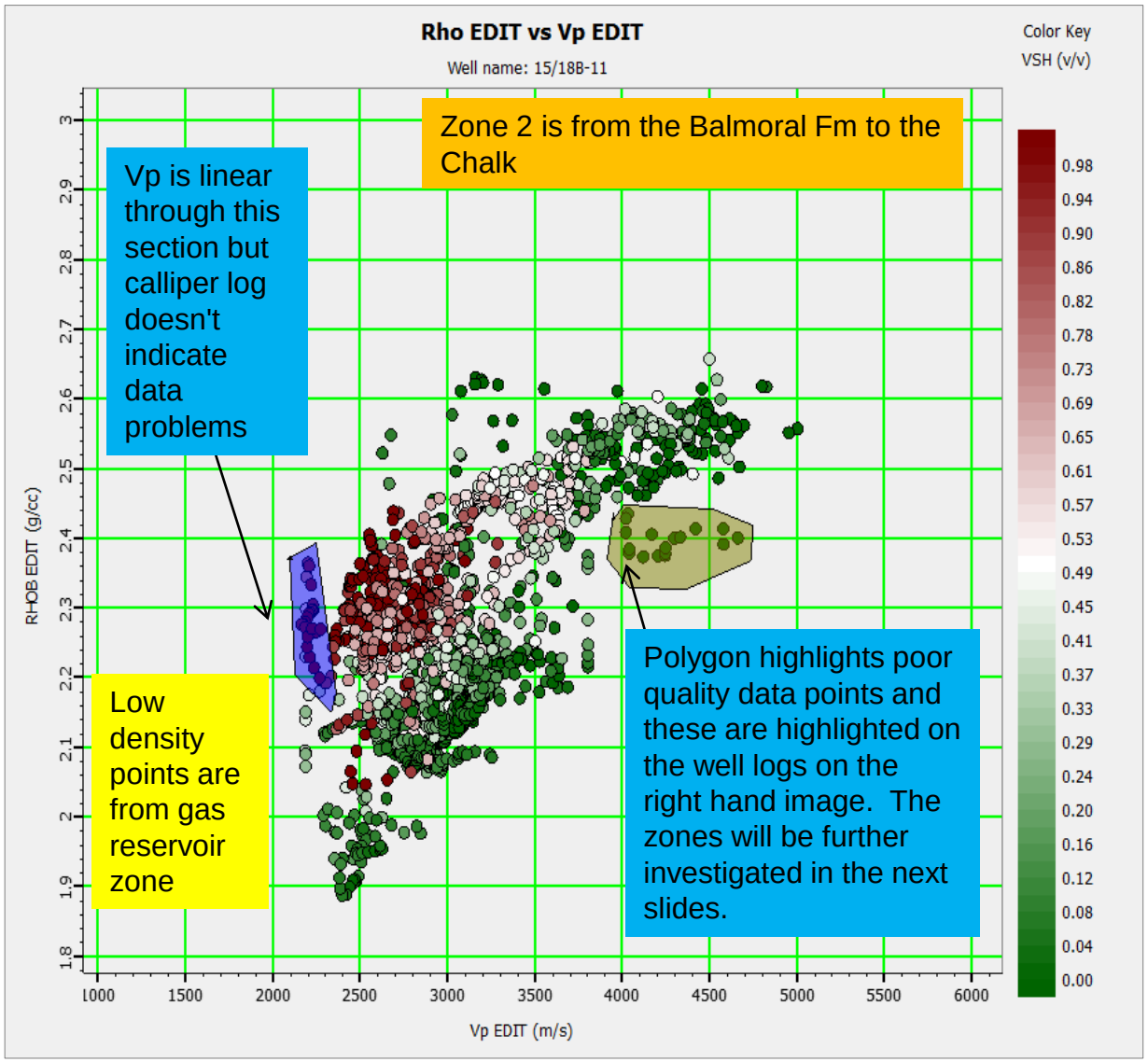
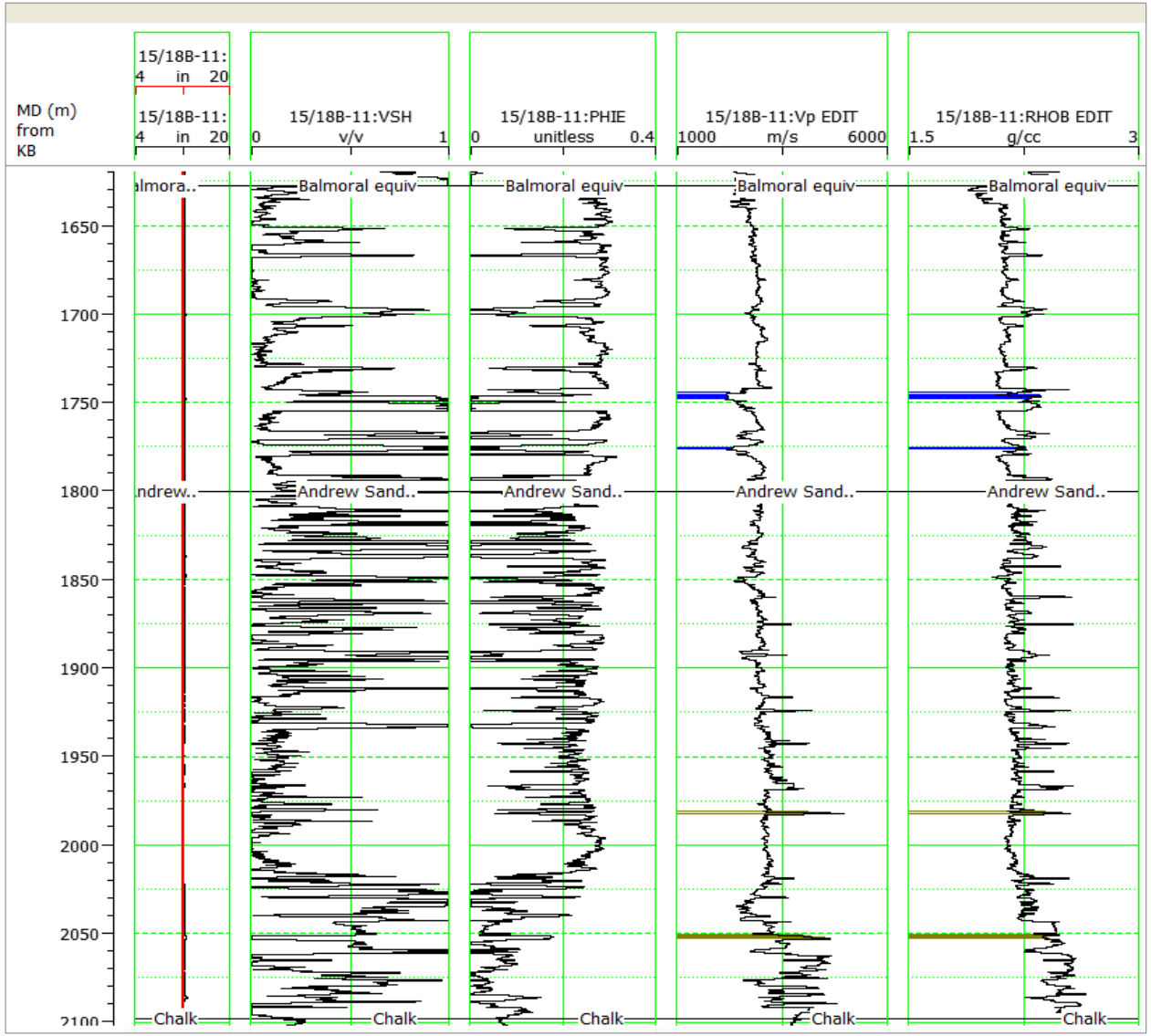
Vp – Rho cross-plot – Zone 2



Corresponding well data



Well 15/18B-11 – Edited data

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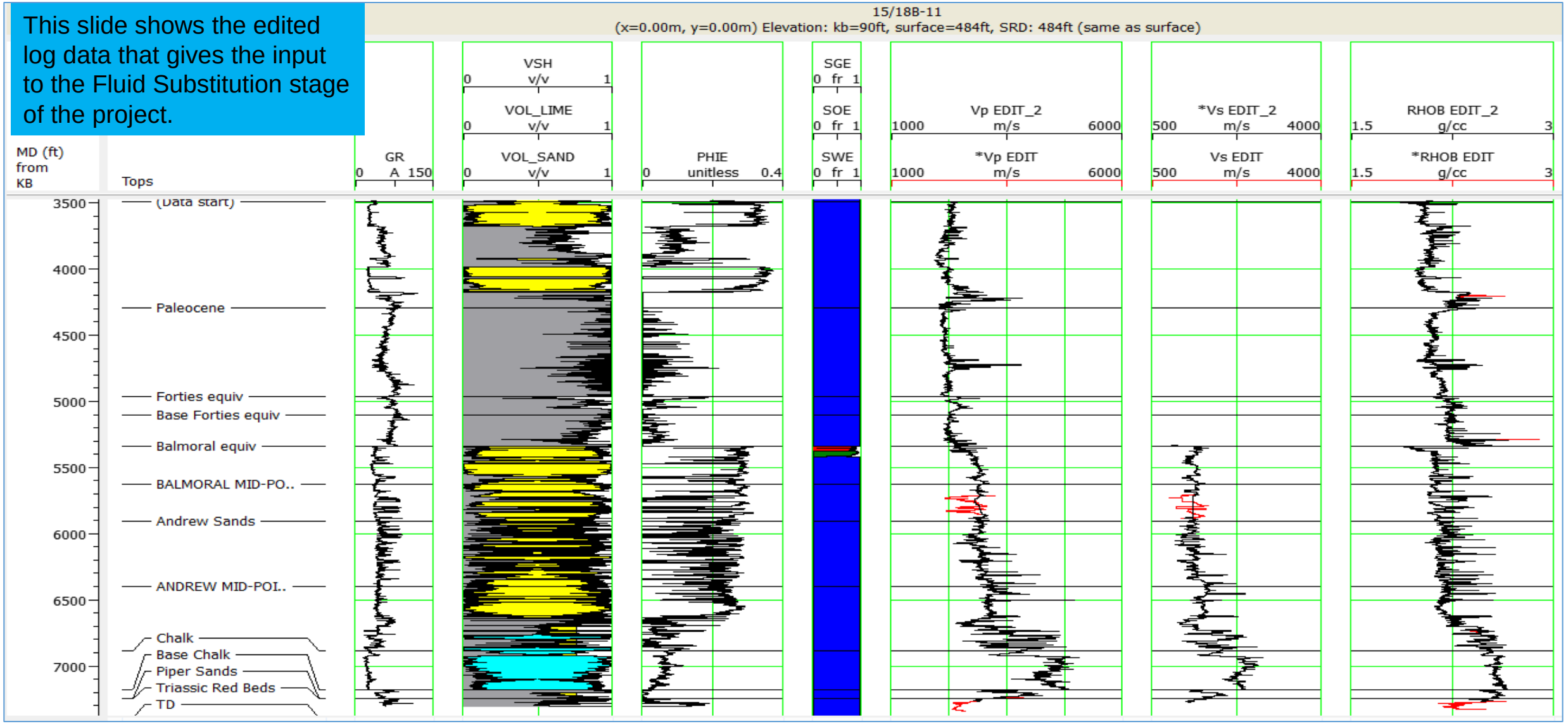
This slide shows the edited log data that gives the input to the Fluid Substitution stage of the project.



Fluid data – 15/18B-11

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The input fluid properties used for Well 15/18B-11 are tabulated below;

	Forties	Balmoral	Andrew
Interval mid-point (ft)	-	5,625	6,397
Reservoir Temperature (deg F)	-	145	162
Reservoir Pressure (psi)	-	2,500	2,847
Salinity (ppm)	-	126,500	129,503
Oil Gravity (API)	-	21	21
GOR (scf/stb)	-	240/400	240/400
Gas Gravity (Air = 1)	-	0.82	0.82

Reservoir temperature is found from the Formation Temperature logs supplied from the Petrophysics and Salinity data is calculated in every formation in the Petrophysics reports.

Default Oil Gravity, GOR and Gas Gravity properties will be used for every well within this pilot study.

Reservoir pressure is found from Formation Pressure values on the composite logs but if this is not available then pressure will be assumed to be hydrostatic and a pressure gradient of 0.445 psi/ft will be used.

The FLAG fluid model is now used to calculate the elastic properties of the fluids and these are shown below for the Balmoral Fm;

Fluid Properties

Oil Density:	0.858846 g/cc 858.846 kg/m3
Oil Bulk Modulus:	1502.86 MPa 1.50286 GPa 15028.6 bar 217972 psi
Oil Velocity:	1322.82 m/s 4339.97 ft/s
Oil Maximum GOR:	80.075 L/L 449.621 scf/bbl
Free Gas:	0 fraction 0 %
Gas Density:	0.197127 g/cc 197.127 kg/m3
Gas Bulk Modulus:	40.048 MPa 0.040048 GPa 400.48 bar 5808.48 psi
Gas Velocity:	450.731 m/s 1478.78 ft/s
Water Density:	1.07641 g/cc 1076.41 kg/m3
Water Bulk Modulus:	3124.69 MPa 3.12469 GPa 31246.9 bar 453198 psi
Water Velocity:	1703.79 m/s 5589.85 ft/s
Water flash Pressure:	0.0152667 MPa 1.52667e-05 GPa 0.152667 bar 2.21425 psi
Fluid Density:	1.07641 g/cc 1076.41 kg/m3
Fluid Bulk Modulus:	3124.69 MPa 3.12469 GPa 31246.9 bar 453198 psi
Fluid Velocity:	1703.79 m/s 5589.85 ft/s

Parameters:
Oil Properties Calculation using FLAG 2014 Global Oil Model
Gas Properties Calculation using FLAG 2014 Global Model
Calculation includes Bubble Point Effect
Bubble Point method: Standing Equation
Saturation mixing law using Homogenous Mix (Reuss Average)
Temperature: 62.7778deg C 145 deg F 335.928 K
Pore Pressure: 2500psi 17.2369 MPa 172.369 bar
Oil Gravity: 21 API
Oil GOR: 42.7427 L/L 240 scf/bbl
Gas Gravity: 0.82
Water Salinity: 126500ppm
Oil saturation: 0 % Gas saturation: 0 % Water saturation: 100 %

Mineral data – 15/18B-11

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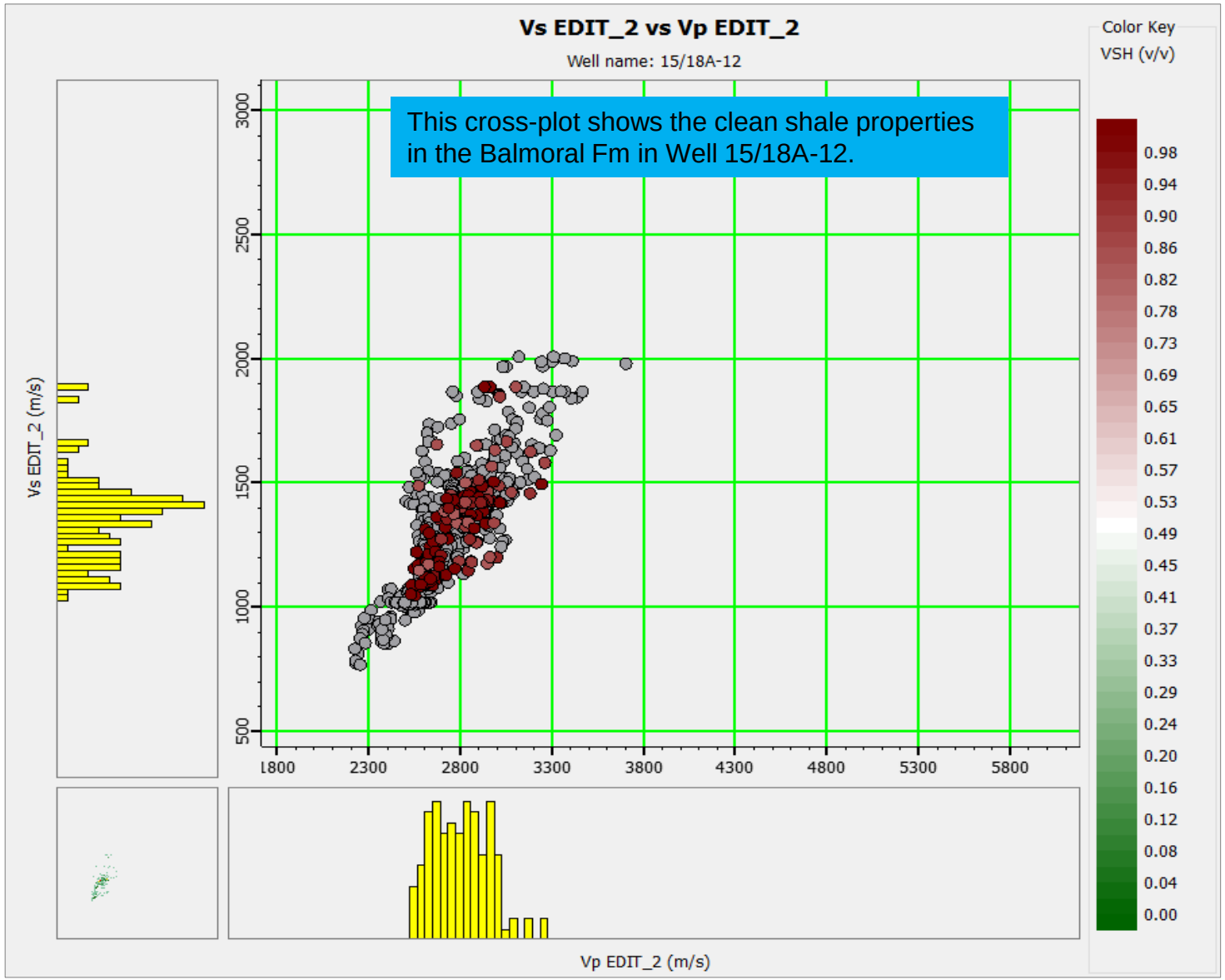
For Gassmann Fluid Substitution, it is necessary to understand the mineral content of the reservoir interval. Quartz and calcite mineral properties stay consistent in any area and are allocated the default mineral values. Shale is much more variable and changes bulk and shear modulus properties.

Vp-Vs and Vp-Rho cross-plots are created and a cut-off of Vsh > 0.8 is applied to the data to isolate the clean shale properties. The average Vp, Vs and RHOB values are taken for the clean points and will be used to make an updated bulk and shear modulus properties for every reservoir interval.

The bulk modulus (k) and shear modulus (μ) are found from Vp, Vs and RHOB values using the following equations;

$K = \rho (Vp^2 - 4Vs^2 / 3)$

$\mu = \rho Vs^2$



Gassmann Fluid Substitution – Well 15/18B-11

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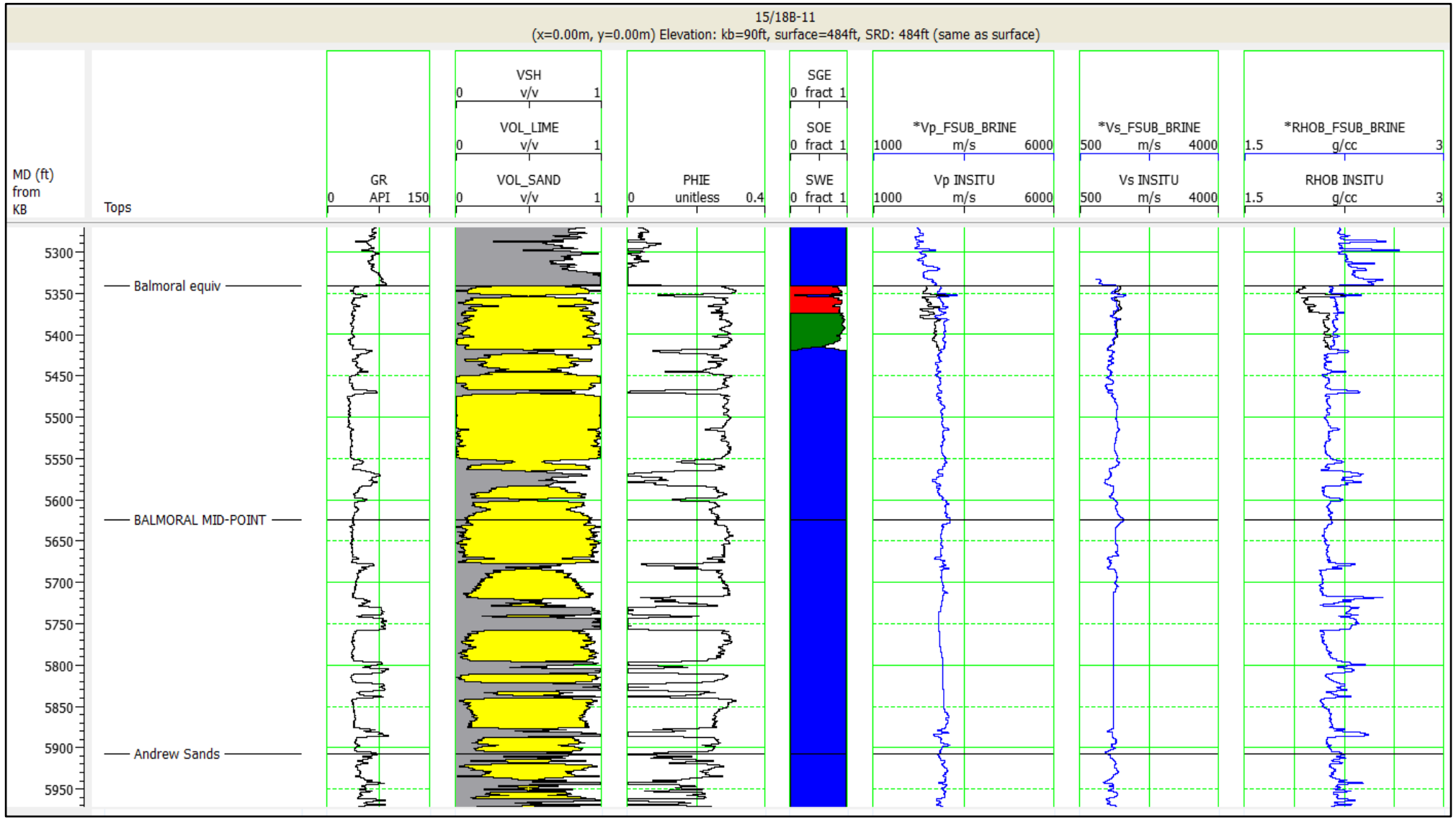
The Gassmann Fluid Substitution results for the Balmoral Fm in Well 15/18B-11 are shown below;



The results show that the hydrocarbons in the Balmoral Fm have been substituted to 100% Brine conditions. The Vp and density logs both increase as brine is denser than the hydrocarbons whereas the Vs log shows a slight decrease.

The increase in the density log is more pronounced over the gas leg of the reservoir.

No hydrocarbons are present in the Andrew Fm (100% Brine conditions) and no fluid substitution is needed in this zone.

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Multi-well analysis

Selected cross-plots are shown from the full study

- *Quad 15 Pilot Study*

Multi-well analysis

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- The multi-well analysis section of the project compares well log data from the project to established Rock Physics models. Only data at 100% Brine conditions is used in this analysis and if Gassmann Fluid Substitution is not possible in Single Well Rock Physics - Part 1 due to missing log data then saturation cut-offs will exclude hydrocarbon zones.
- The cross-plots of Vp-Rho and Vp-Vs will be made using data from every well in the following intervals Palaeocene, Forties (including Forties and Base Forties), Balmoral and Andrew Sands Fm and these will be for clean lithology points of clean shale (VSh>0.8) and clean sand (Vol_Sand>0.8).
- The trends derived from these cross-plots will be used to accurately model missing log data and derive a full suite of Vp, Vs and Rho logs over the interval of interest.

	Vp-Rho (Shale)	Vp-Rho (Sand)
Palaeocene		
Forties		
Balmoral		
Andrew		

	Vp-Vs (Shale)	Vp-Vs (Sand)
Palaeocene		
Forties		
Balmoral		
Andrew		

Any missing log data outside the interval of interest will be modelled using default Greenberg-Castagna and Gardner coefficients.

Forties Interval (Vp-Rho)

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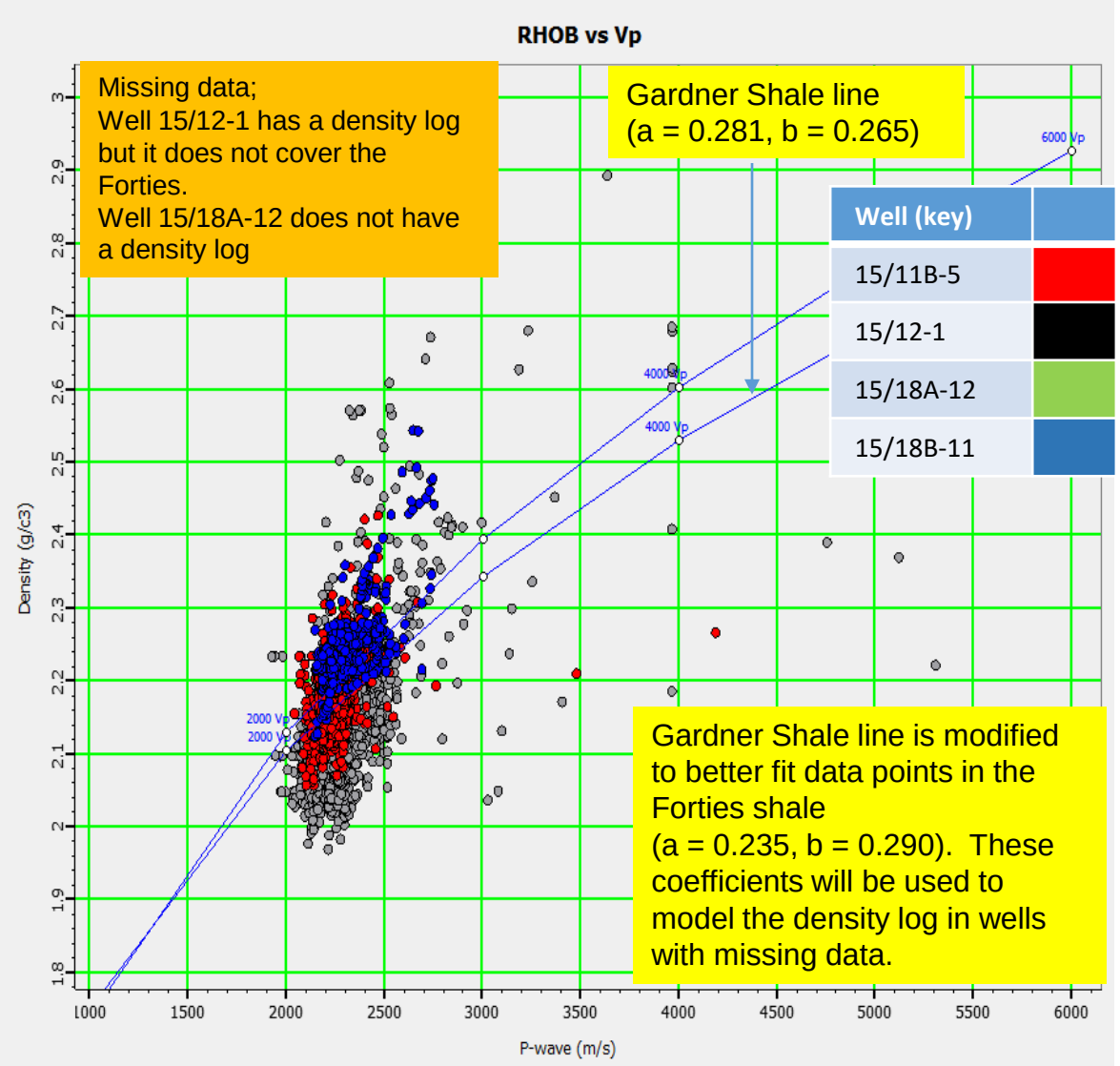
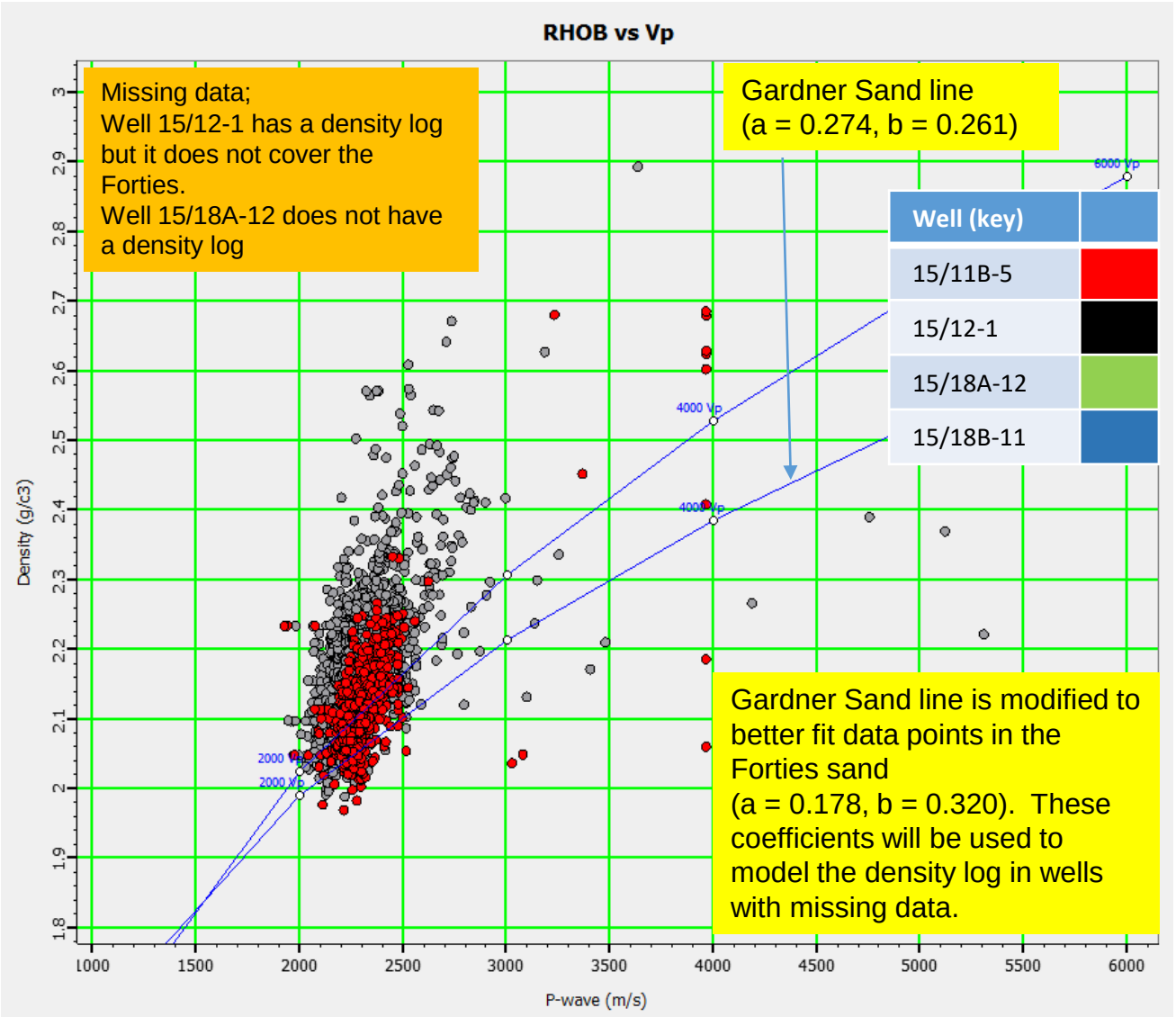
Vp – Rho cross-plot – Clean Shale data (VSh>0.8)



Vp – Rho cross-plot – Clean Sand data (Vol_Sand>0.8)



Forties Interval (Vp-Rho)

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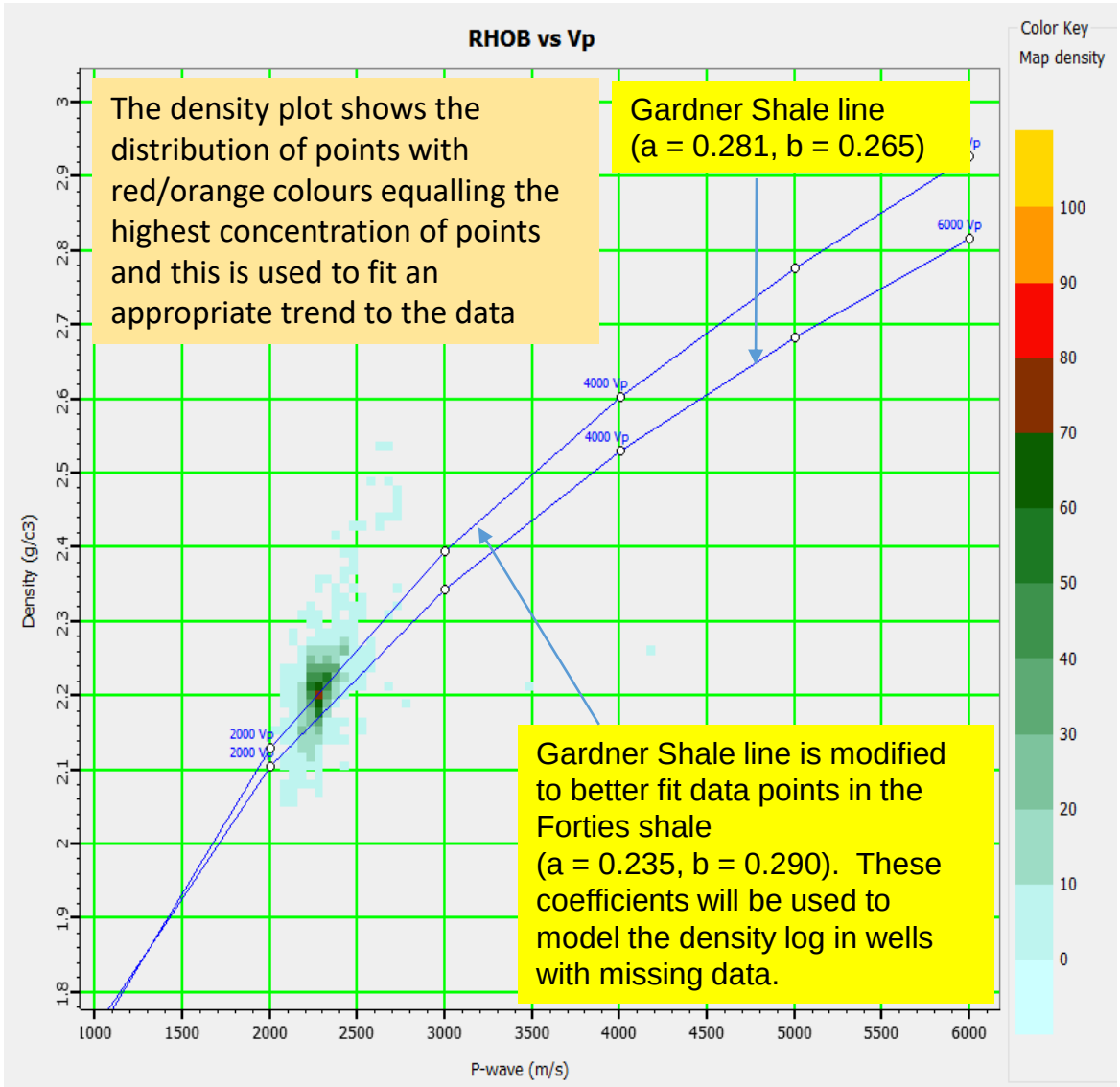
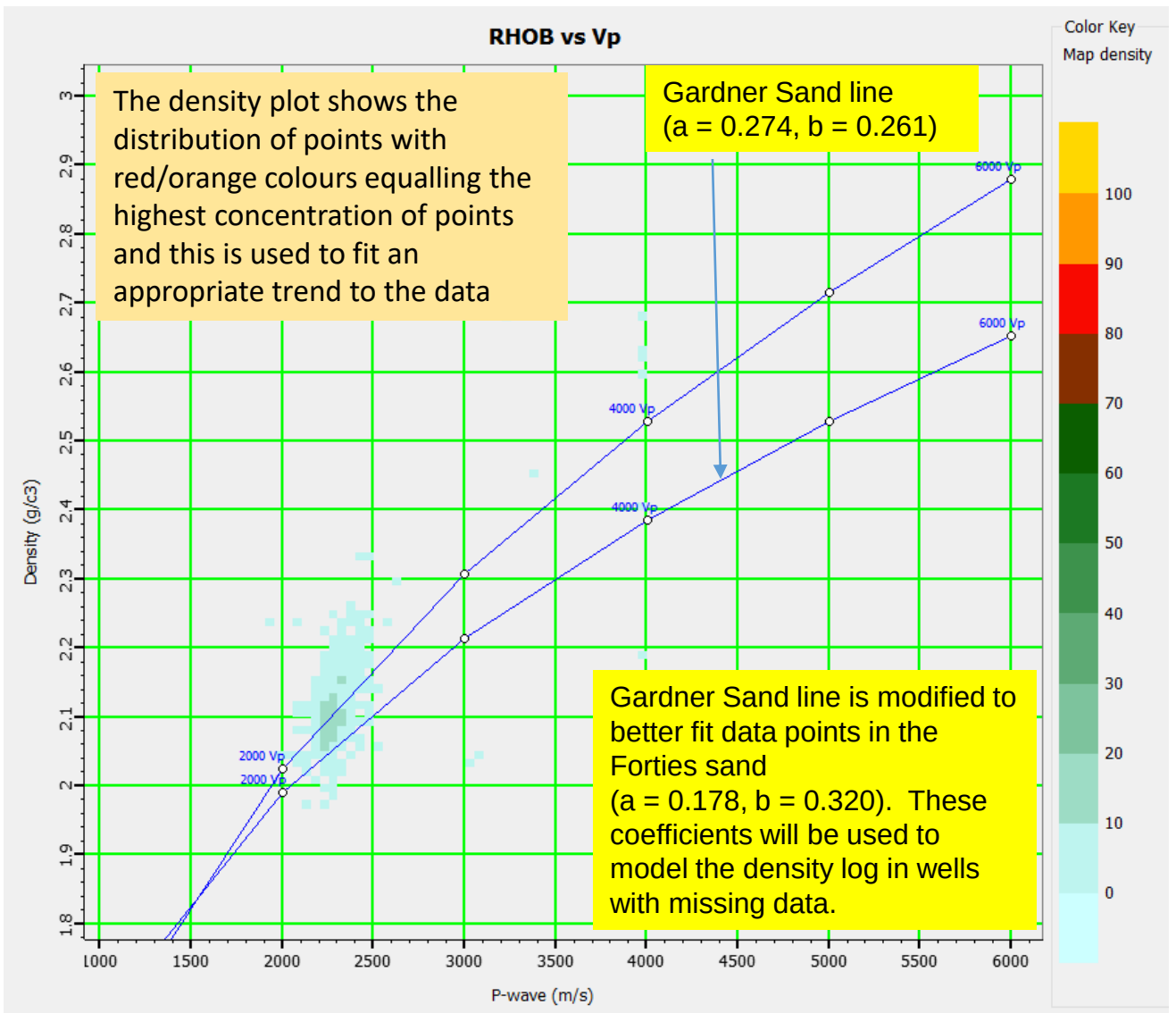
Vp – Rho cross-plot – Clean Shale data (VSh>0.8)



Vp – Rho cross-plot – Clean Sand data (Vol_Sand>0.8)



Modelling – Vp-Rho relationship

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This cross-plot analysis of Vp-Rho in the intervals of interest has given the following Rock Physics relationships and Gardner's law has been adjusted to best fit the data. The missing well log data will be modelled in the next stage of the project.

	Vp-Rho (Shale)	Vp-Rho (Sand)
Palaeocene	Modified Gardner line; a = 0.276, b = 0.265	
Forties	Modified Gardner line; a = 0.235, b = 0.290	Modified Gardner line; a = 0.178, b = 0.320
Balmoral	Modified Gardner line; a = 0.284, b = 0.265	*Default Gardner line;* *a = 0.274, b = 0.261*
Andrew	*Default Gardner line;* *a = 0.281, b = 0.265*	*Default Gardner line;* *a = 0.274, b = 0.261*

Any missing log data outside the interval of interest will be modelled using default Gardner coefficients.

Balmoral Interval (Vp-Vs)

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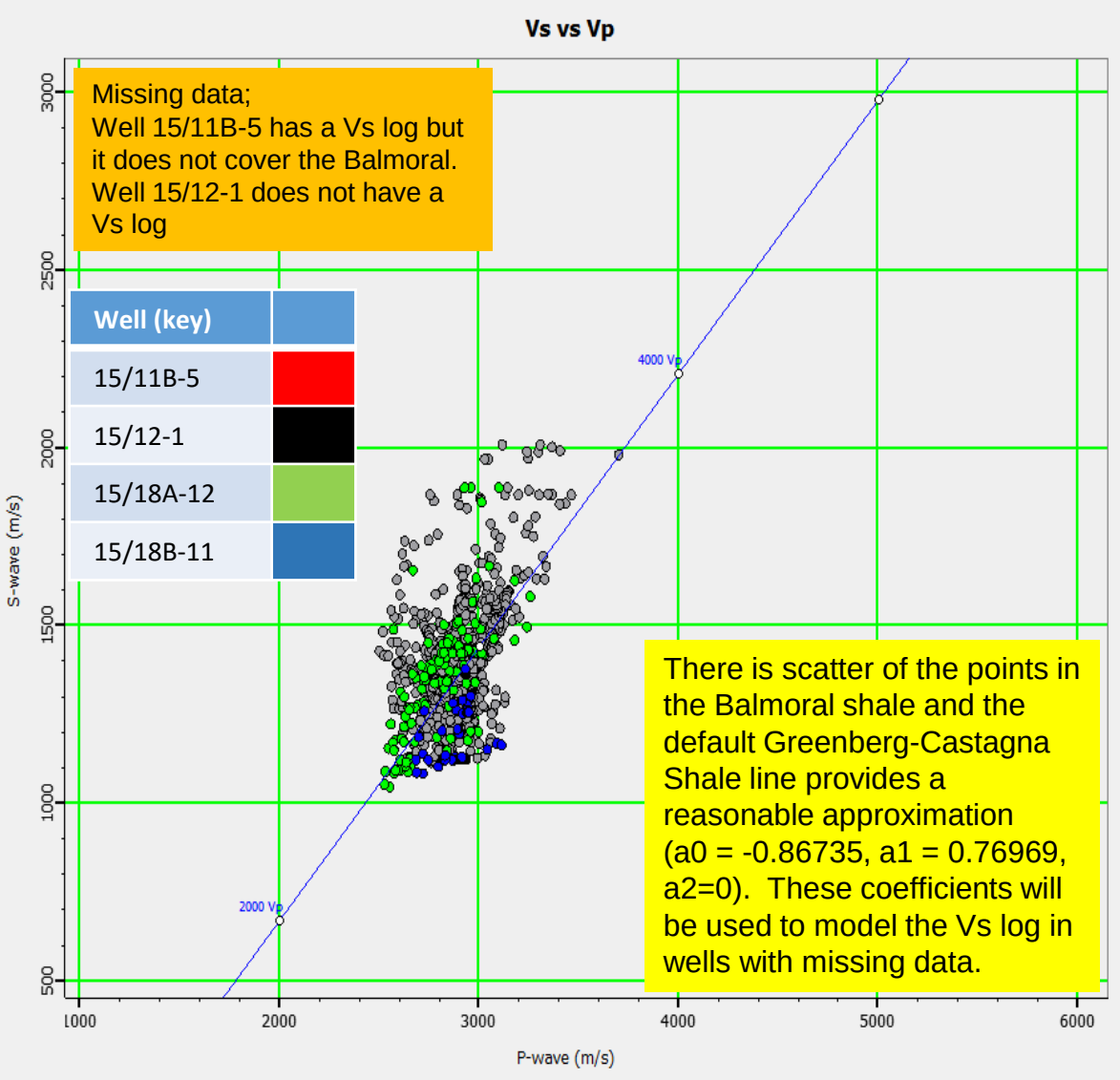
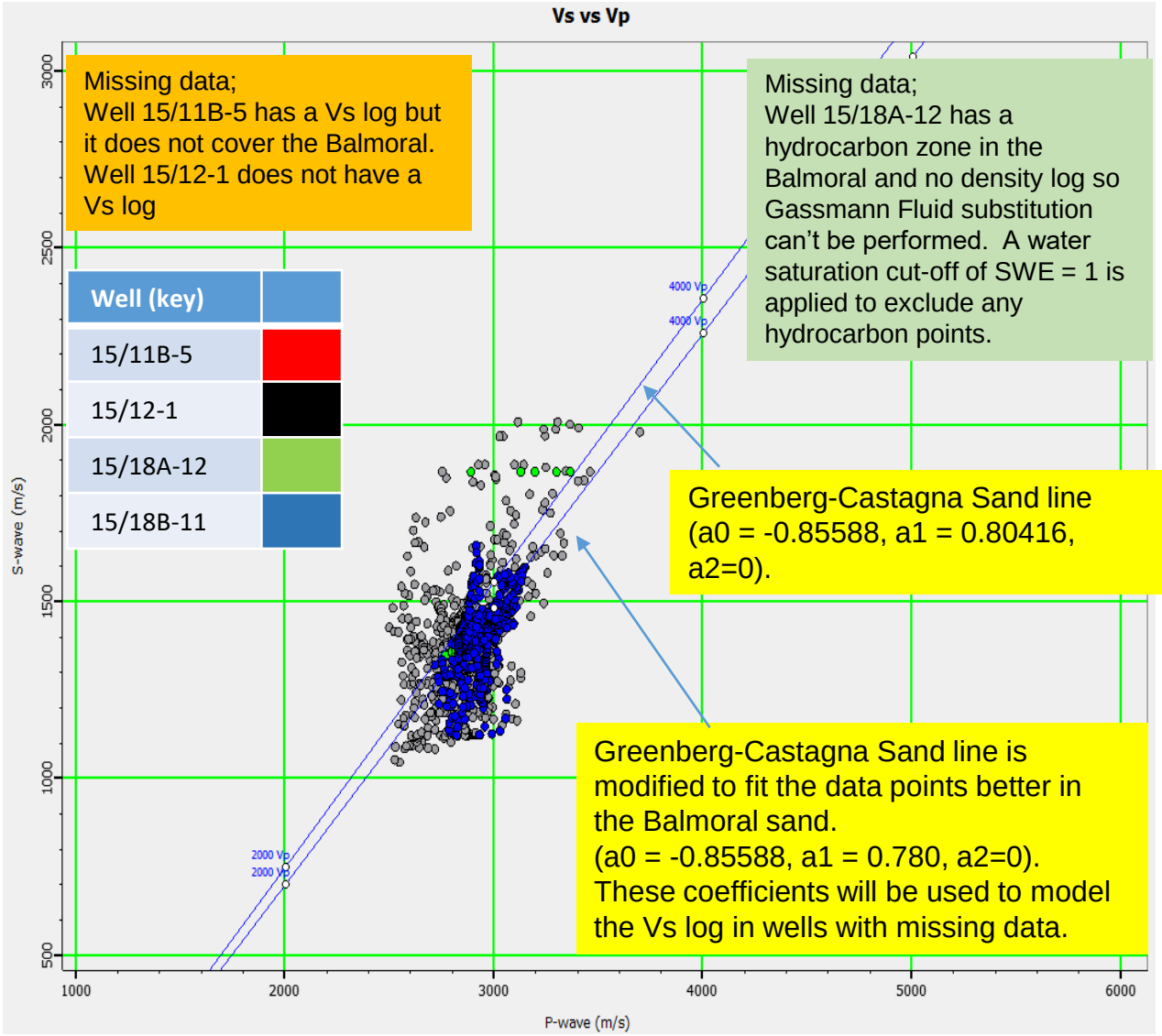
Vp – Vs cross-plot – Clean Shale data (VSh>0.8)



Vp – Vs cross-plot – Clean Sand data (Vol_Sand>0.8)



Balmoral Interval (Vp-Vs)

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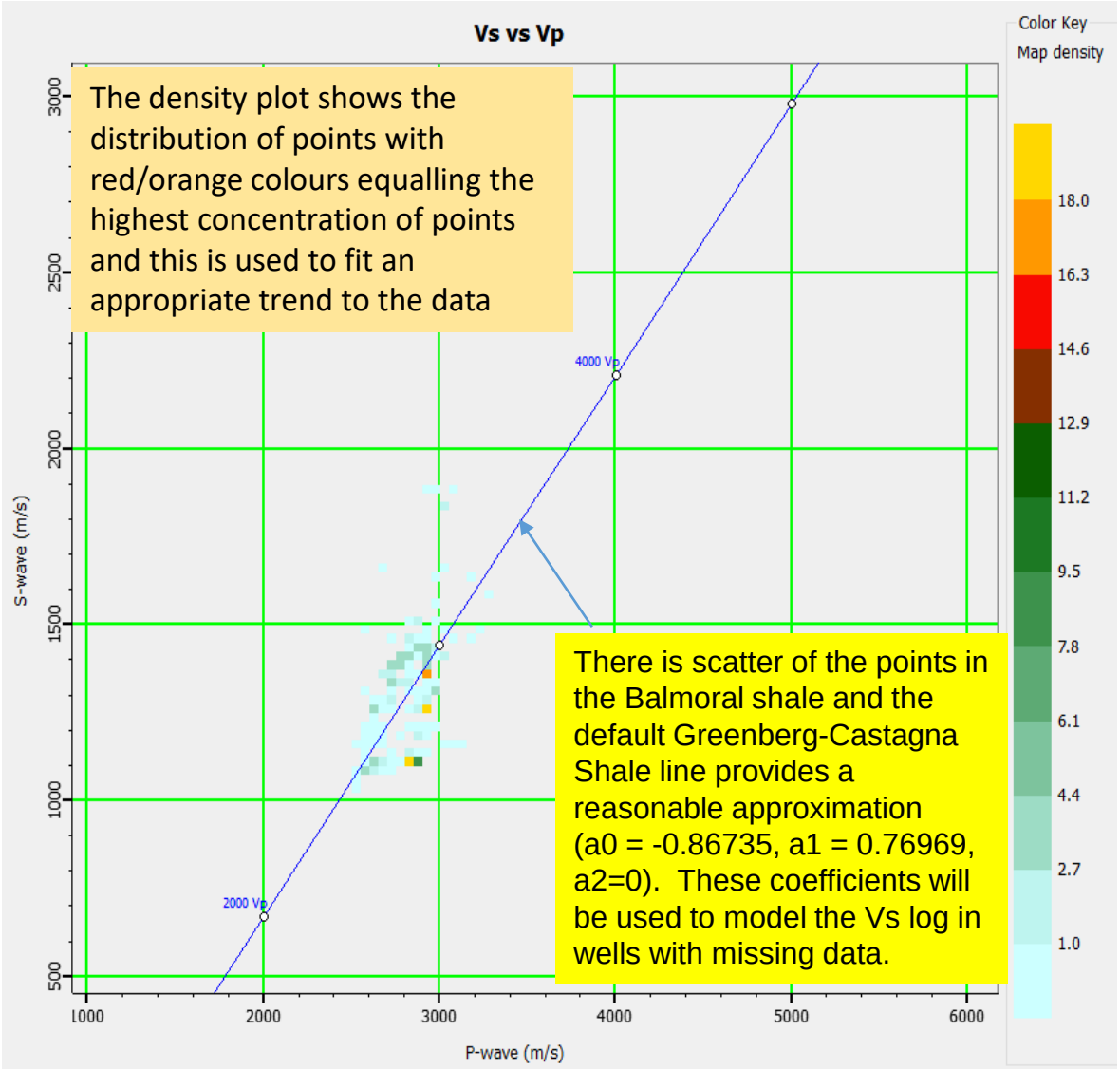
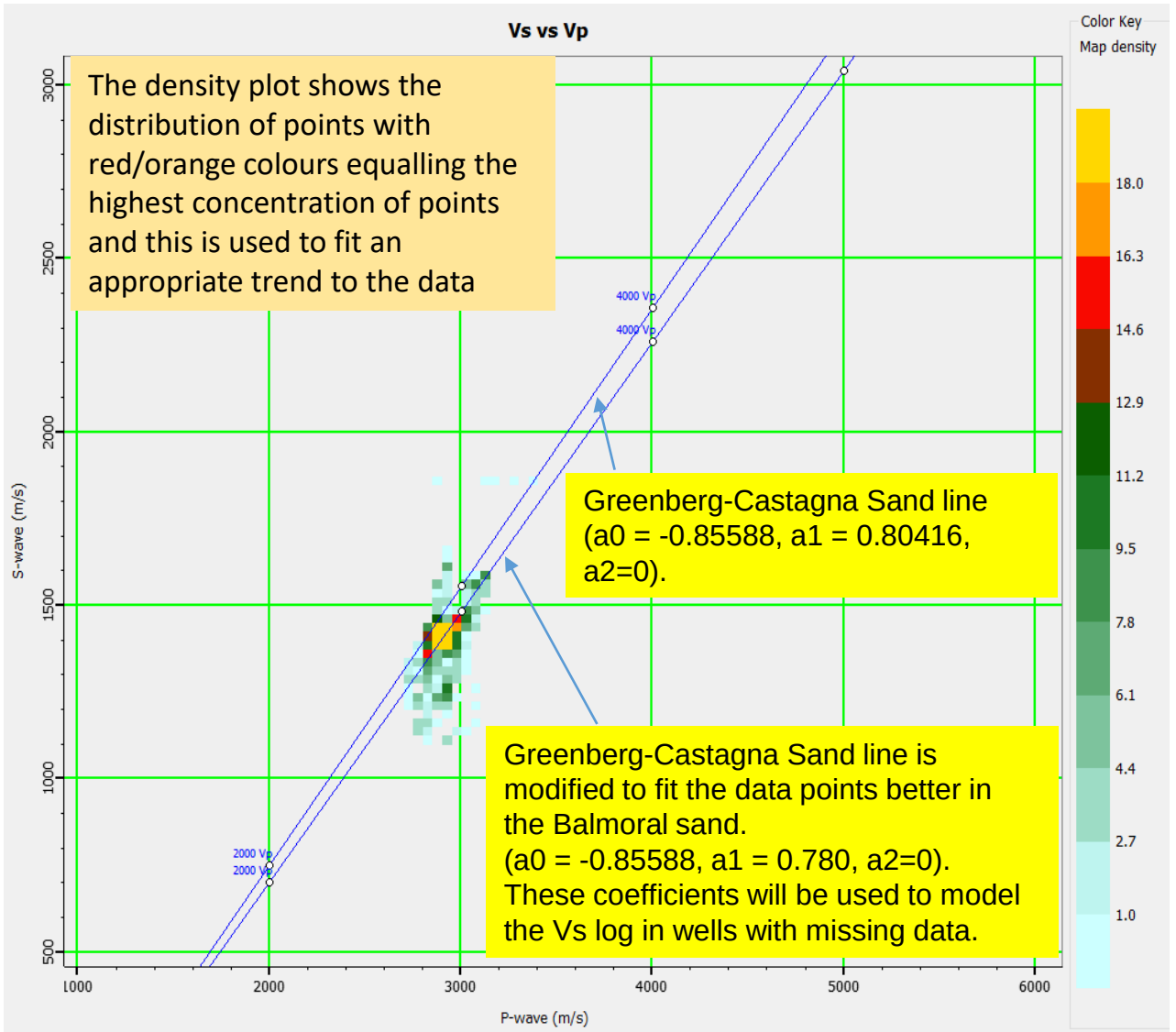
Vp – Vs cross-plot – Clean Shale data (VSh>0.8)



Vp – Vs cross-plot – Clean Sand data (Vol_Sand>0.8)



Modelling – Vp-Vs relationship

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This cross-plot analysis of Vp-Vs in the intervals of interest has given the following Rock Physics relationships and Greenberg Castagna's law has been adjusted to best fit the data. The missing well log data will be modelled in the next stage of the project.

	Vp-Vs (Shale)	Vp-Vs (Sand)
Palaeocene	Default G/C line; a0 = -0.86735, a1 = 0.76969, a2=0	
Forties	*Modified G/C line;* *a0 = -0.86735, a1 = 0.782, a2=0*	Default G/C line; a0 = -0.85588, a1 = 0.80416, a2=0
Balmoral	Default G/C line; a0 = -0.86735, a1 = 0.76969, a2=0	*Modified G/C line;* *a0 = -0.85588, a1 = 0.780, a2=0*
Andrew	*Modified G/C line;* *a0 = -0.470, a1 = 0.605, a2=0*	*Modified G/C line;* *a0 = -1.110, a1 = 0.850, a2=0*

Any missing log data outside the interval of interest will be modelled using default Greenberg Castagna coefficients.

Single Well Rock Physics – Part 2

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Single Well Rock Physics - Part 2 is the name given to the section of the workflow containing the results for the Rock Physics project and end of the core workflow.

The aim of this section is work is to ensure that each well has a full suite of Vp, Vs and RHOB logs and examine how the elastic properties will change for each fluid case in the reservoir intervals. These results are used to guide Inversion work or any other more advanced Rock Physics modelling.

The following steps are typically carried out;

- Modelling missing sections of log data with derived trends from the Multi-well analysis
- Carrying out Gassmann fluid substitution to ensure that all remaining log data was at 100% Brine conditions
- Carrying out Gassmann fluid substitution to model the log response to 80% Oil and 90% Gas conditions
- Generating elastic logs to observe the elastic response at each fluid case as an overview at each well
- Constructing simple Blocky AVO models using average properties of clean sand points
- Generating Synthetic Gathers with a simple Ricker wavelet
- Generating AI-PR and LR-MR cross-plots to guide the Inversion stage of the project

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Log Modelling and Fluid Replacement Modelling
Selected slides are shown from the full study

- *Quad 15 Pilot Study*

Well 15/18A-12 – Modelled data

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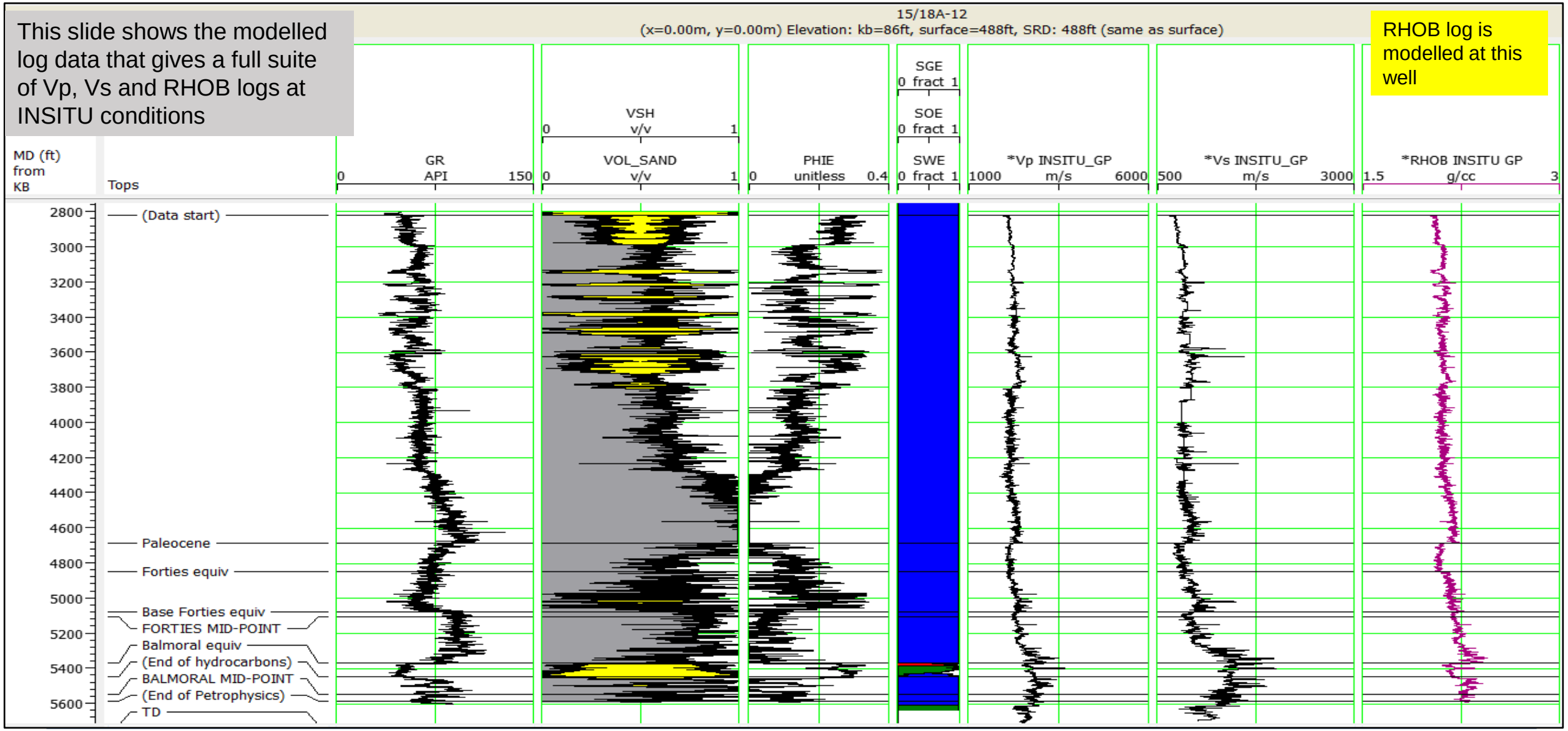
This slide shows the modelled log data that gives a full suite of Vp, Vs and RHOB logs at INSITU conditions

RHOB log is modelled at this well



Well 15/12-1 – Modelled data

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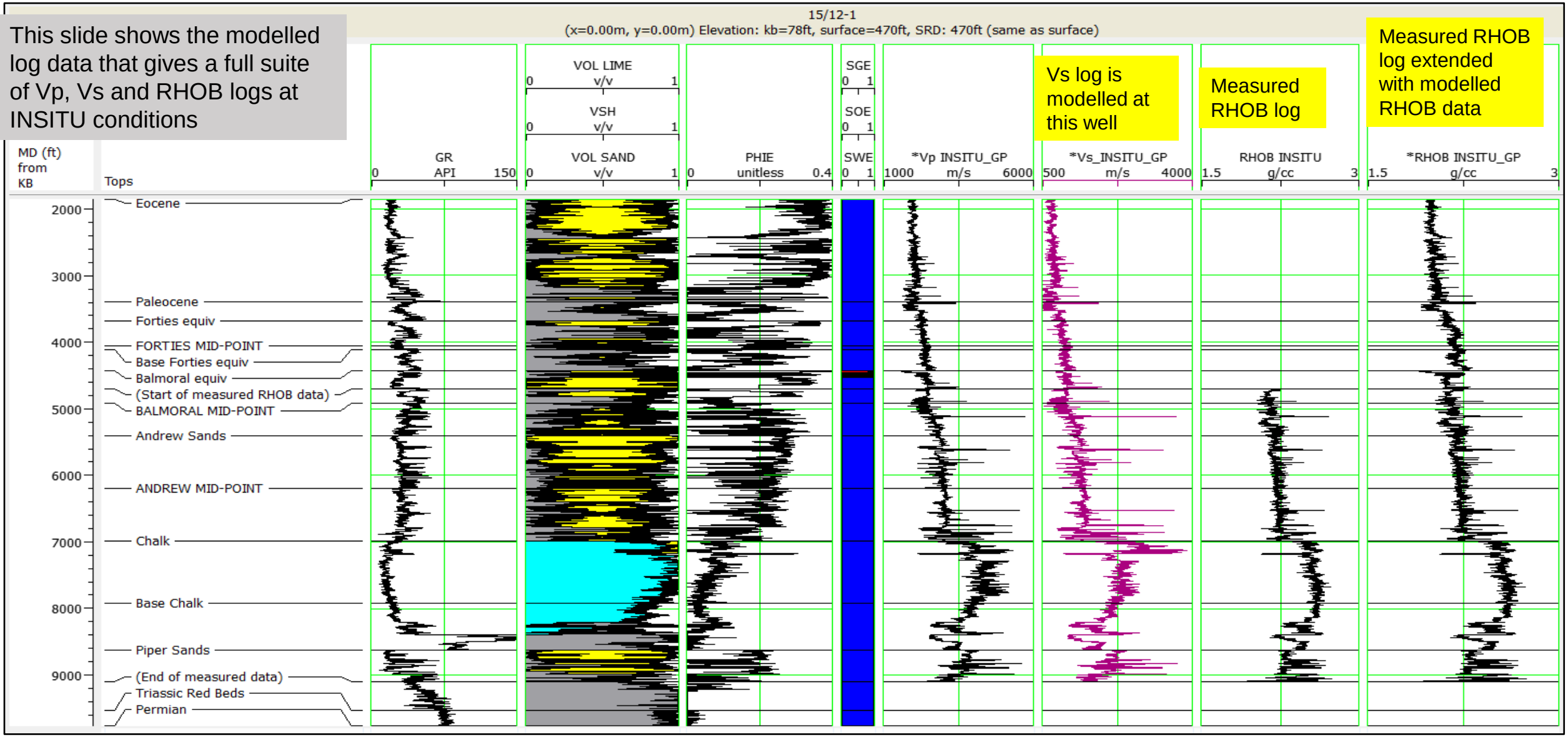
This slide shows the modelled log data that gives a full suite of Vp, Vs and RHOB logs at INSITU conditions



Vs log is modelled at this well

Measured RHOB log

Measured RHOB log extended with modelled RHOB data

Well 15/18B-11 – Fluid substitution results

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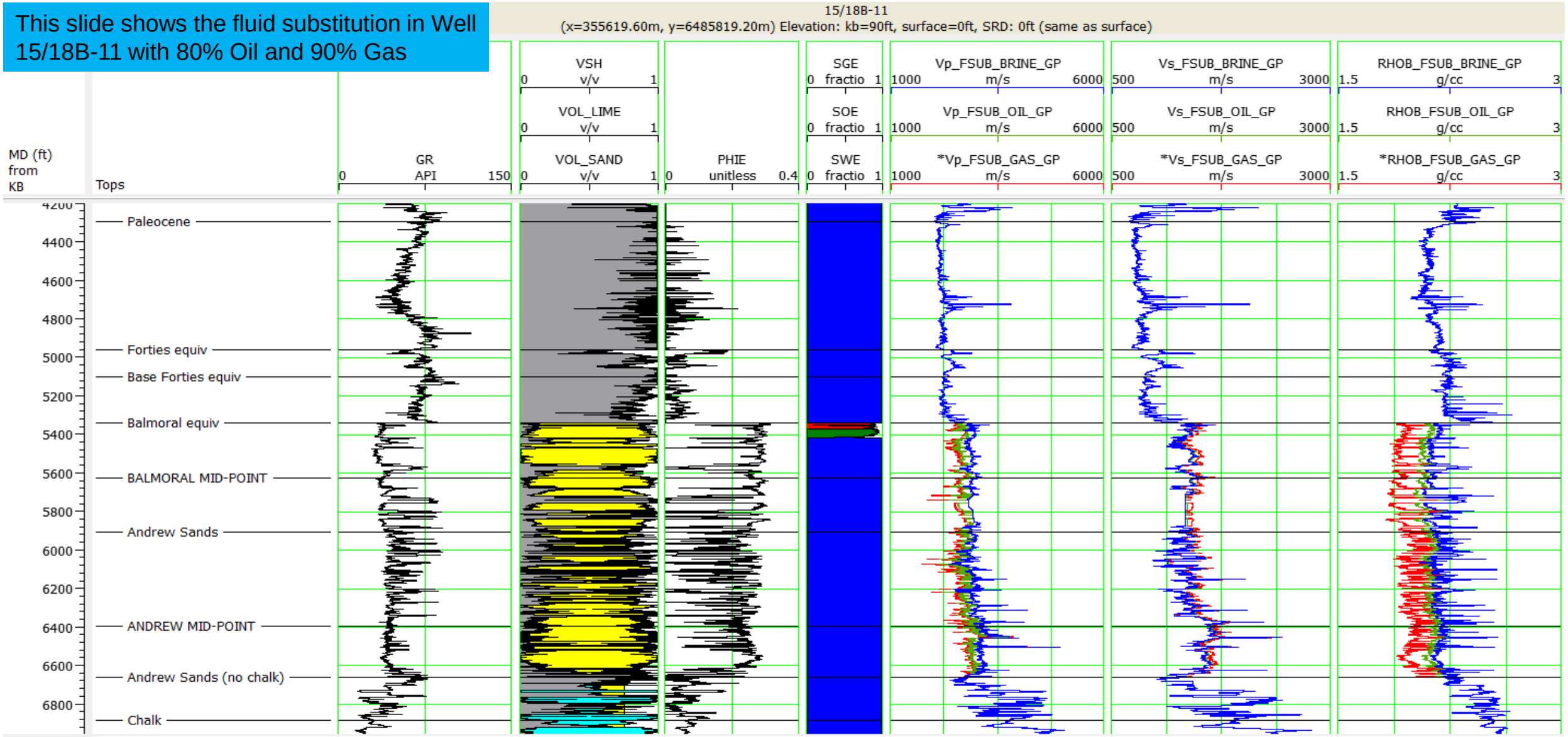
This slide shows the fluid substitution in Well 15/18B-11 with 80% Oil and 90% Gas



Well 15/18A-12 – Fluid substitution results

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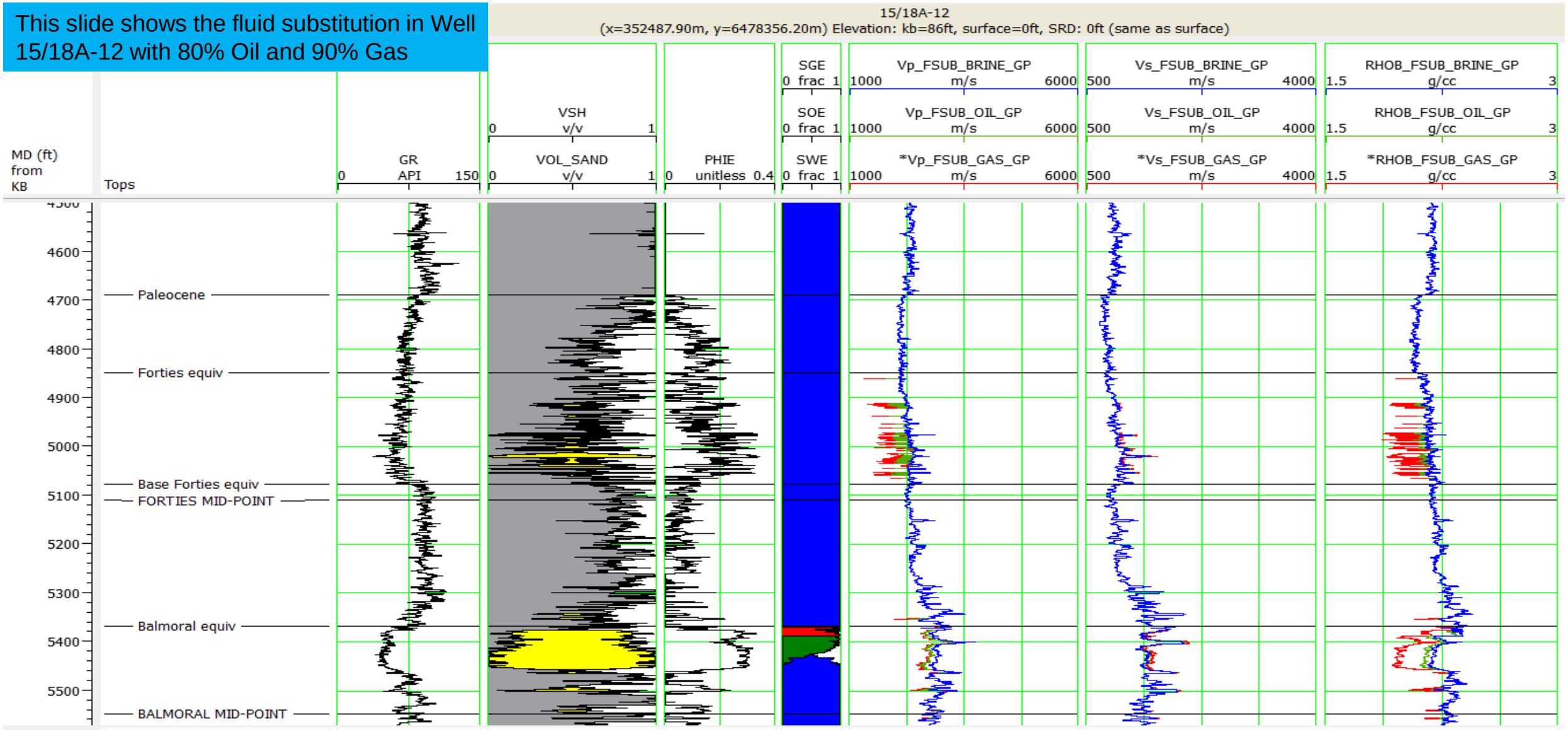
This slide shows the fluid substitution in Well 15/18A-12 with 80% Oil and 90% Gas



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Elastic Properties

Selected slides are shown from the full study

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Well 15/18B-11 – Elastic logs

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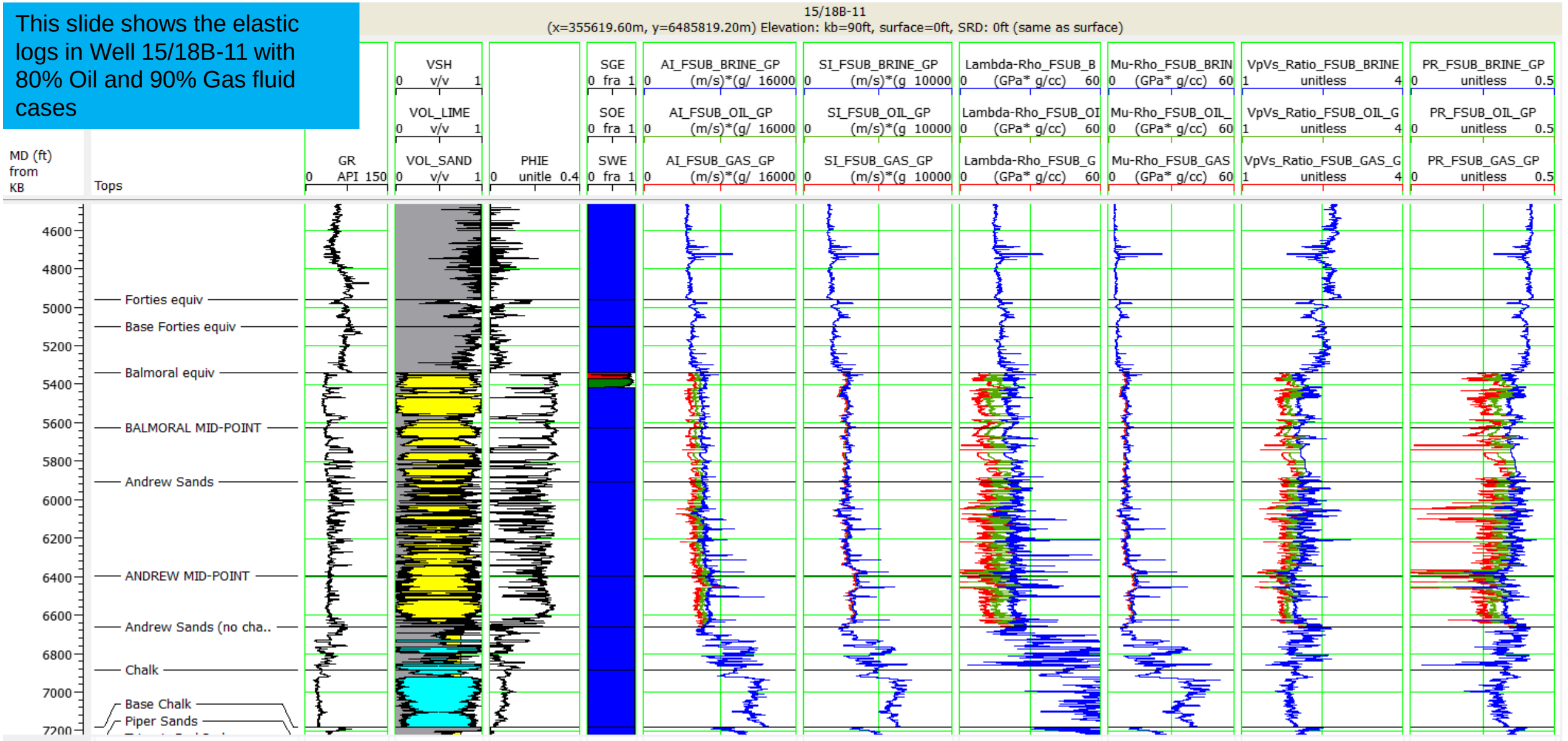
This slide shows the elastic logs in Well 15/18B-11 with 80% Oil and 90% Gas fluid cases



Well 15/12-1 – Elastic logs

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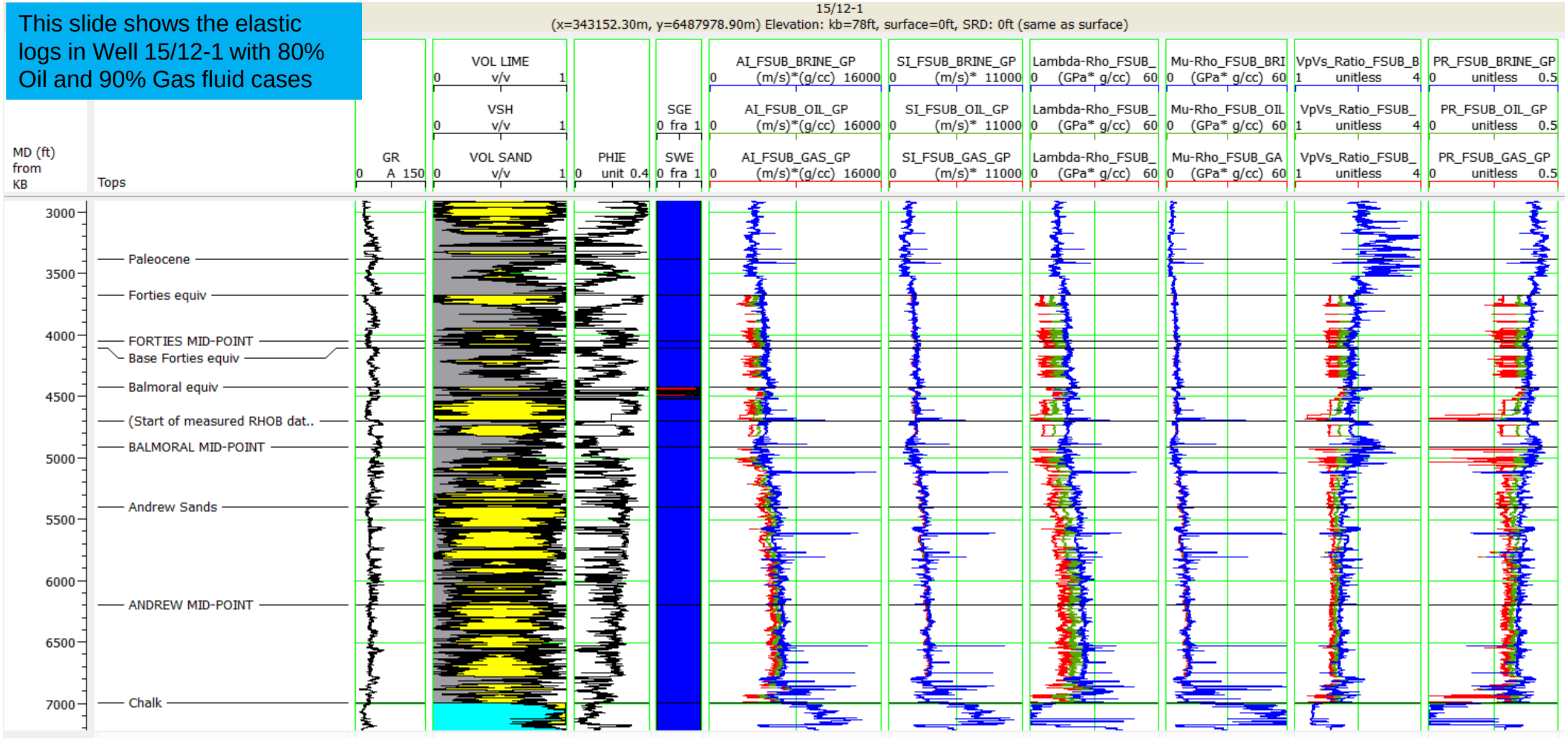
This slide shows the elastic logs in Well 15/12-1 with 80% Oil and 90% Gas fluid cases



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Blocky AVO models
Selected slides from Well 15/18B-11

- *Quad 15 Pilot Study*

Clean Sand reservoir data

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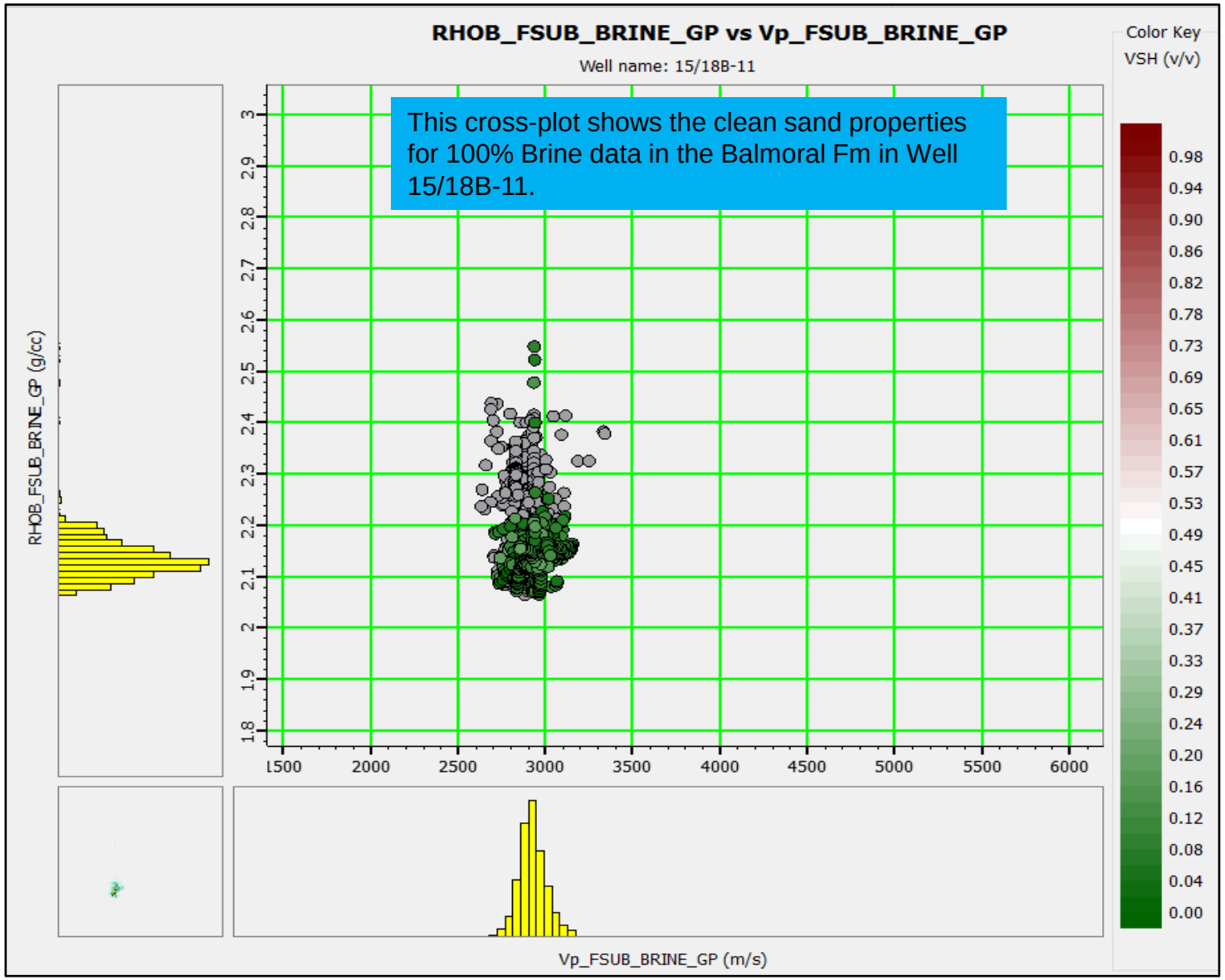
Gassmann Fluid Substitution is now complete to the hydrocarbon cases of 80% Oil and 90% Gas.

Vp-Vs and Vp-Rho cross-plots are created at each reservoir interval and a cut-off of Vol_Sand > 0.8 is applied to the data to isolate the clean sand properties.

The average Vp, Vs and RHOB values are taken for the clean sand points and will be used to in forthcoming Blocky AVO modelling to compare with the previously derived clean shale points at each reservoir interval.



Clean sand – Average values (Well 15/18B-11)

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The tables below show the Vp, Vs and RHOB average values in each reservoir interval.

Reservoir	Fluid case	Vp (m/s)	Vs (m/s)	RHOB (g/cc)
Balmoral	100% Brine	2,919	1,374	2.14
Balmoral	80% Oil	2,697	1,392	2.08
Balmoral	90% Gas	2,633	1,451	1.92
Reservoir	**Fluid case**	**Vp (m/s)**	**Vs (m/s)**	**RHOB (g/cc)**
Andrew	100% Brine	3,125	1,523	2.20
Andrew	80% Oil	2,920	1,540	2.15
Andrew	90% Gas	2,858	1,590	2.02

Blocky AVO – Well 15/18B-11

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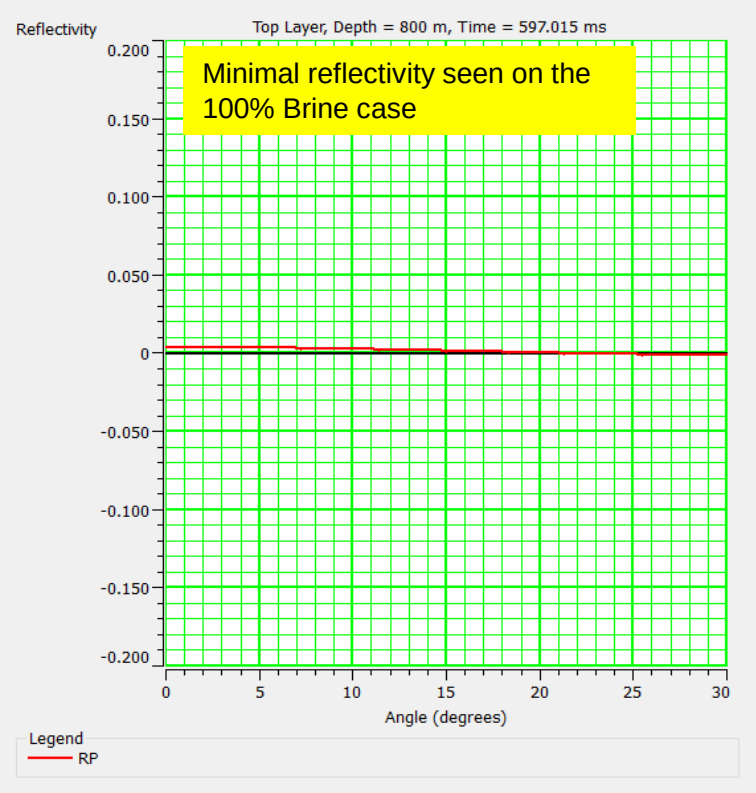
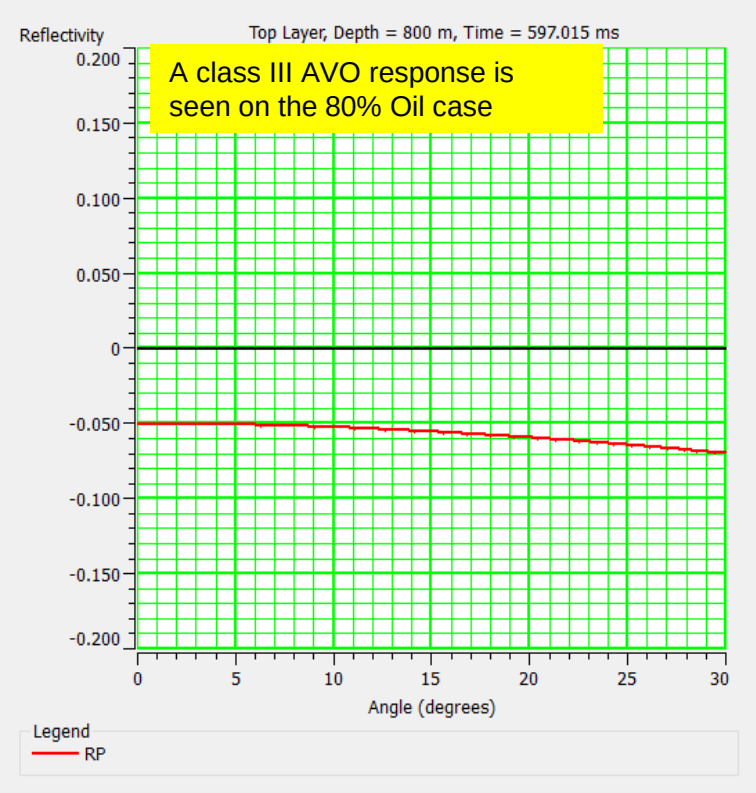
Blocky AVO models are displayed below for the Balmoral Fm reservoir interval.

Overburden	Shale
Reservoir	100% Brine sand



Overburden	Shale
Reservoir	80% Oil sand



Overburden	Shale
Reservoir	90% Gas sand

Blocky AVO – Well 15/18B-11

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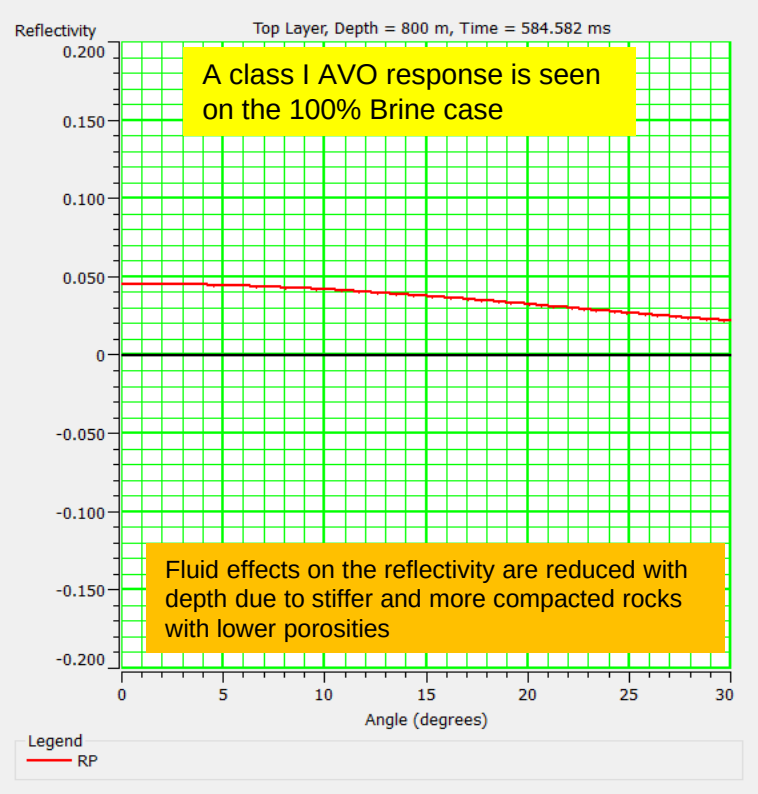
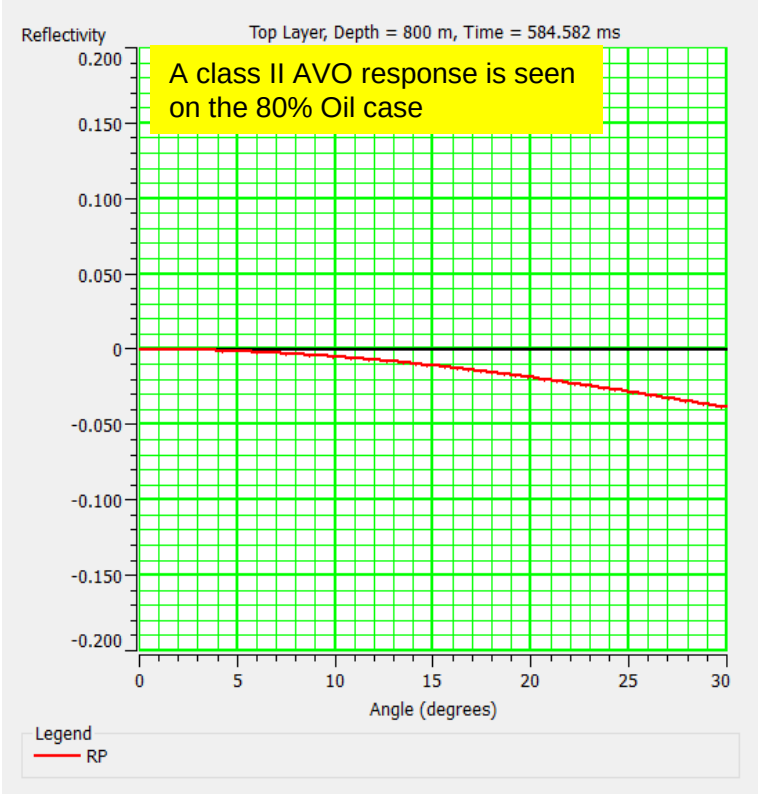
Blocky AVO models are displayed below for the Andrew Fm reservoir interval.

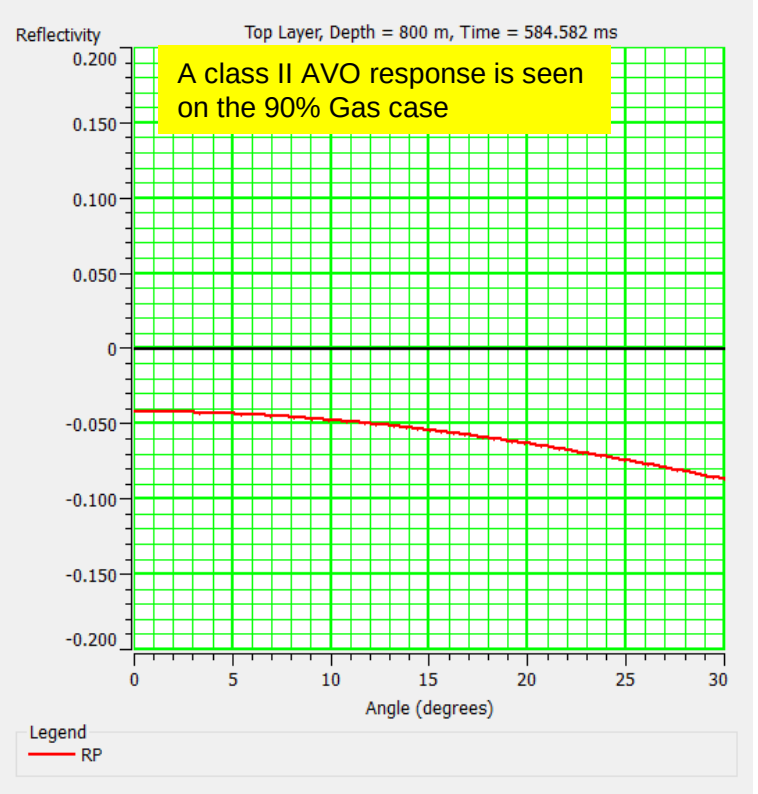
Overburden	Shale
Reservoir	100% Brine sand



Overburden	Shale
Reservoir	80% Oil sand



Overburden	Shale
Reservoir	90% Gas sand



BQI FUM Innovation

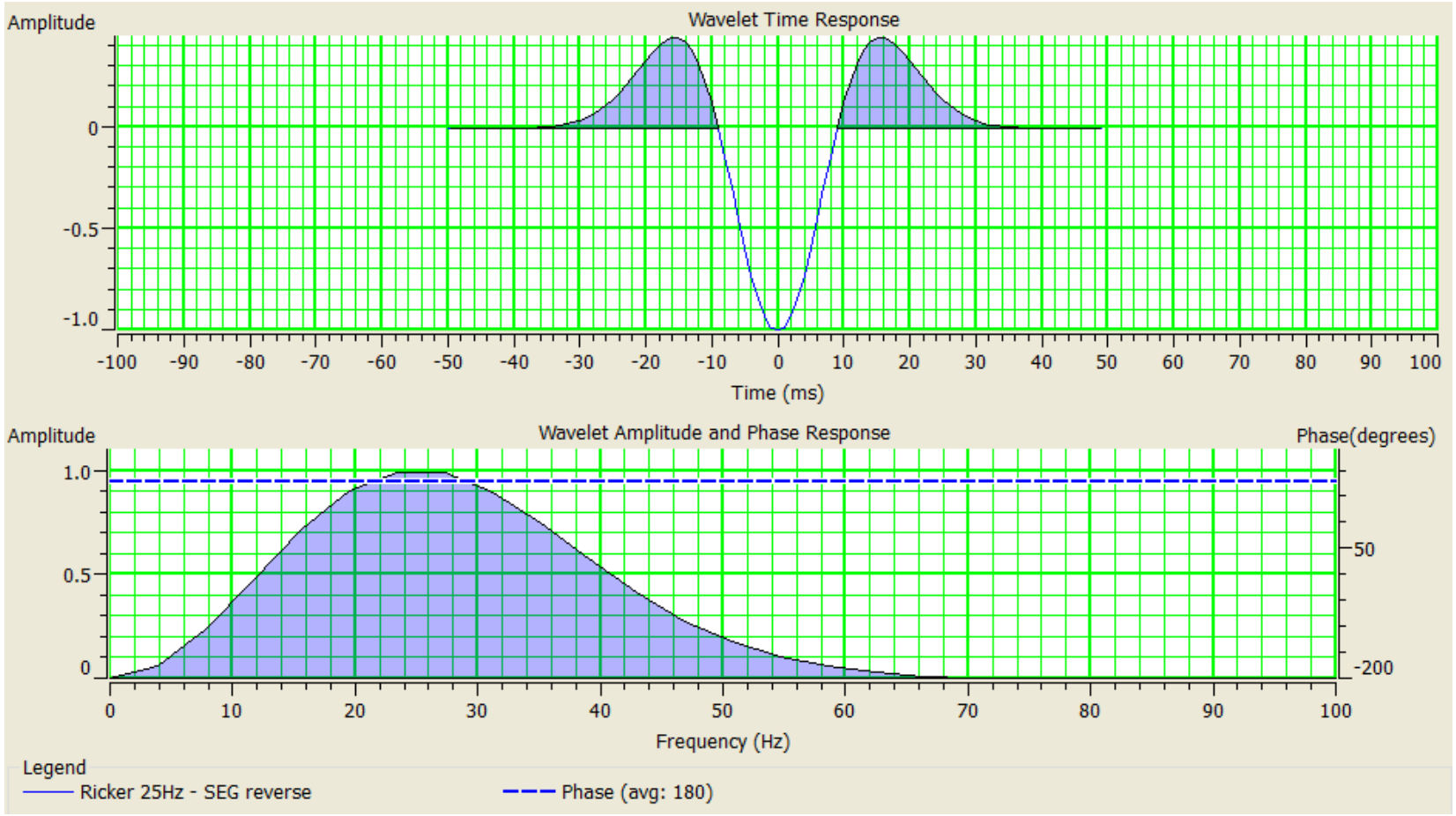
Synthetic Gathers
Selected slides from Well 15/18B-11

- *Quad 15 Pilot Study*

Synthetic gathers

BQI FUM Innovation

A 25Hz Ricker wavelet at SEG reverse polarity (shown below) will be used to model the Synthetic Gathers at each well.

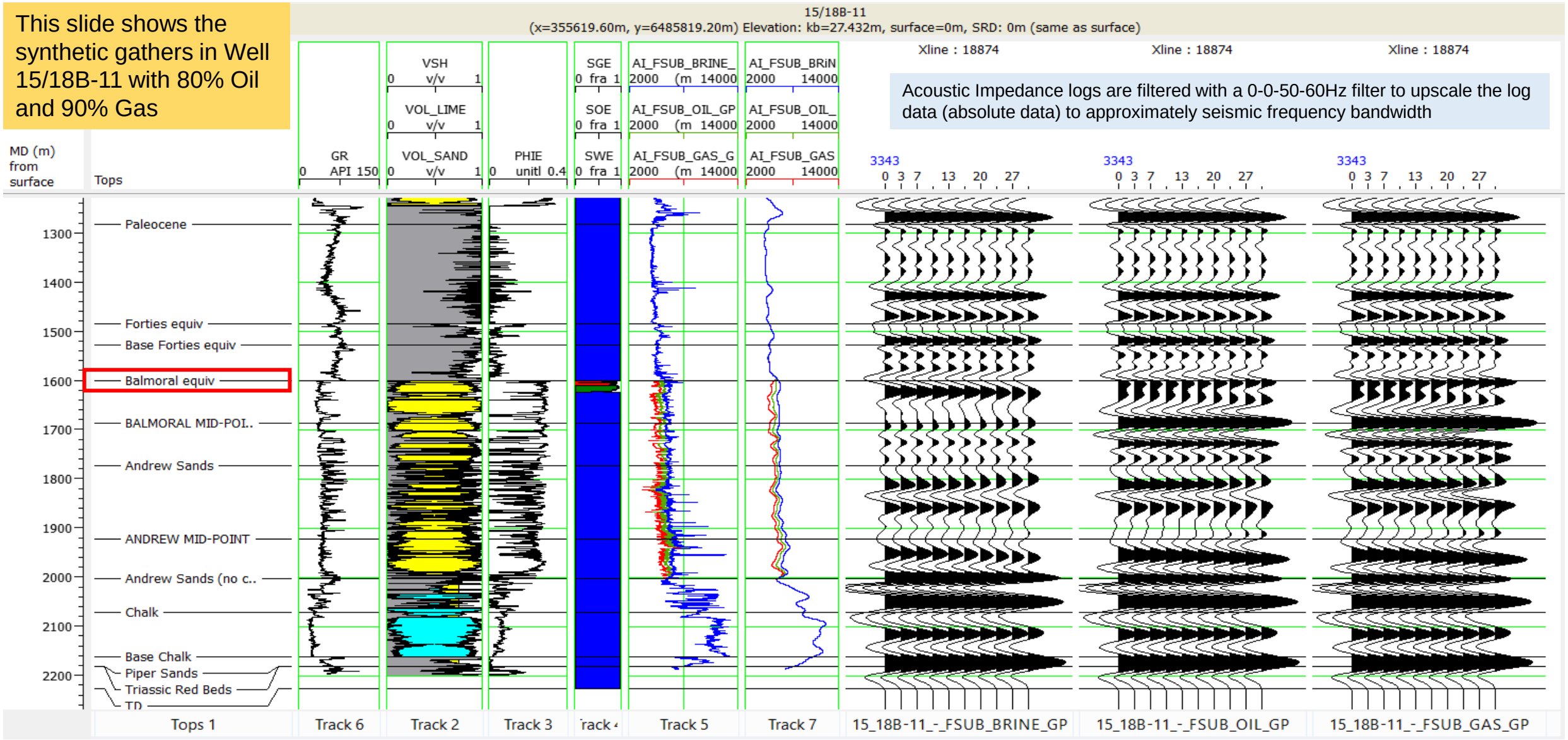


SEG reverse polarity means that an increase in Acoustic Impedance will result in a trough and a decrease in Acoustic Impedance will result in a peak.

Well 15/18B-11 – Synthetic gathers

BQI FUM Innovation

This slide shows the synthetic gathers in Well 15/18B-11 with 80% Oil and 90% Gas



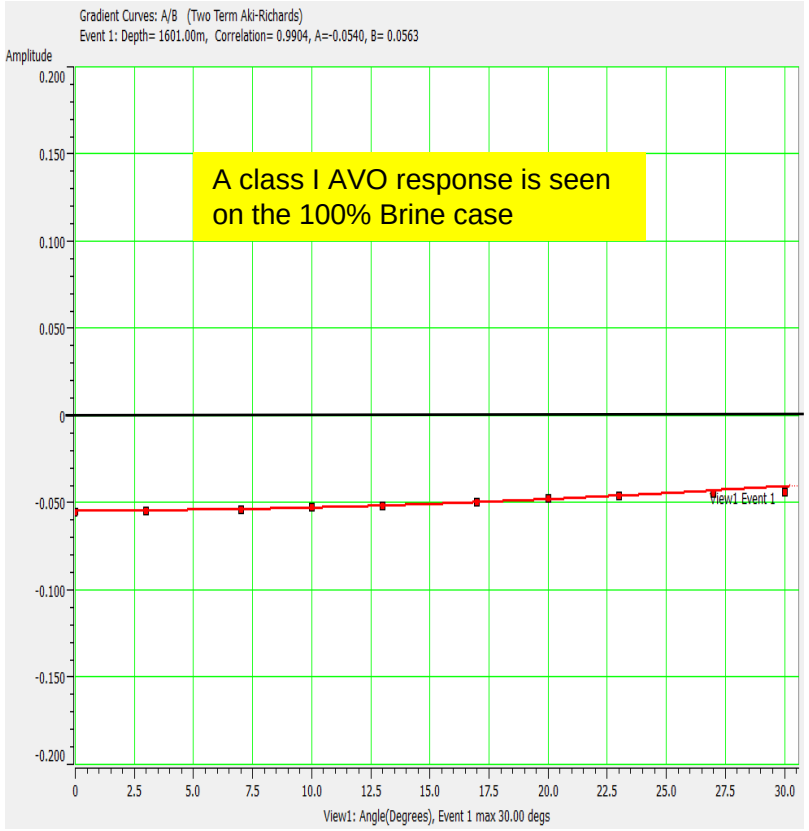
Well 15/18B-11 – AVO gradients

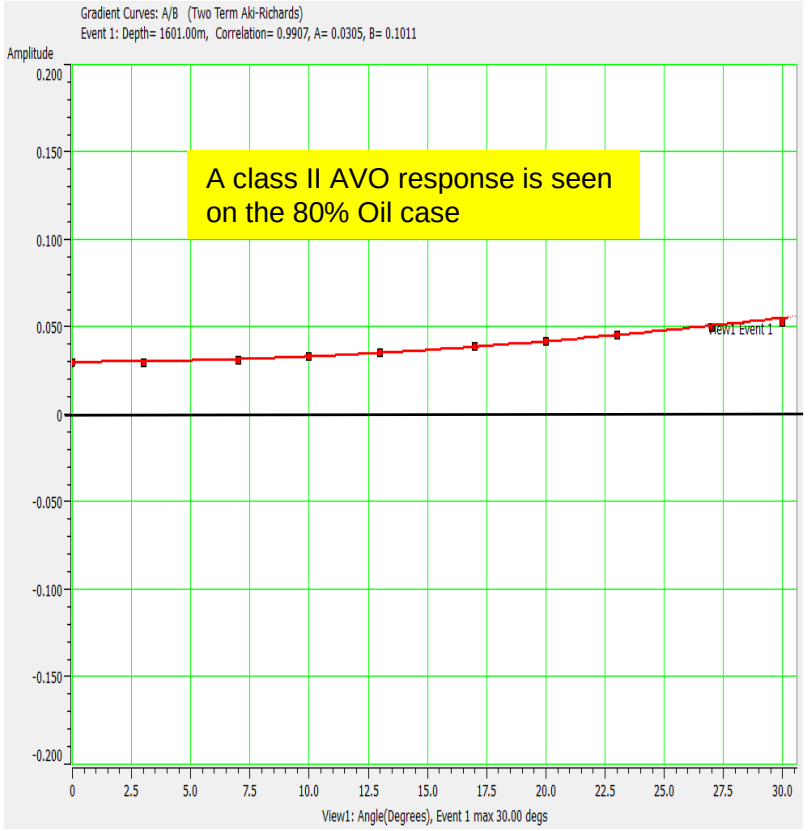
BQI FUM Innovation

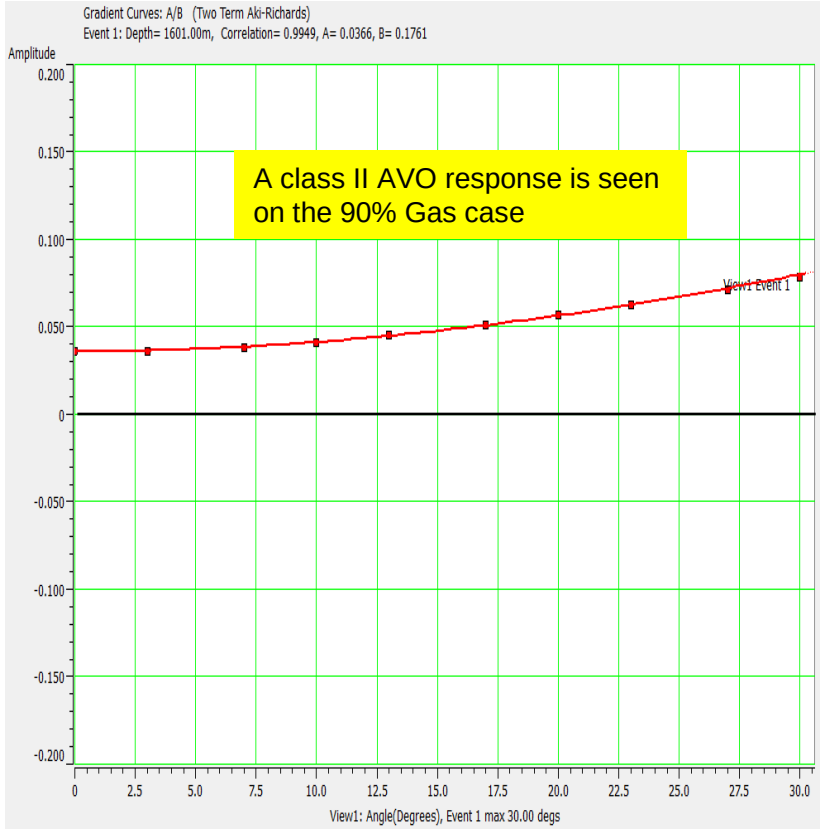
This image shows the AVO gradient at the top reservoir for the Balmoral Fm (1601m MD from surface) with 100% Brine saturation.

This image shows the AVO gradient at the top reservoir for the Balmoral Fm (1601m MD from surface) with 80% Oil saturation.

This image shows the AVO gradient at the top reservoir for the Balmoral Fm (1601m MD from surface) with 90% Gas saturation.







The hydrocarbon fluid cases change the top reservoir reflectivity for the Balmoral Fm at this well. The overburden shale is within the Forties Fm in this instance.

BQI FUM Innovation

Inversion Feasibility

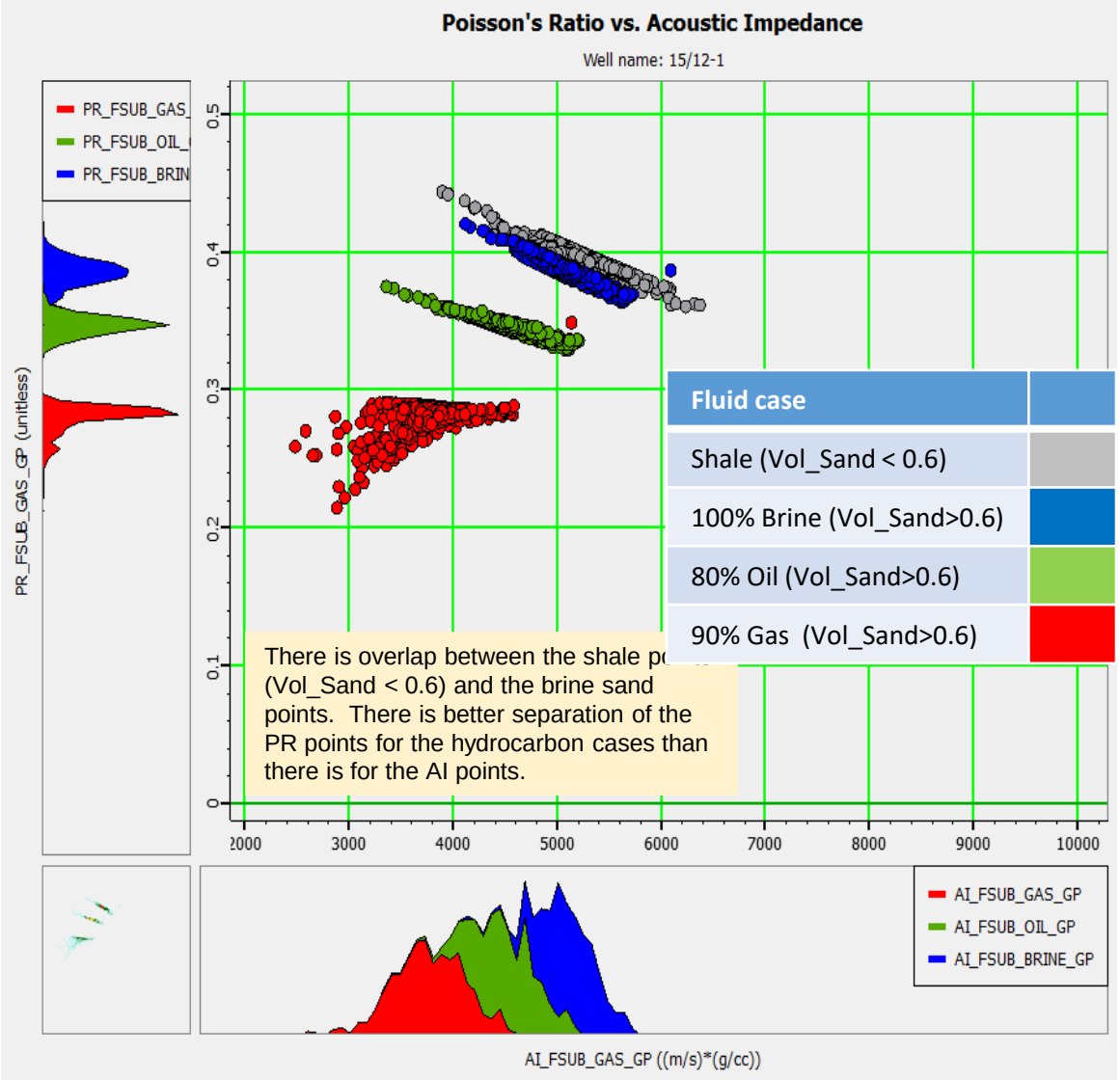
Selected slides are shown from the full study

- *Quad 15 Pilot Study*

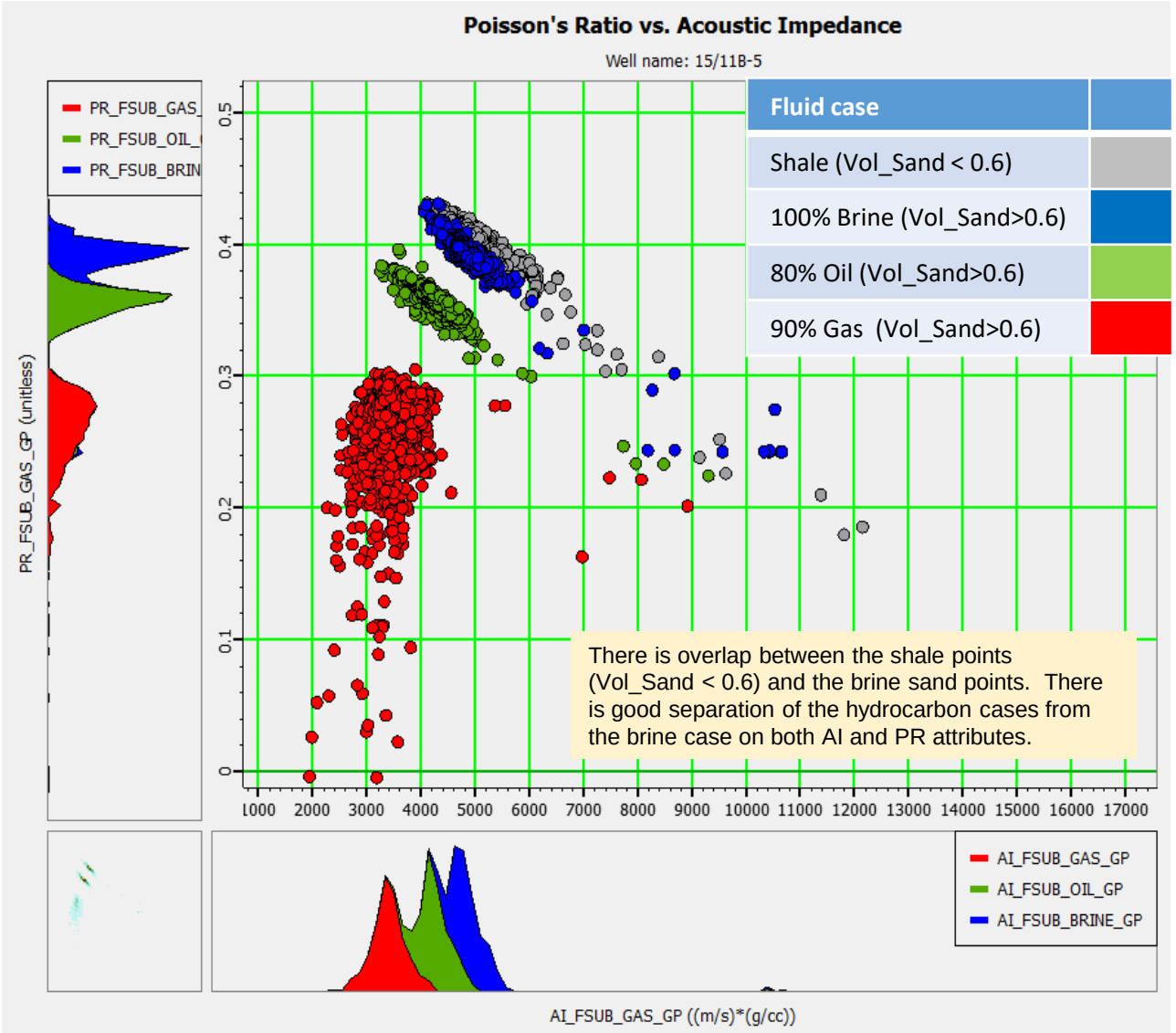
Forties Interval (AI - PR)

BQI FUM Innovation

AI – PR cross-plot – Well 15/12-1 (Modelled Vs data)



AI – PR cross-plot – Well 15/11B-5 (Modelled Vs data)

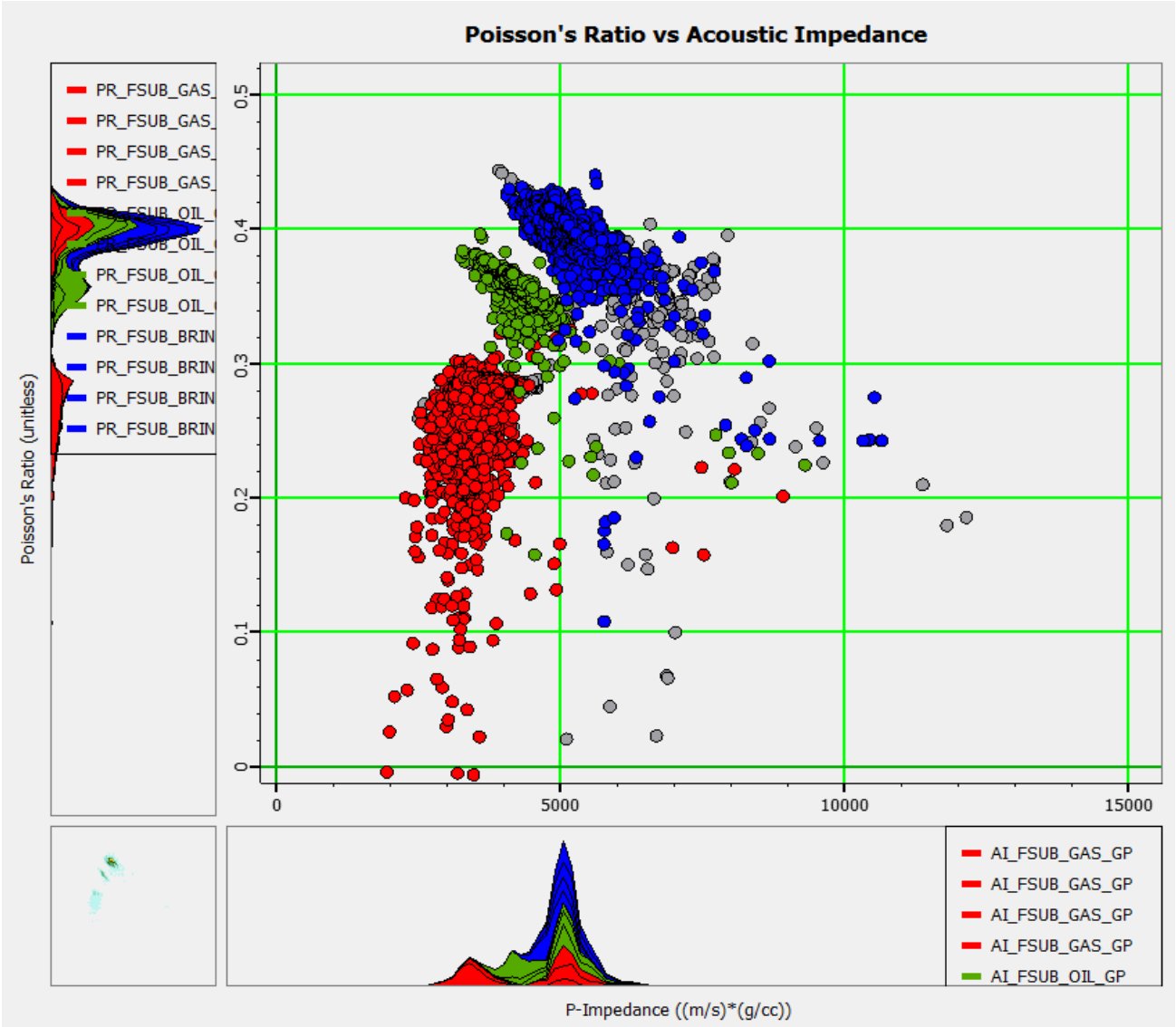


Forties Interval (AI - PR)

BQI FUM Innovation

AI – PR cross-plot – All wells – apart from Well 15/18B-11

Fluid case	
Shale (Vol_Sand < 0.6)	
100% Brine (Vol_Sand>0.6)	
80% Oil (Vol_Sand>0.6)	
90% Gas (Vol_Sand>0.6)	

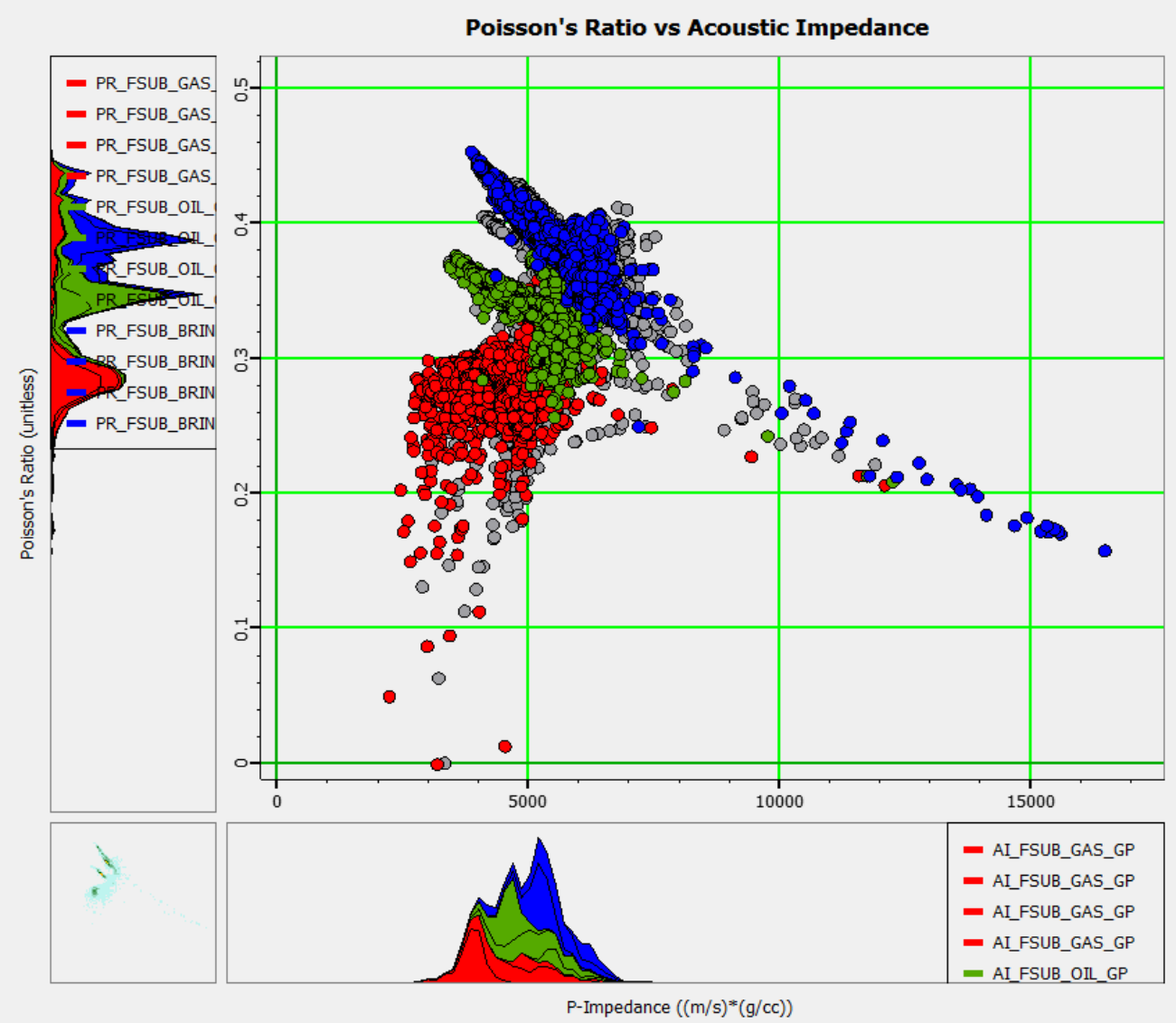


Balmoral Interval (AI - PR)

BQI FUM Innovation

AI – PR cross-plot – All wells

Fluid case	
Shale (Vol_Sand < 0.6)	
100% Brine (Vol_Sand>0.6)	
80% Oil (Vol_Sand>0.6)	
90% Gas (Vol_Sand>0.6)	



The rocks gradually get more rigid with depth and the fluid effects reduce as a result.

Project Summary

BQI FUM Innovation

- A Rock Physics study was carried out on four wells in the Balmoral Field Central North Sea.
- Initial set up work in Single Well Rock Physics - Part 1 involved data loading, a visual overview at each well, QC cross-plots of Vp-Vs and Vp-Rho log data, log edits of erroneous log data, deriving fluid properties, deriving elastic properties (bulk modulus, shear modulus) for clean shale points and Gassmann fluid substitution to ensure that all log data was at 100% Brine conditions.
- Trend analysis in Multi-well analysis involved cross-plots of Vp-Vs and Vp-Rho log data and local variations of the Greenberg-Castagna and Gardner law's were calibrated to match measured well log data at 100% Brine conditions.
- The main section of the Rock Physics work in Single Well Rock Physics - Part 2 involved modelling missing sections of log data with derived trends from the Multi-well analysis, carrying out Gassmann fluid substitution to ensure that all remaining log data was at 100% Brine conditions and carrying out Gassmann fluid substitution to model the log response to 80% Oil and 90% Gas conditions. Elastic logs were then generated to observe the elastic response at each fluid case as an overview at each well, simple Blocky AVO models were constructed using average properties of clean sand points and a further set of AI-PR and LR-MR cross-plots were generated to guide the Inversion stage of the project