Reducing Risk and Adding Value to Infill Wells Using 4D Seismic – Experience from Golden Eagle

A Presentation to the Seismic 2025 Conference

Andrew J. S. Wilson

Acknowledgements

- Golden Eagle coventurer group
  - CNOOC International
  - EnQuest
  - NEO Energy
  - ONE-Dyas
- Many colleagues at CNOOC International and in the GEAD coventurer group
- Many helpful contacts in the wider 4D seismic community and in particular from the Edinburgh Time Lapse Project at Heriot Watt University
- Many seismic acquisition and processing teams

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Outline

Part One:

- Introduction to Golden Eagle

Part Two:

- Interpreting simple 4D seismic responses to simple production mechanisms

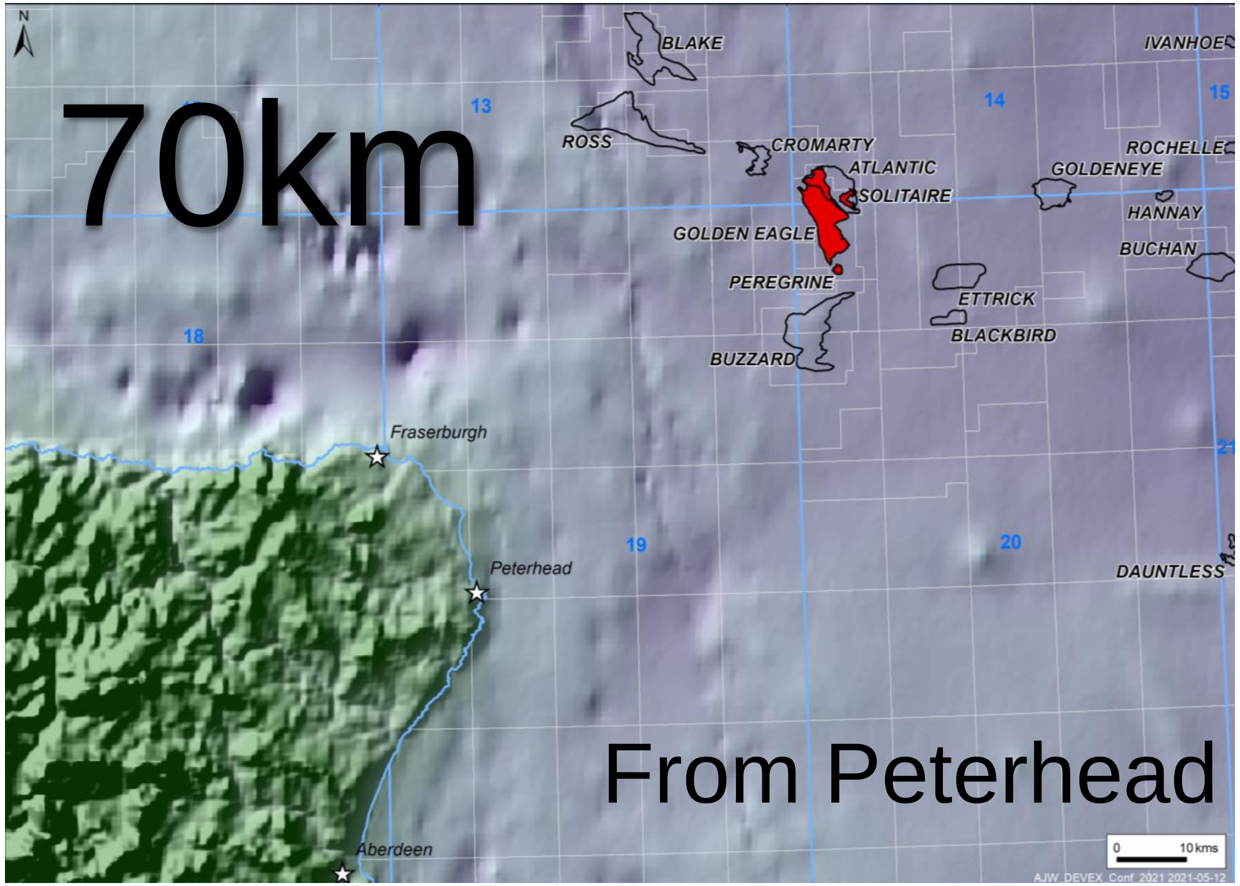
Part Three:

- Simple strategies for interpreting 4D seismic responses to pressure and saturation changes

Summary, Conclusions, Discussion

- 4D seismic does not lie, but it can keep secrets

First Phase of Golden Eagle Area Development (GEAD)



3 fields

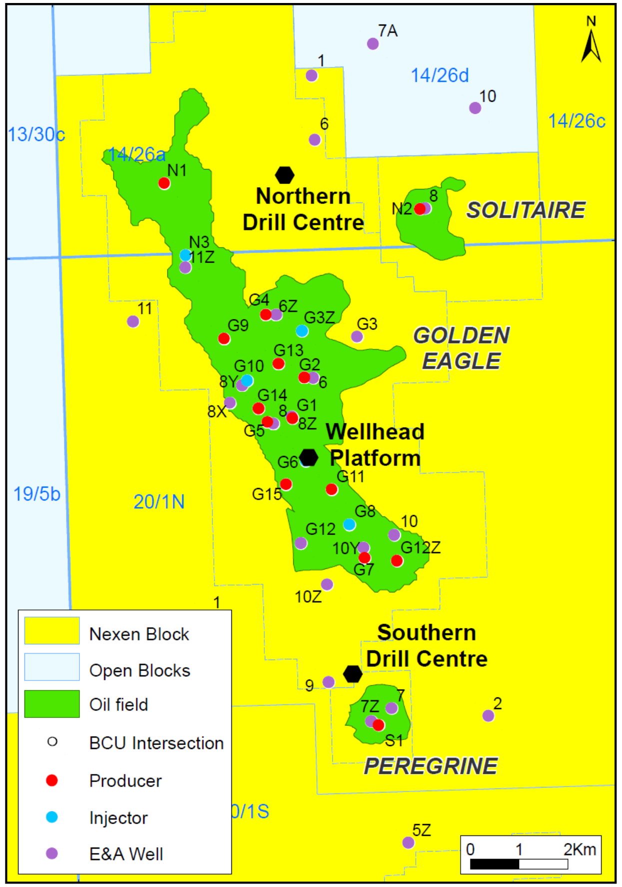
Golden Eagle

Solitaire

Peregrine

2

Reservoirs



100m

Water depth

After first phase of development drilling

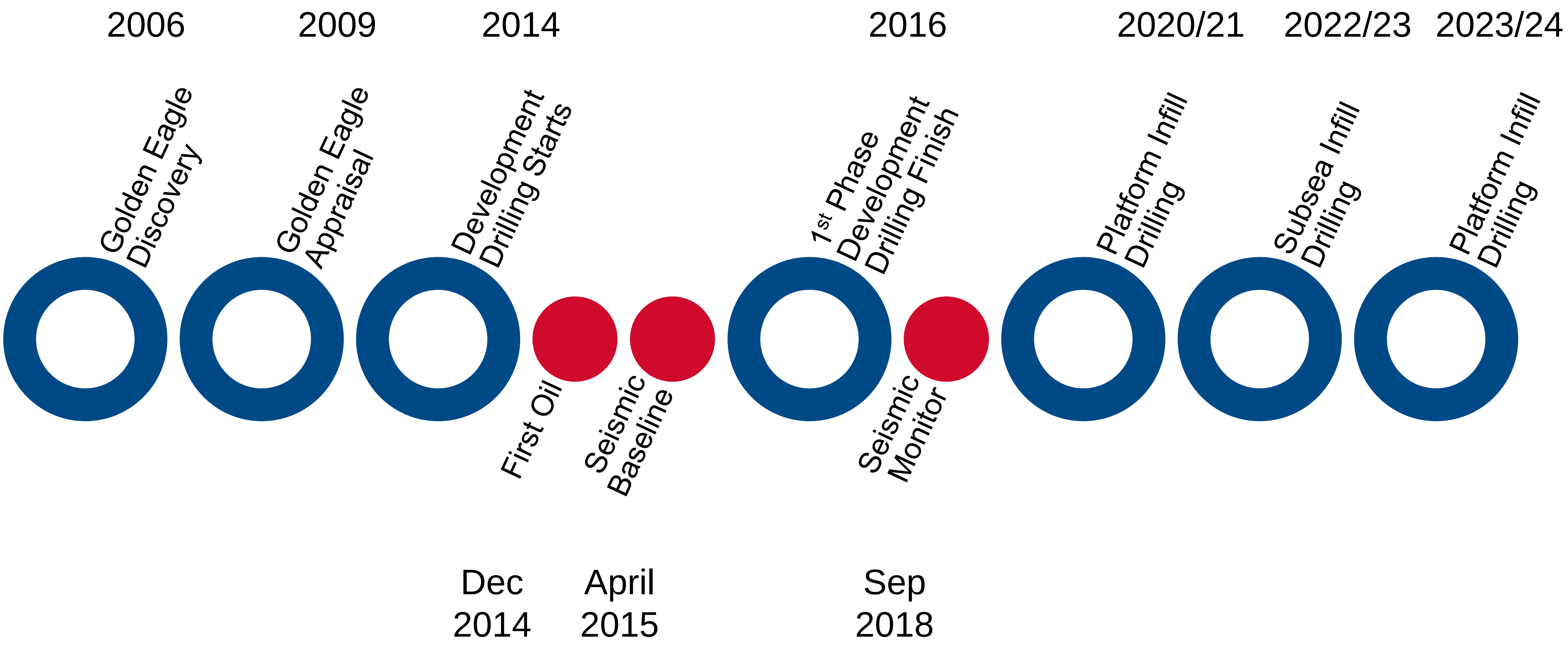
14 Producers, 5 Injectors

Intelligent well technology

7000ft

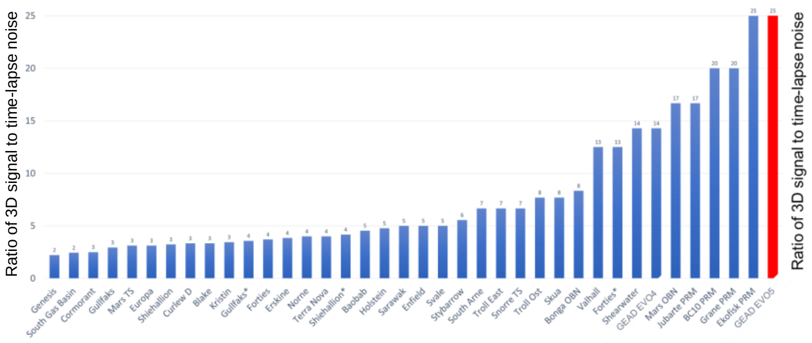
Average reservoir depth

Golden Eagle: Timeline of Surveys and Infills



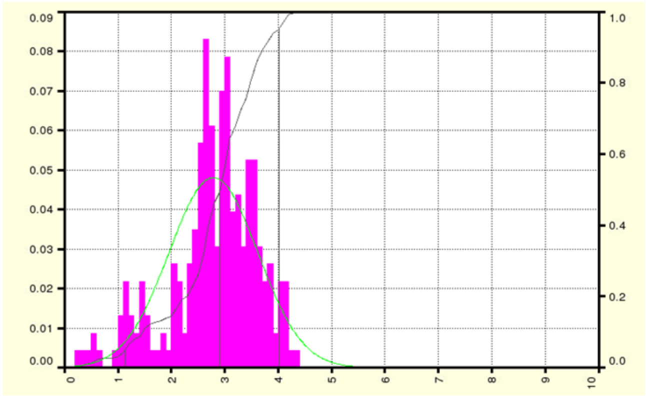
Three Things About Golden Eagle

Exceptional 4D Quality



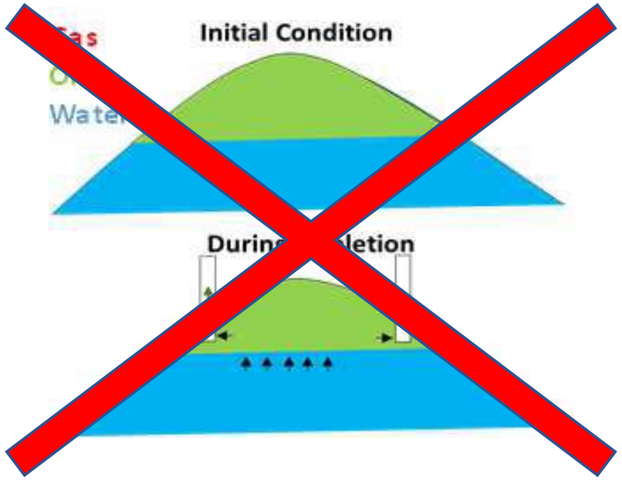
- Golden Eagle was one of the first of a new breed of 4D which use high-density retrievable OBN to achieve excellent 4DNRMS
- Since 2020 other 4D projects have joined "the 5% club"

Exceptional 4D Challenge



- Porosity is modest, contrasts are small, 3D and 4D signatures are very subtle
- ΔAI circa 3% in best sands
- Differential sweep and depletion in stacked reservoirs layers below seismic resolution

NOT Simple Bottom-Up Sweep



- Golden Eagle has two reservoirs sands, the Lower Cretaceous Punt and the Upper Jurassic Burns
- In both of these we now recognise some degree of lateral sweep, with some units being dominated by edge-drive sweep

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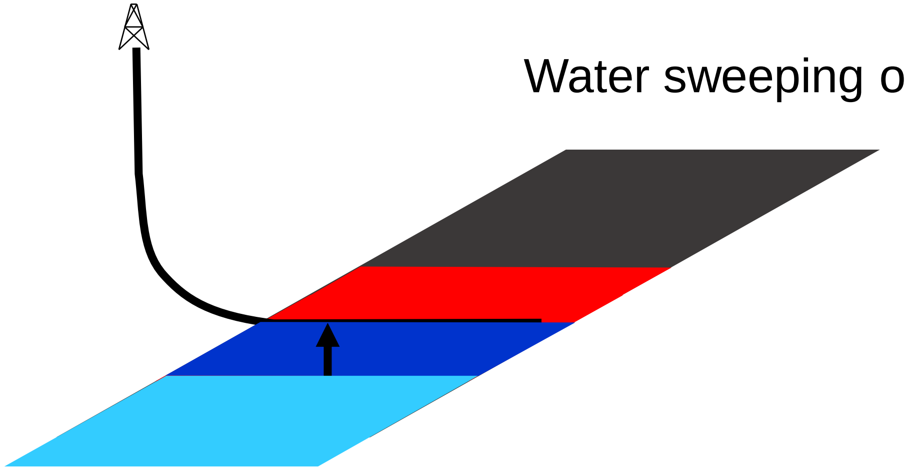
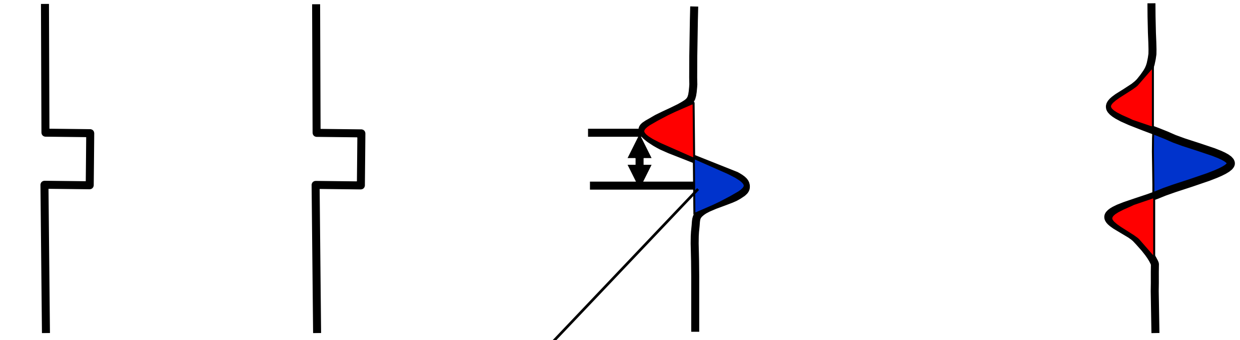
4D Seismic Signature of Simple Bottom-Up Water Sweep

In an oil field under water flood with a simple bottom-up pattern of water-sweeping-oil the 4D seismic signature will show on quadrature of 4D seismic difference as a strong central blue loop with smaller red sidelobes

Water sweeping oil



	change in water saturation	***change in impedance***	***change in seismic***	***aligns central blue loop with swept interval***
	ΔSw	ΔAI	Monitor - Base Wiggle Reflectivity	4D Quadrature



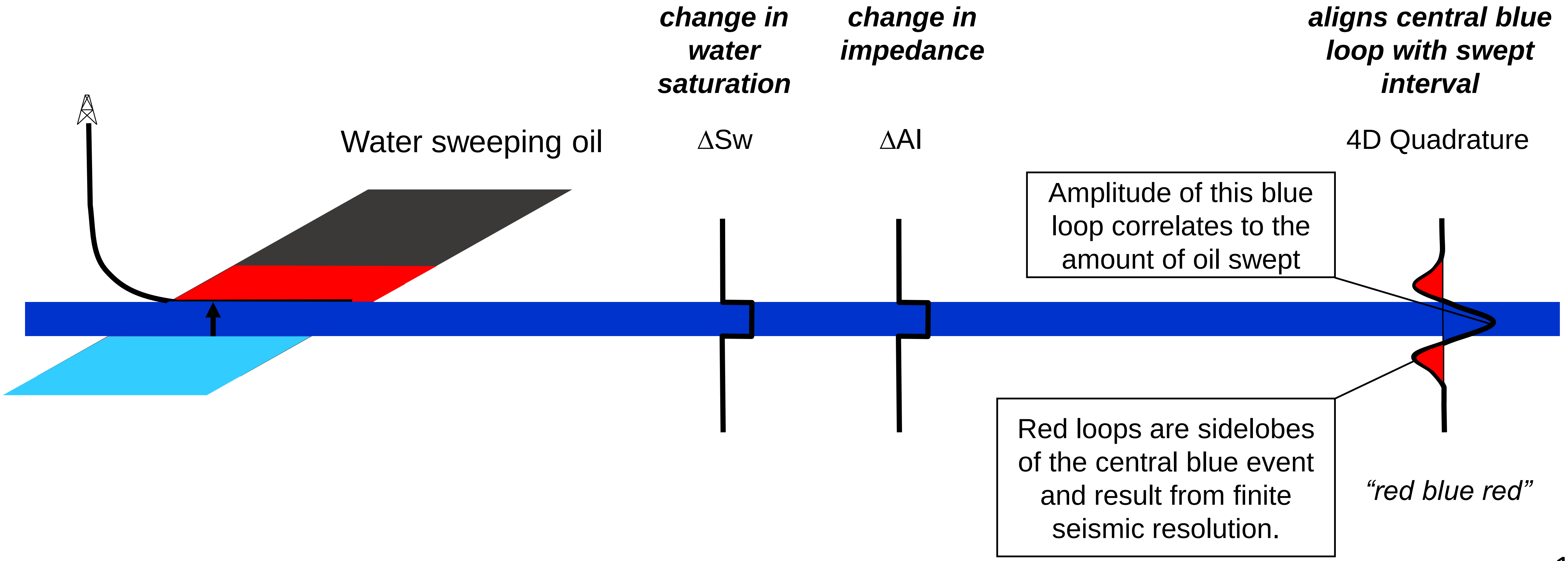
"red over blue"

"red blue red"

Golden Eagle is a low-relief field and Burns oil column is usually thin compared to vertical resolution of 4D seismic.

4D Seismic Signature of Simple Bottom-Up Water Sweep

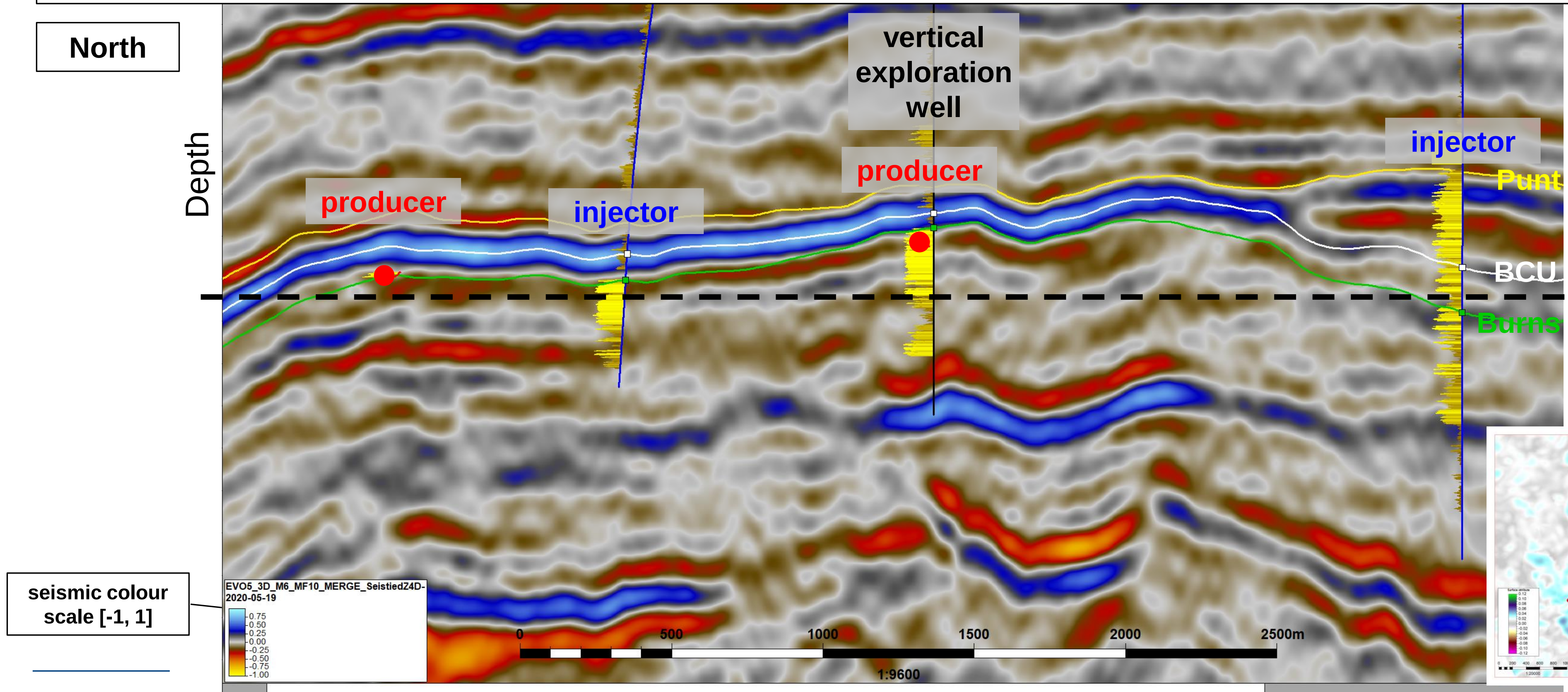
In an oil field under water flood with a simple bottom-up pattern of water-sweeping-oil the 4D seismic signature will show on quadrature of 4D seismic difference as a strong central blue loop with smaller red sidelobes

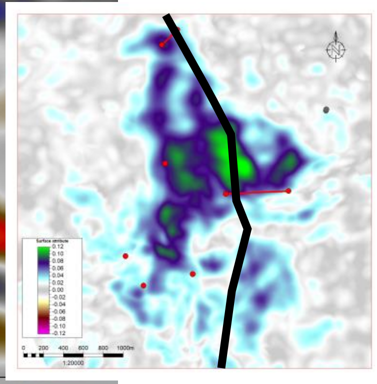


Golden Eagle 3D Seismic Image

Well logs are Vshale and show location of sands. Horizontal producers are oriented orthogonal to seismic section. The central producer is a twin of a vertical exploration well (shown in black). In order to make the best possible 3D seismic image this seismic image uses data from both the 2015 and 2018 OBN seismic acquisition.

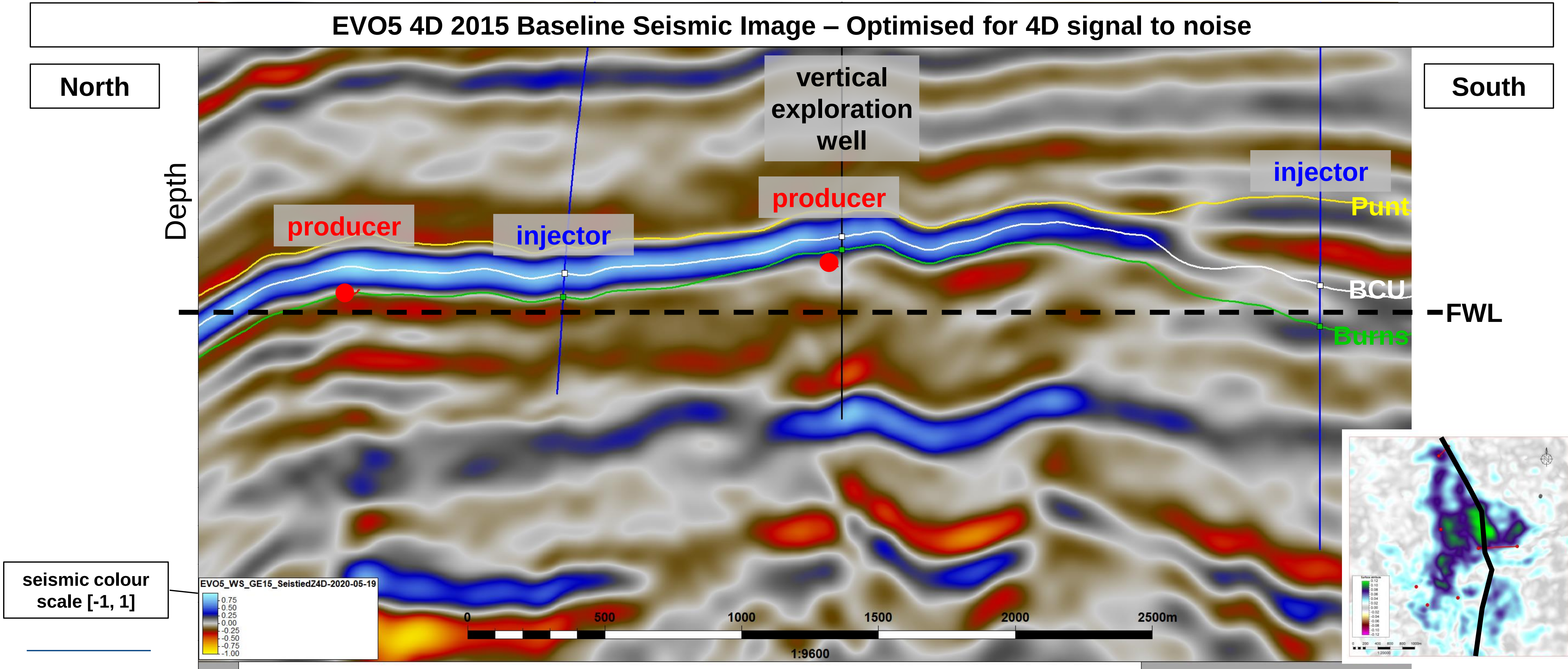
3D Seismic Image – Optimised for 3D character and vertical resolution





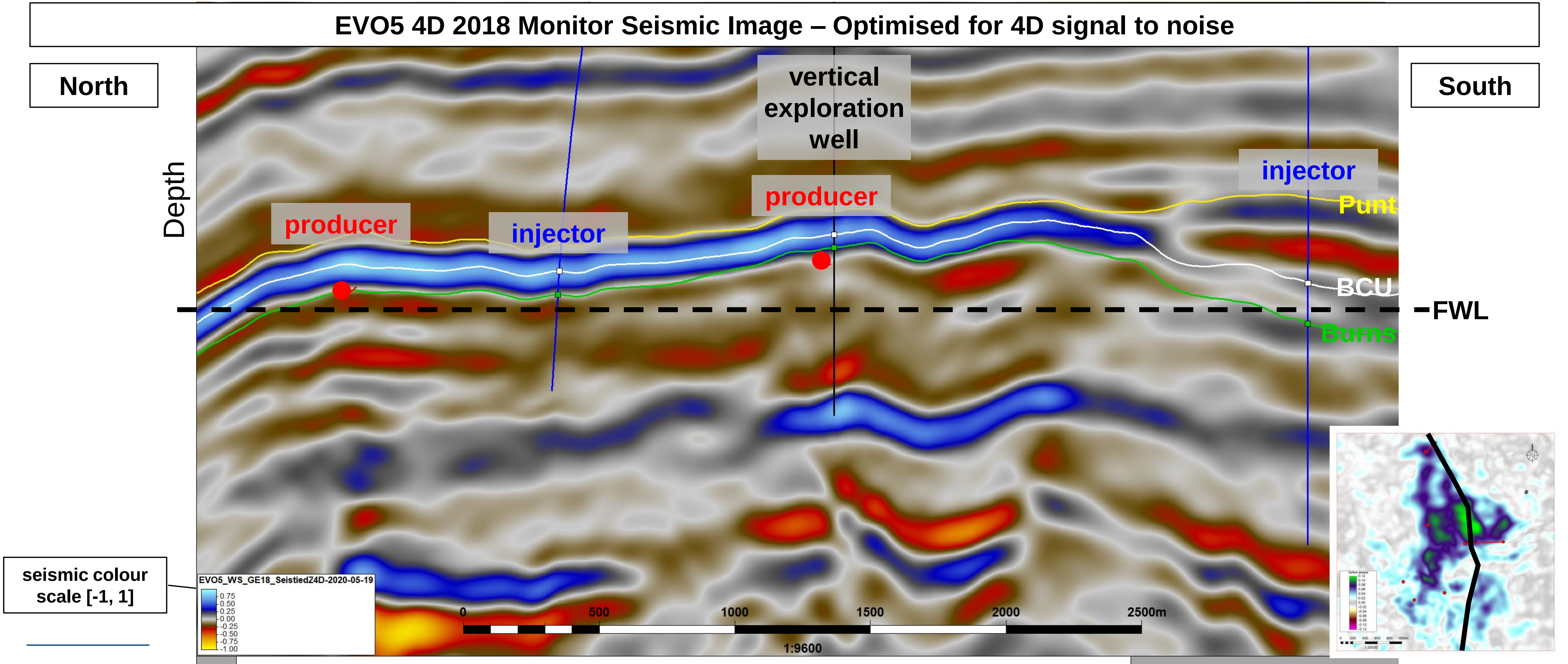
2015 Baseline Seismic Image From 4D Processing

This baseline seismic image is made with data from the 2015 baseline OBN seismic acquisition only.



2018 Monitor Seismic Image From 4D Processing

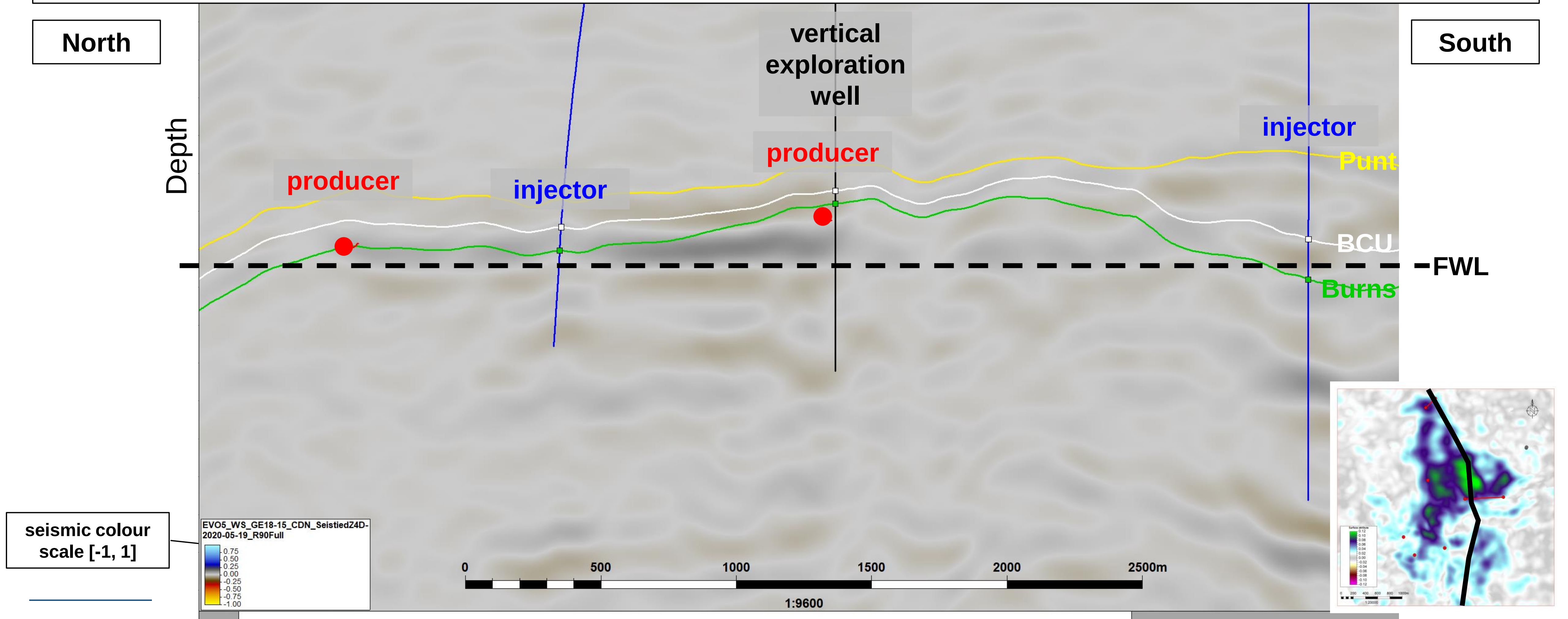
This monitor seismic image is made with data from the 2018 monitor OBN seismic acquisition only.



Amplitude of 4D Seismic Difference is Small Compared to 3D Seismic

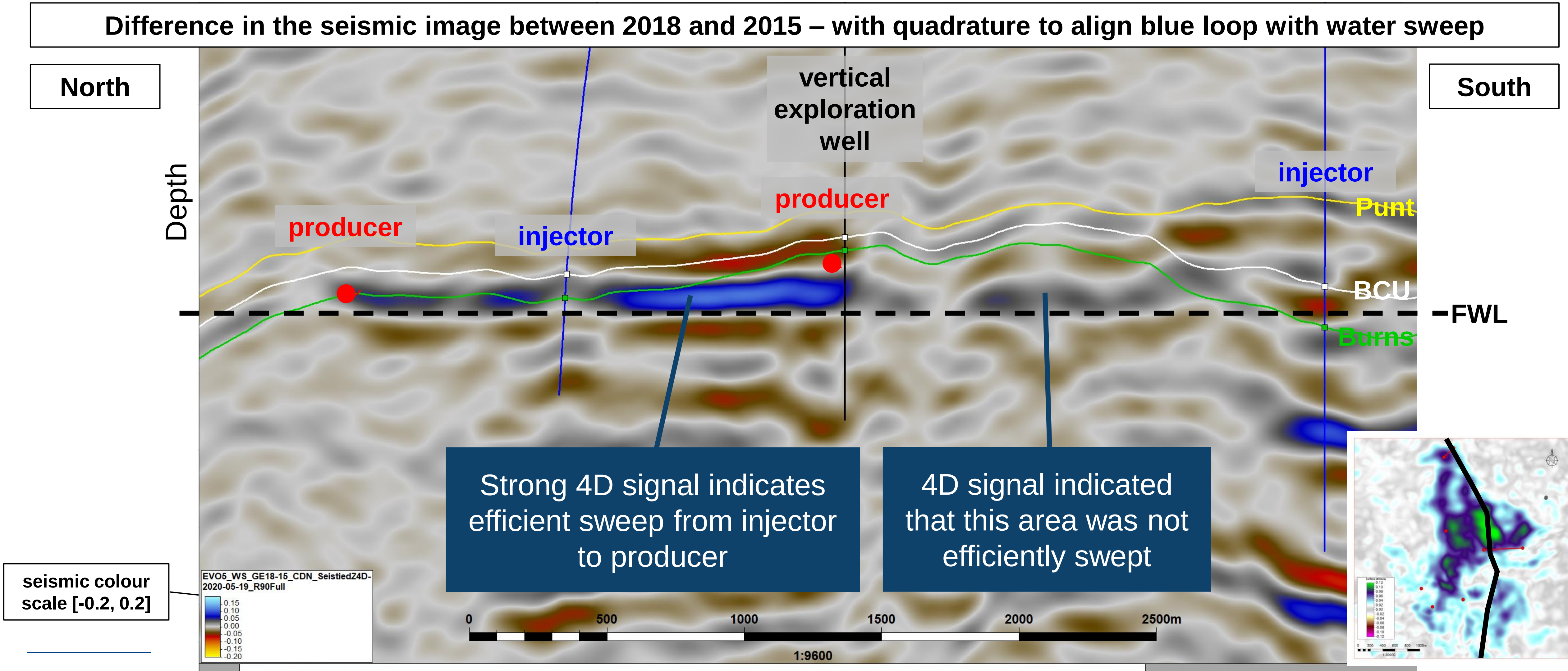
The difference between the 2018 and 2015 seismic image is small. If we display the difference using the same colour scale as the 3D seismic then the difference is very faint. On the next slide we will show the seismic difference on a brighter colour scale.

Difference in the seismic image between 2018 and 2015 – with quadrature to align blue loop with water sweep



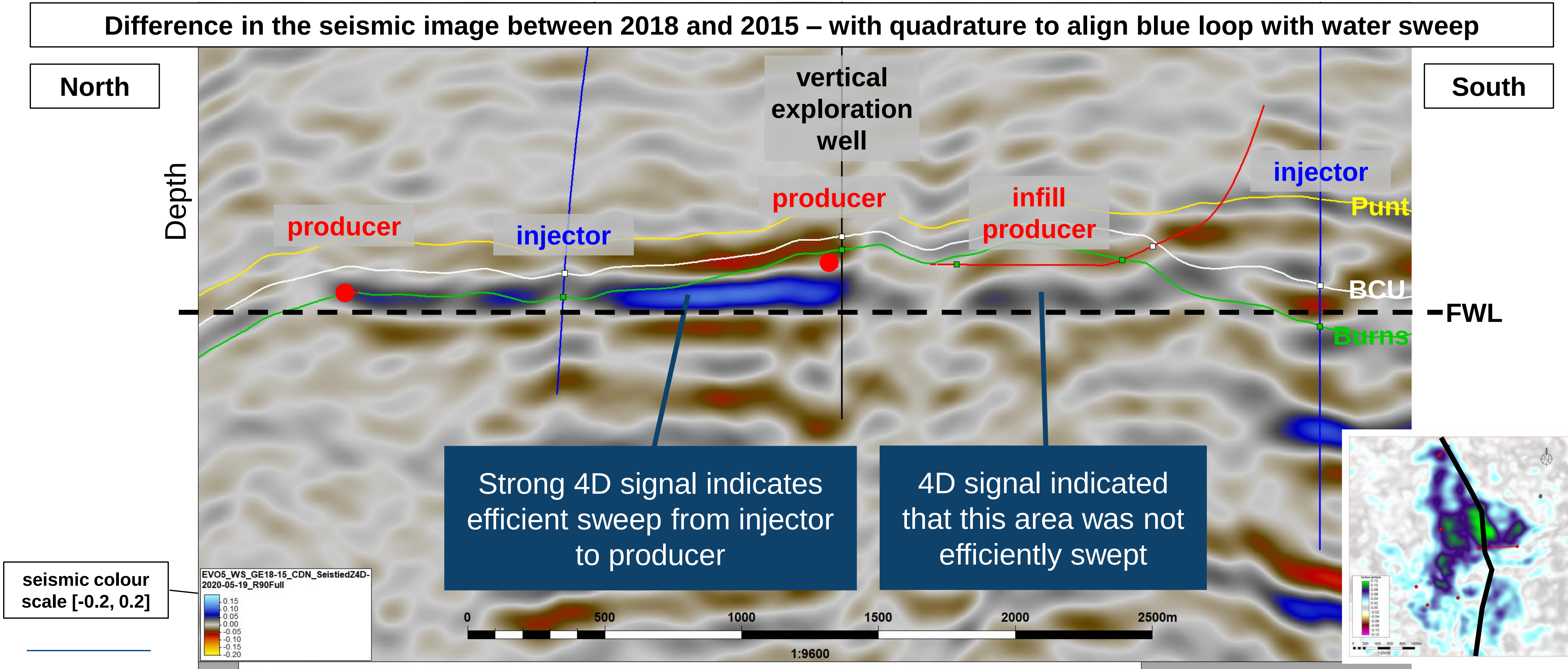
GEAD 4D Revealed that Sweep Pattern Was Not So Simple

Sweep in the GEAD Burns reservoir is more concentrated between injectors and producers than was expected before field start up



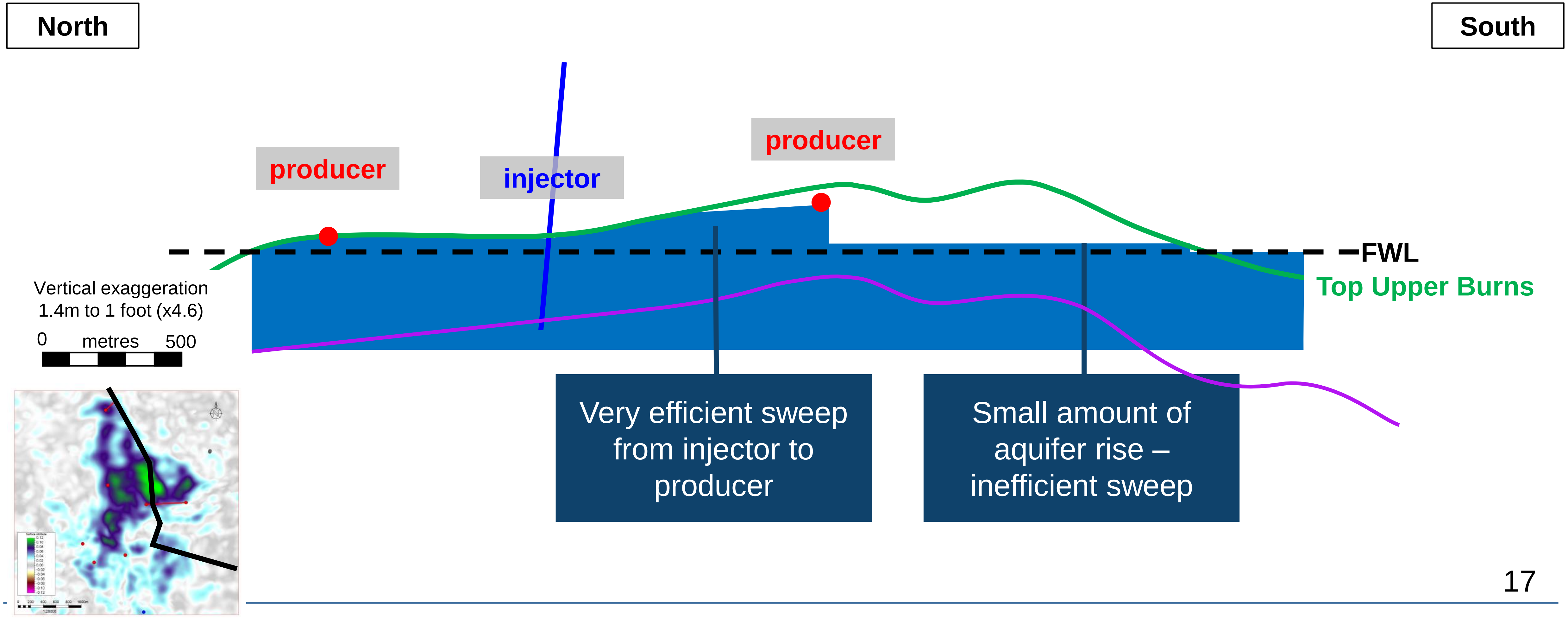
Burns Infill Well Targeted an Area Which 4D Seismic Indicated was Not Efficiently Swept

Burns infill well found dry oil and became the best producer on the Golden Eagle field.



When Sweep Is Not So Simple, It Leaves Potential for Infills

GEAD early life production (2015 to 2018)

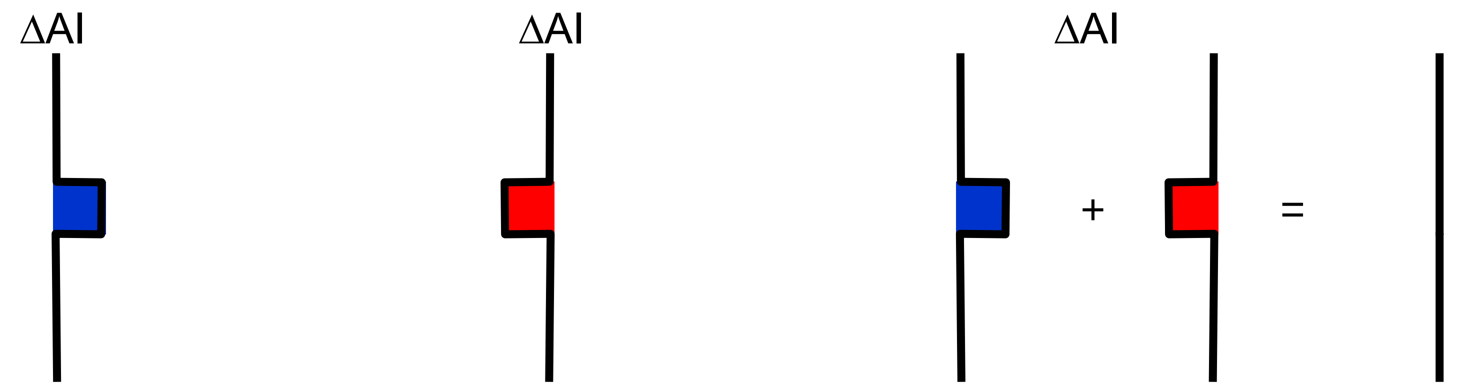


Why is 4D Seismic Dim at Water Injector?

Water injection can result in a pressure increase, either in the near-wellbore region of an injector or across a more widespread area. Pressure increase results in a decrease in AI, which can cancel out the increase in AI caused by water replacing oil, resulting in a dim area on 4D quadrature maps. It is important not to mis-interpret this lack of energy on 4D quadrature maps as indicating an area of no sweep.

Water sweeping oil *(oil-water contact rise)*	Pressure increase	Water sweep + pressure increase

change in impedance



AI change from water sweep is cancelled out by AI change from pressure increase resulting in no change in AI and no signal on 4D quadrature attribute

How Can We Recognise “false dims” on 4D Quadrature?

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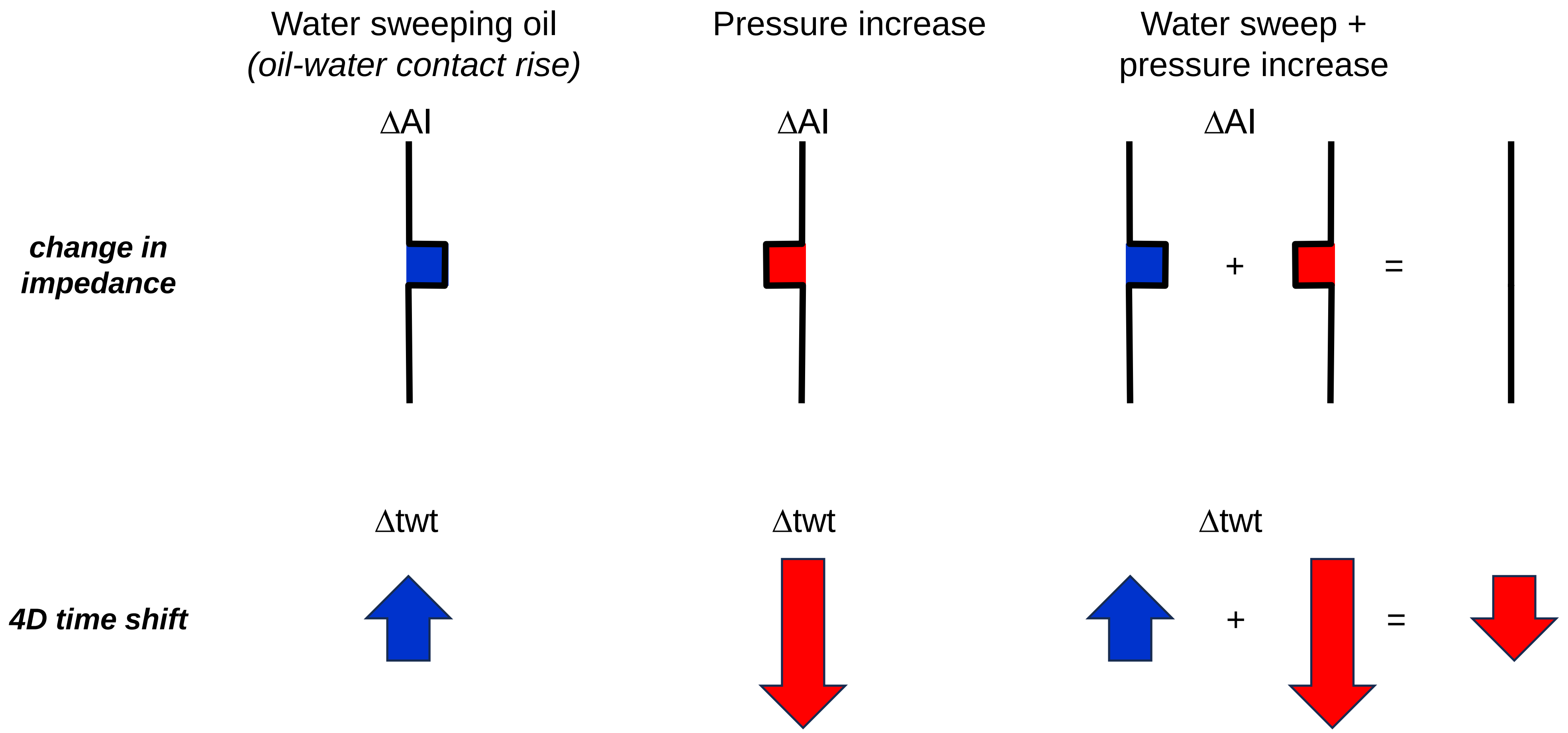


AI change from water sweep is cancelled out by AI change from pressure increase resulting in no change in AI and no signal on 4D quadrature attribute.

However the pressure effect is likely to dominate time-shift maps. Using these two attributes together reduces the risk of mis-interpretation.

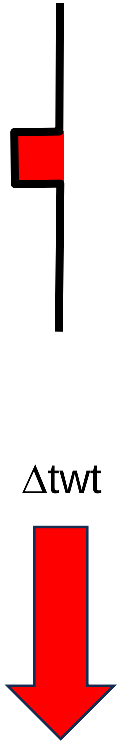
How Can We Recognise Unswept but Pressured-Up?

In the Golden Eagle Punt we identified an area which showed softening on 4D seismic quadrature and a strong red (downward) 4D time shift. We interpreted this as in good pressure connection to nearby water injectors but not efficiently swept. This area was targeted by an infill producer which confirmed the 4D seismic interpretation.

Pressure increase

change in impedance

ΔAI



Softening on 4D seismic quadrature maps

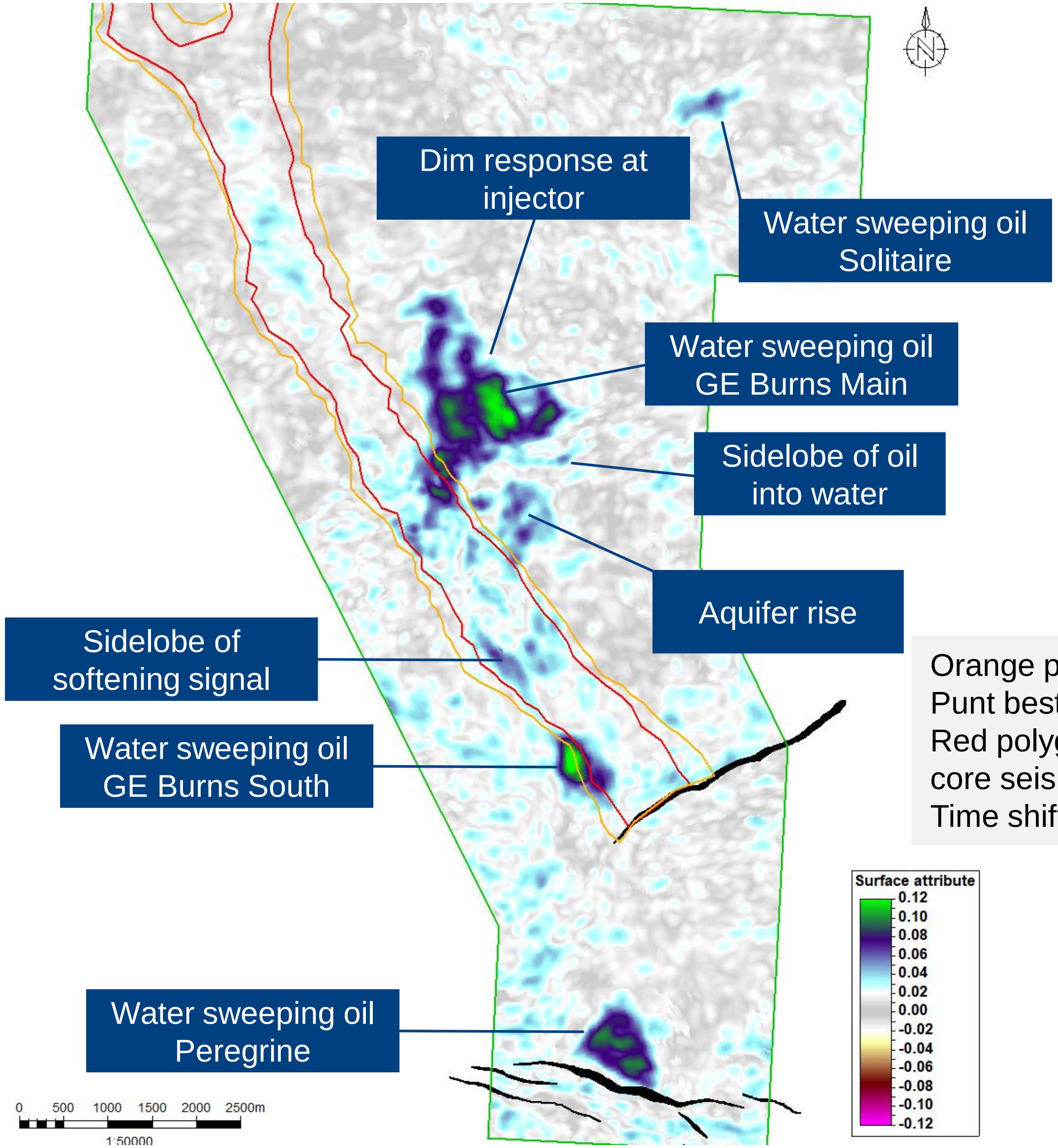
4D time shift

Δtwt

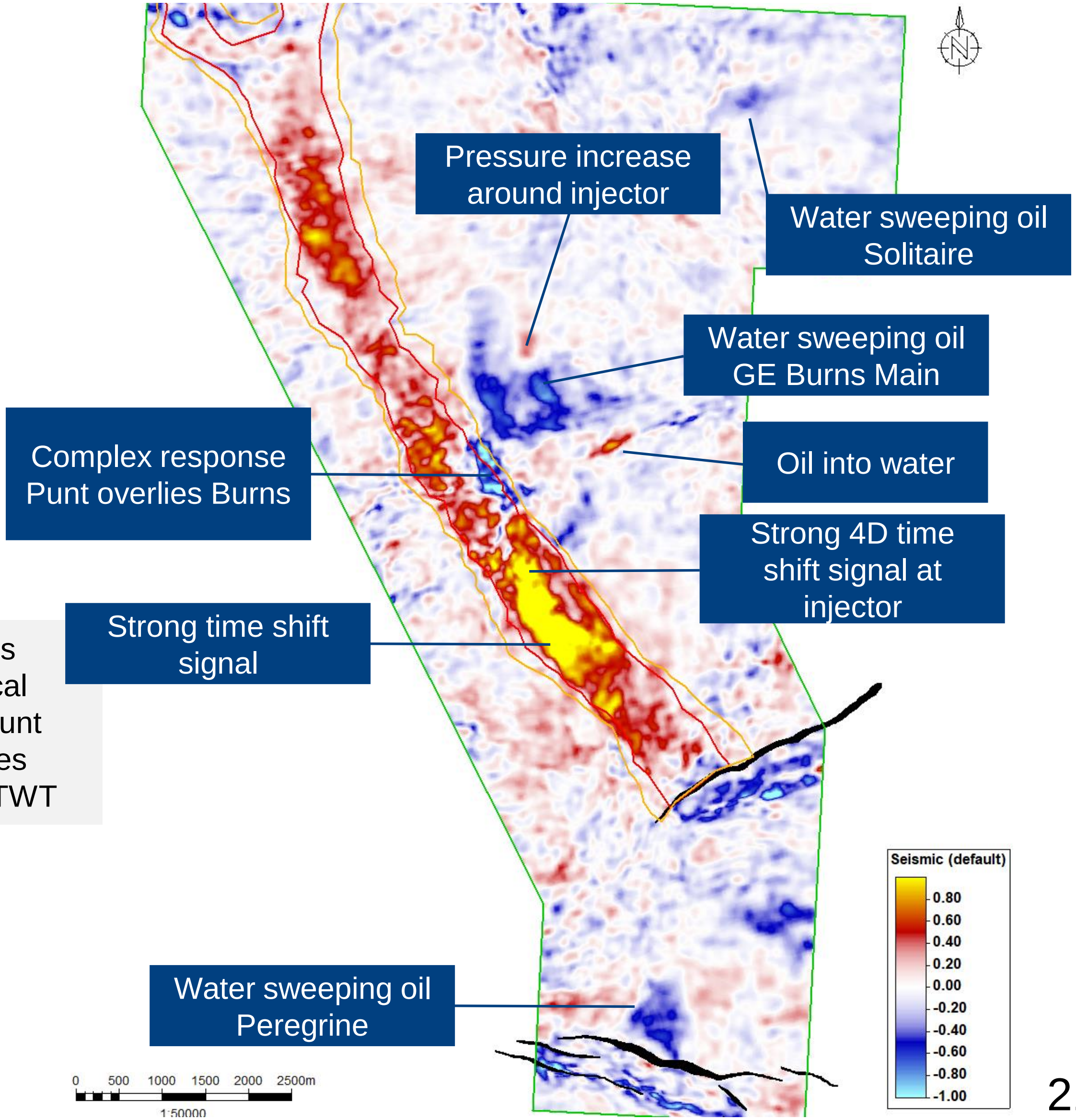
Red (downward) time shift on 4D time shift maps

4D Burns Hardening vs 4D Time Shift Map

4D Quadrature Max Hardening in 50ms Window Below BCU



4D Time Shift

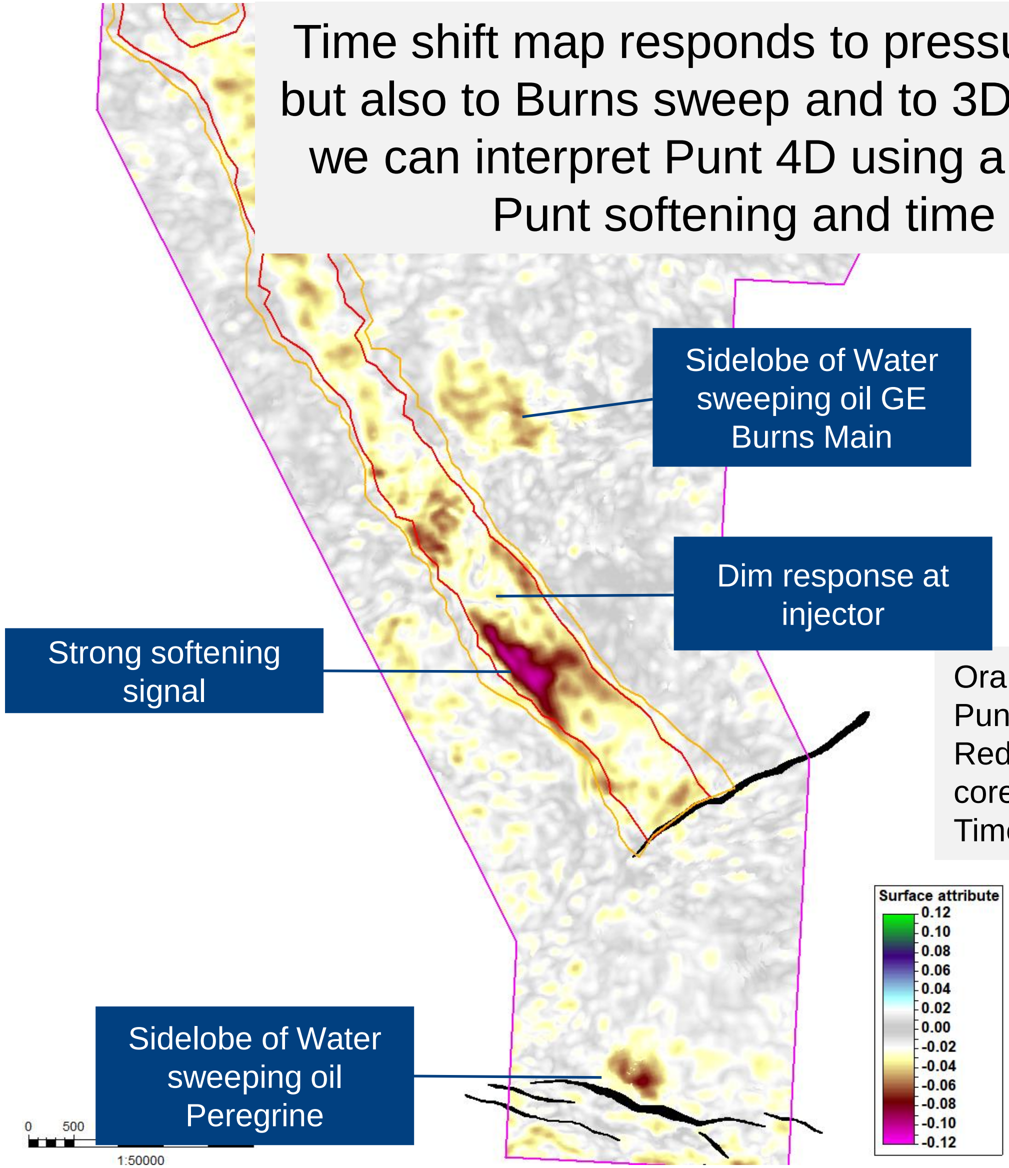


Orange polygon is Punt best technical
Red polygon is Punt core seismic facies
Time shift in ms TWT

4D Punt Softening vs 4D Time Shift Map

Time shift map responds to pressure changes in Punt but also to Burns sweep and to 3D seismic character – we can interpret Punt 4D using a combination of the Punt softening and time shift maps

4D Quadrature Max Softening in 50ms Window Above BCU



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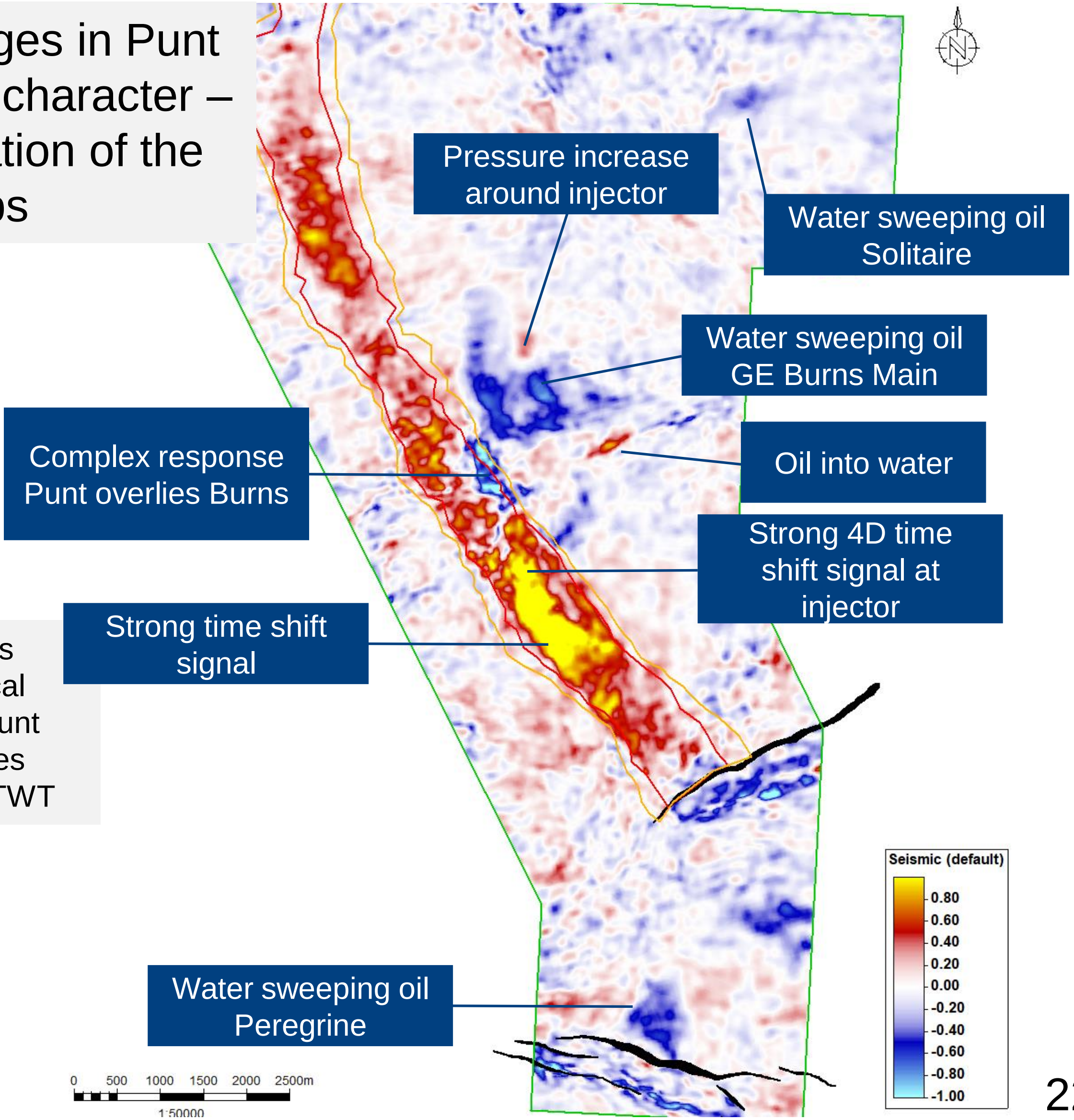
4D Time Shift



Summary So Far

In a relatively homogenous sand with relatively simple production mechanism

- Water sweep + pressure up (at injector) => dim on 4D quadrature, red on time shift
- Efficient water sweep, no pressure change => strong hardening (blue) on 4D quadrature, blue on time shift
- Inefficient water sweep, no pressure change => weak hardening (dim blue) on 4D quadrature, weak time shift
- Inefficient water sweep + big pressure up => softening (red) on 4D quadrature, red on time shift

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What about inhomogeneous sands and/or more complicated production mechanism?

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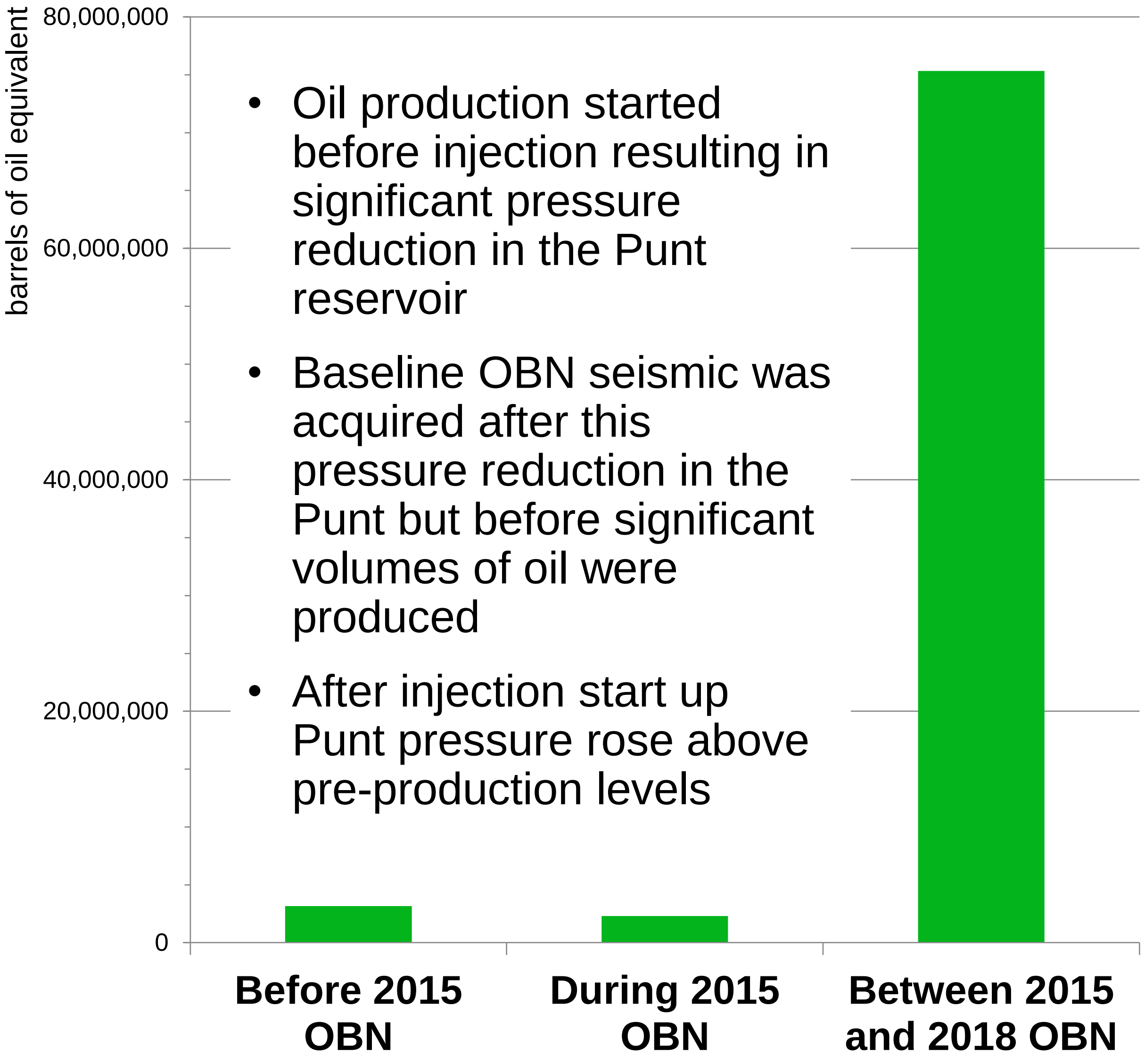
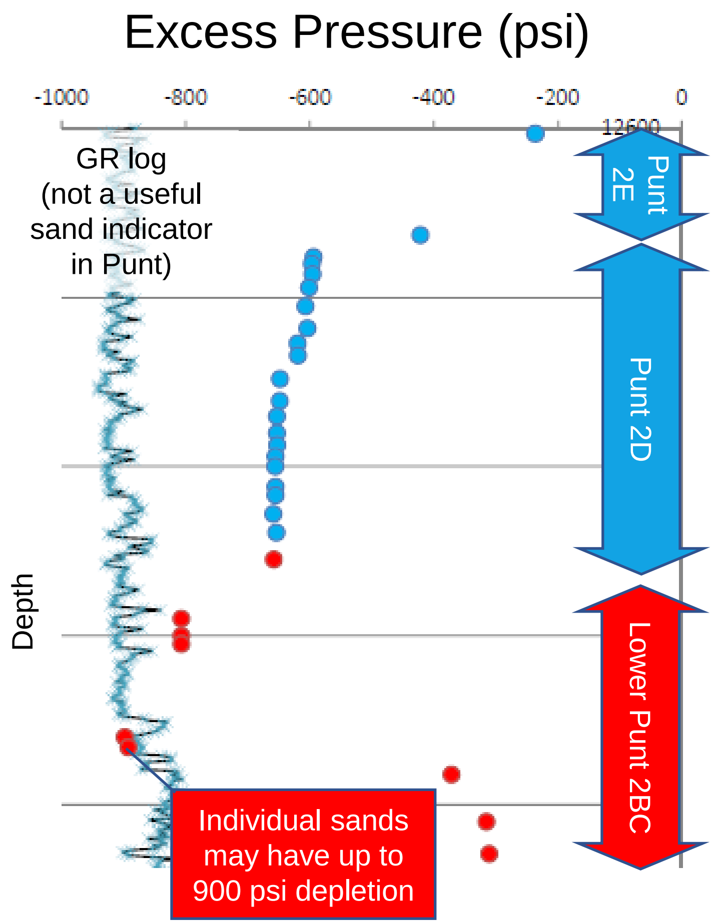
Differential Depletion in the Golden Eagle Punt Reservoir

Timing of OBN Surveys



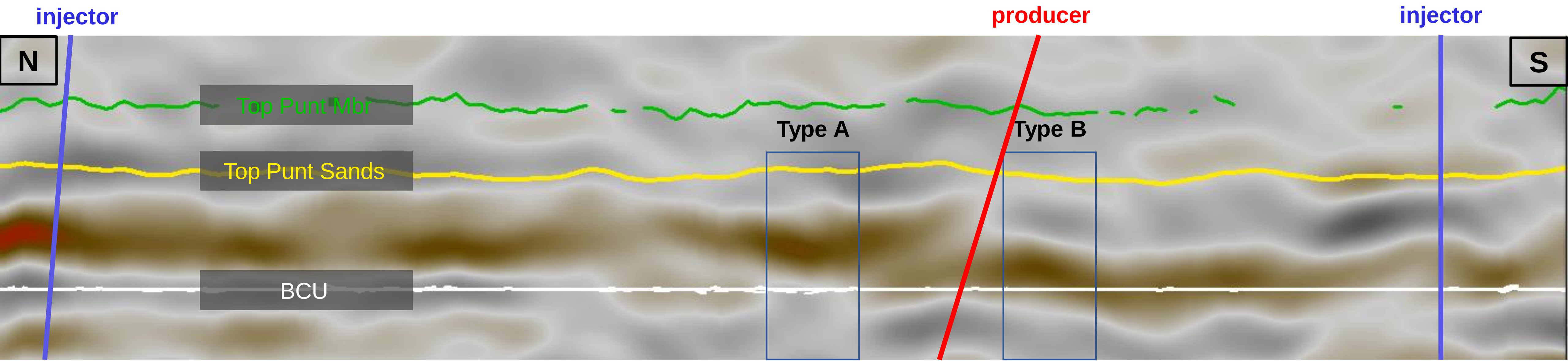
Differential Depletion Profile in Punt Producer

(time of drilling is before significant water injection into Punt)



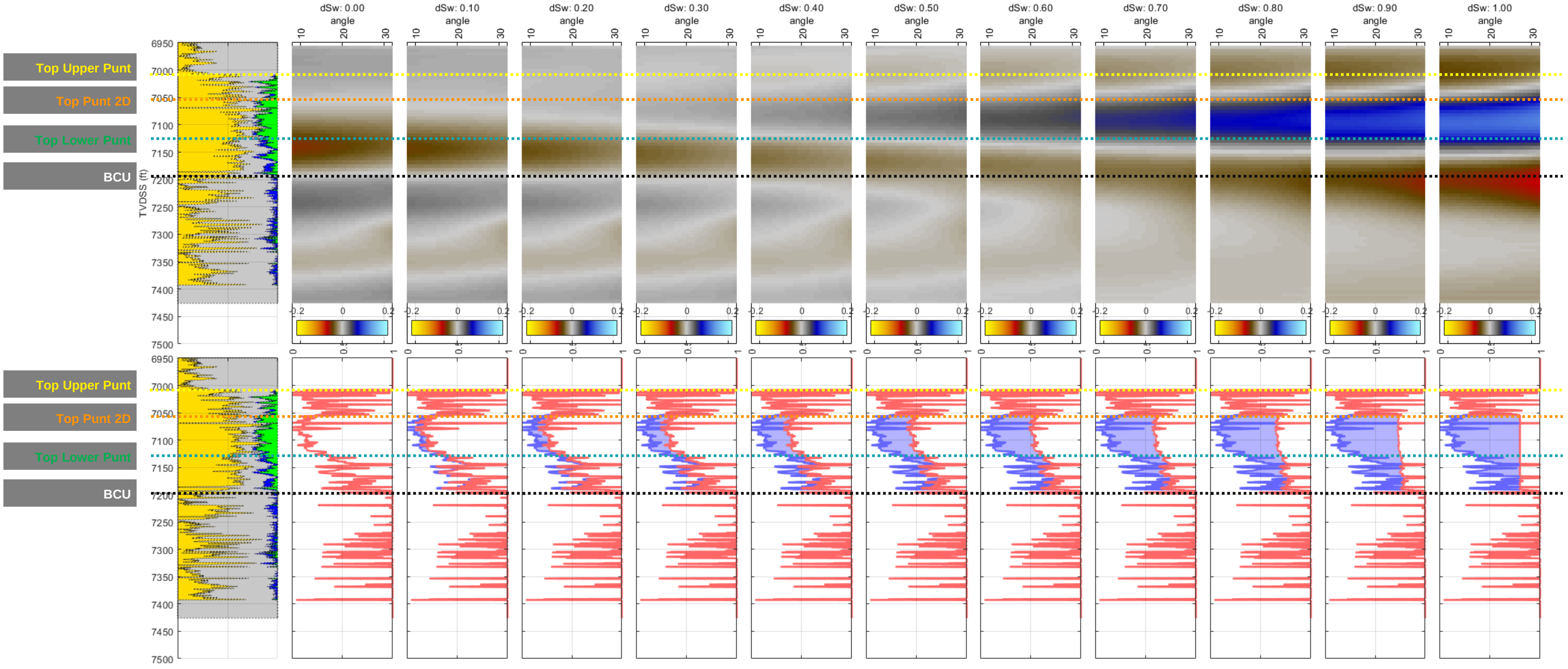
Learning to Read Complicated 4D Seismic Responses

- This seismic section shows the observed GEAD 4D difference quadrature on a line along the Punt channel sands which lie between Top Upper Punt (yellow horizon) and the BCU (white horizon)
  - the section has been flattened on the BCU
  - red indicates a softening, associated with pressure increase in the Punt
- In this area the Golden Eagle Punt has consistent 3D seismic character but there is a change in the 4D seismic character which happens from the North to South sides of the Producer
  - North of the producer, the 4D quadrature shows broad red (Type A)
  - South of the producer, the 4D quadrature shows blue-over-red (Type B)
- We created "4D Response Panels" to help us learn what these 4D seismic characters mean



4D Response Panel: Edge Drive From the Southern Injector

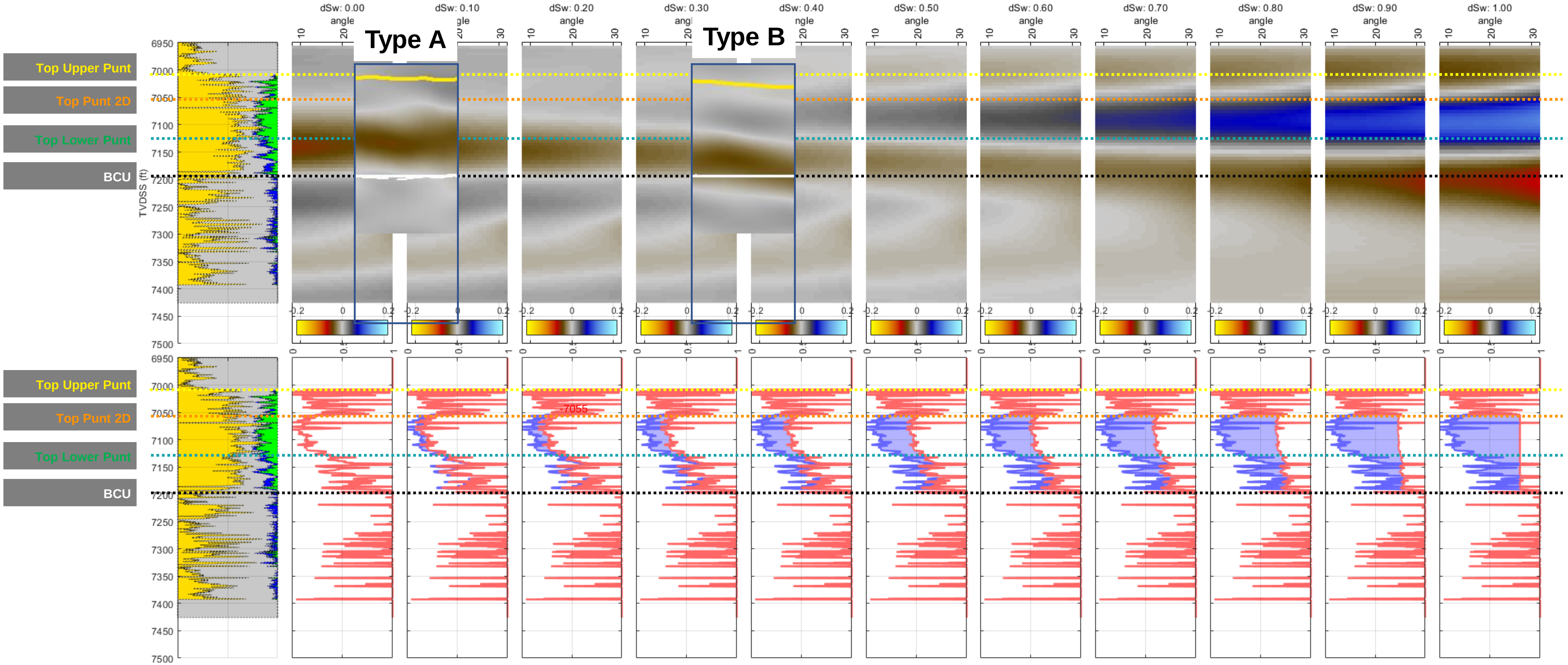
This response panel connects the languages of geology, petrophysics, reservoir engineering and 4D seismic. The upper panel shows the synthetic 4D seismic character while the lower panel shows the equivalent sweep pattern. The same pressure changes are used in each track.



4D Response Panel: Edge Drive From the Southern Injector

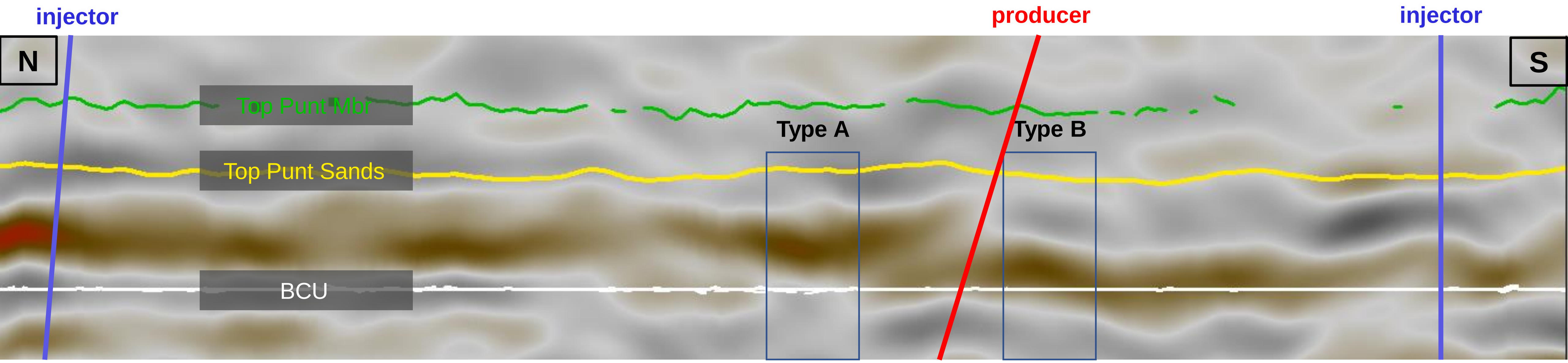
Type A seismic character matches 0 to 10% sweep.

Type B seismic character matches 30 to 40% sweep.



Learning to Read Complicated 4D Seismic Responses

- In this area the Golden Eagle Punt has consistent 3D seismic character but there is a change in the 4D seismic character which happens from the North to South sides of the Producer
  - North of the producer, the 4D quadrature shows broad red (Type A)
  - South of the producer, the 4D quadrature shows blue-over-red (Type B)
- Analysis using a 4D response panel indicates
  - Type A 4D seismic response – inefficient sweep from injector on northern side of the producer
  - Type B 4D seismic response – efficient sweep from injector on southern side of the producer



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- Inefficient water sweep, no pressure change => weak hardening (dim blue) on 4D quadrature, weak time shift
- Inefficient water sweep + pressure up => softening (red) on 4D quadrature, red on time shift

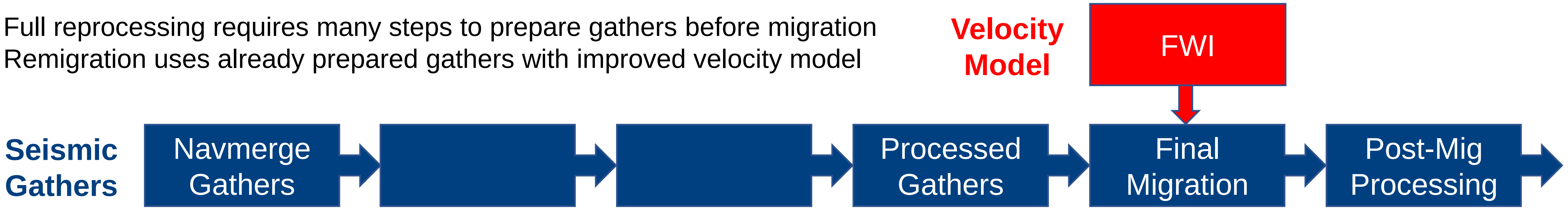
In a sand with differential depletion and sweep

- We found that “4D Response Panels” were an effective way to semi-quantitatively interpret lateral and vertical patterns of differential sweep and pressure change

Improved Velocity Models Can Improve 4D Images

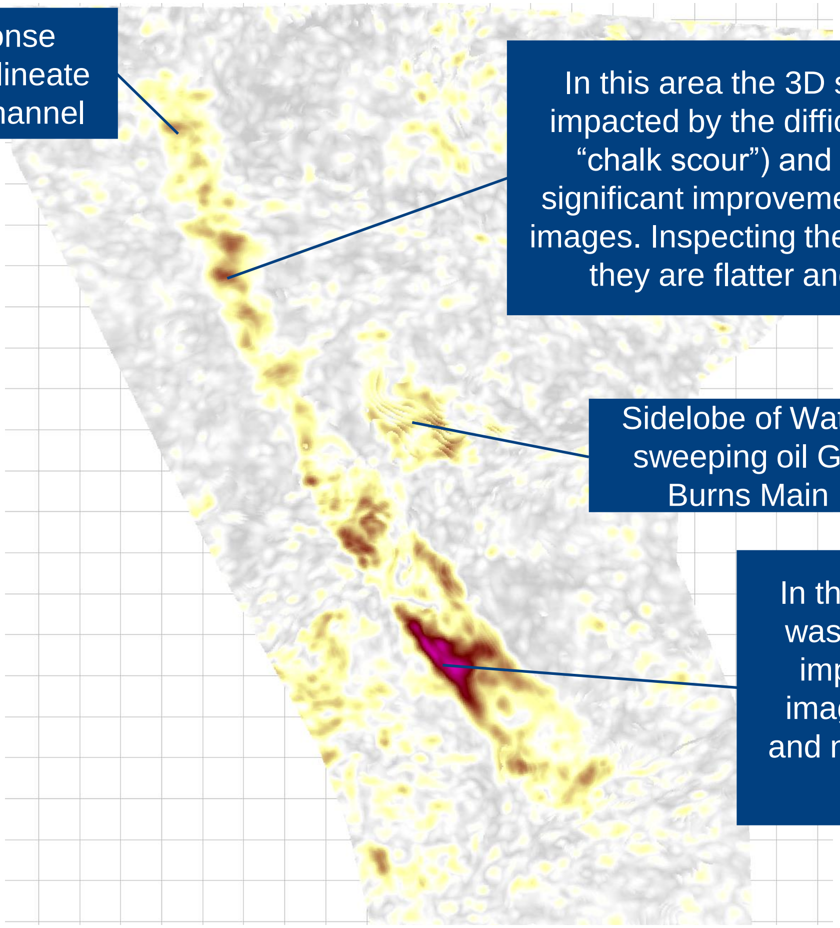
- Velocity modelling and depth conversion at GEAD is very challenging because of large velocity contrasts in the overburden
  - Jones, I.F. (2013) Tutorial: the seismic response to strong vertical velocity change. First Break, 31(6), 79-90 https://doi.org/10.3997/1365-2397.2013018
- In 2023/24 GEAD generated an improved velocity model using elastic full waveform inversion (eFWI) which has yielded improved 3D and 4D seismic images
- This improvement was achieved by a re-migration of existing processed gathers (not a full re-processing from field data) which confirms that the uplift results from improvement in velocity model, not from improvements in processing or migration
- In addition the 4D signal is flatter which provides an independent confirmation that the eFWI is achieving more accurate depthing between wells (because the water-sweeping-oil signal should be conformable to the original oil-water-contact)

Full reprocessing requires many steps to prepare gathers before migration
Remigration uses already prepared gathers with improved velocity model

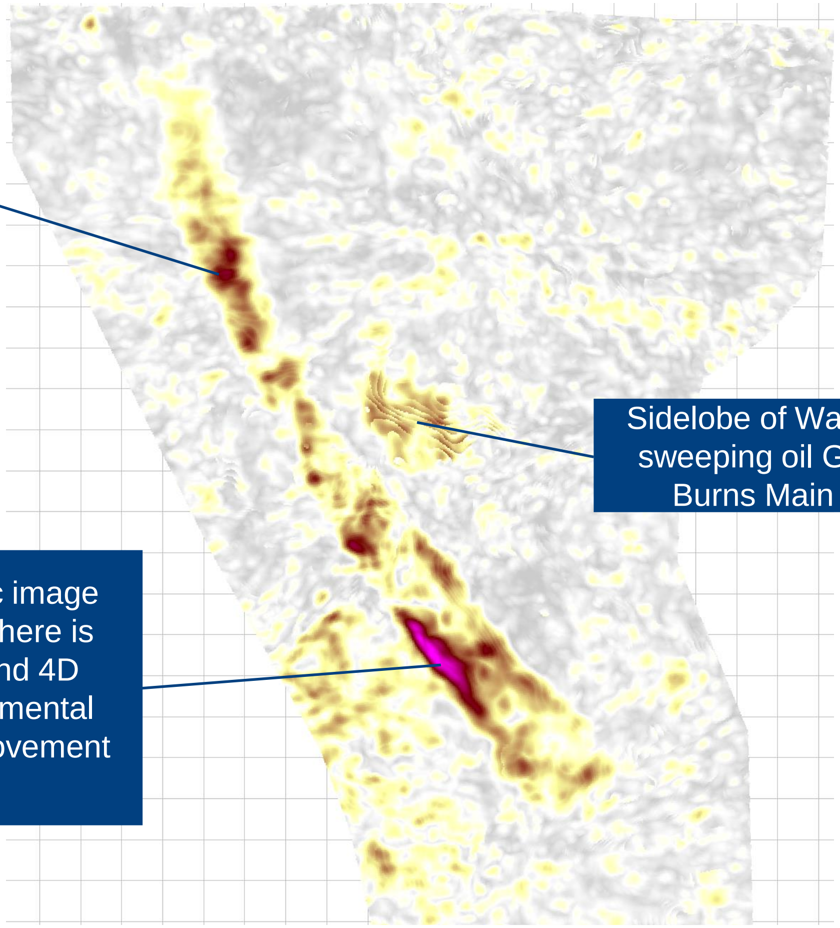


Example of Uplift from Improved Velocity Model

4D Softening Signal – Tomographic Velocity Model

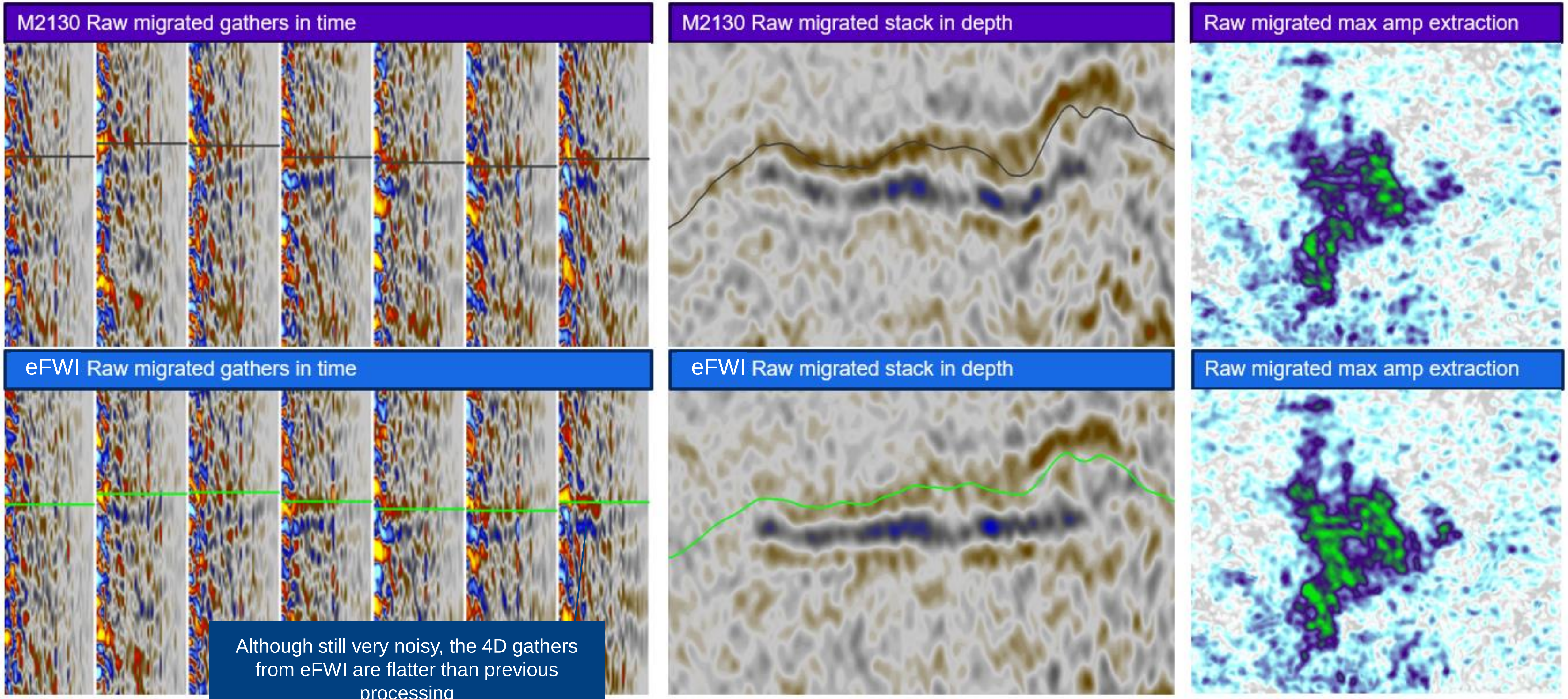


4D Softening Signal – eFWI Velocity Model



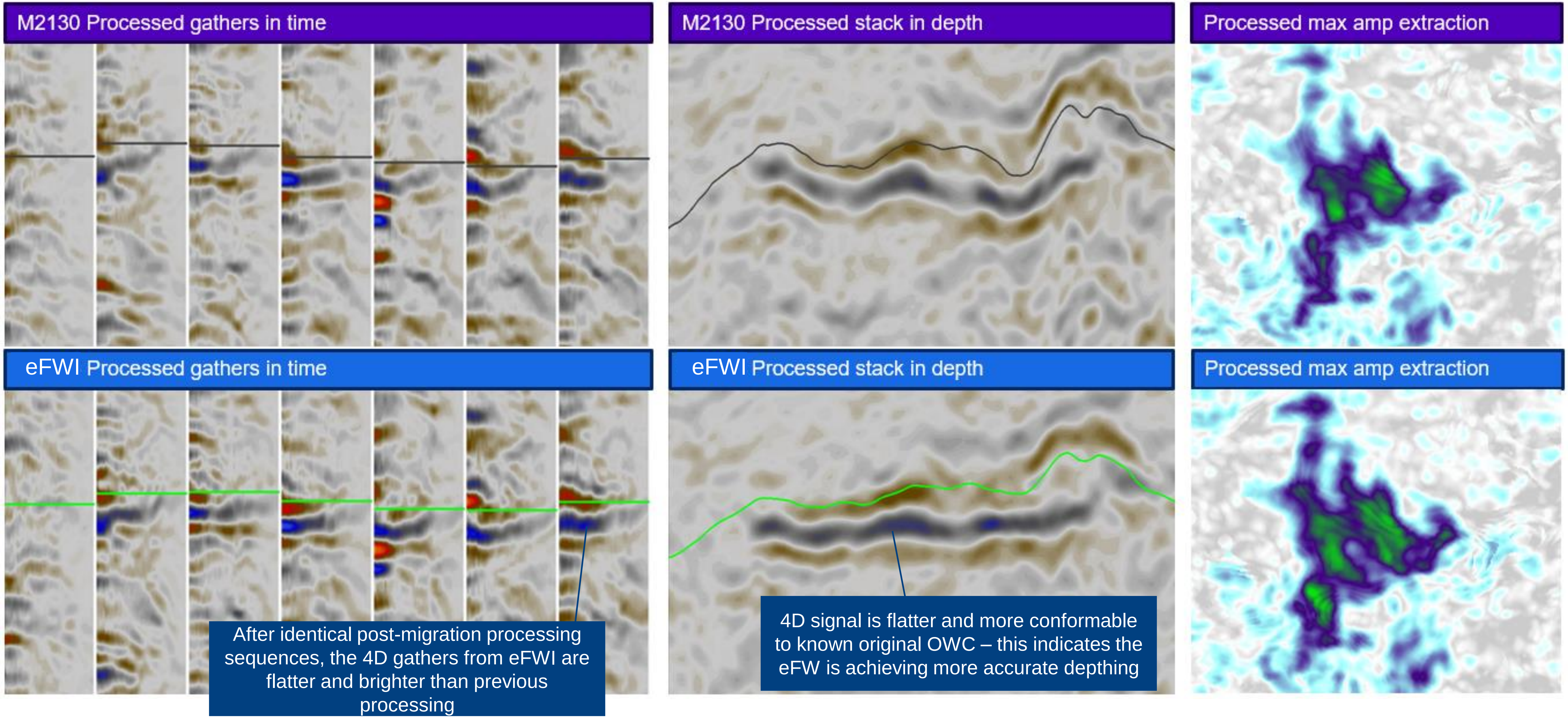
Maps show the 4D seismic quadrature softening signal in a 50ms window above BCU, which helps to delineate the Punt channel. Using the improved velocity model obtained using eFWI results in the 3D and 4D images which are brighter and less noisy than with the previous velocity model. This is because the improved velocity model results in better focusing and flatter gathers, which can then be more successfully de-noised.

Example of Uplift from Improved Velocity Model



Although still very noisy, the 4D gathers from eFWI are flatter than previous processing

Example of Uplift from Improved Velocity Model



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- Inefficient sweep with pressure up => softening (red) on quadrature, red on time shift

In a sand with differential depletion and sweep

- We found that “4D Response Panels” were an effective way to semi-quantitatively interpret lateral and vertical patterns of differential sweep and pressure change

Improved eFWI velocity models can result in improved 3D and 4D images

- We were able to achieve this using re-migration (much faster and cheaper than a full re-processing)
- But 4D gathers may remain noisy (making 4D AVO very challenging)

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In Conclusion: 4D Seismic Does Not Lie – But It Can Keep Secrets

- The outcome of all of our infill wells has been consistent with the observed 4D seismic signal
- Failed infill wells were either outside the 4D seismic area, or targeting areas with no 4D signal (in the hope that the absence of a sweep signal indicated unswept oil)
- Areas of no 4D seismic signal could indicate unswept oil, but could also result from sands below the OWC, or from the absence of reservoir quality sand
- Our most successful infill wells targeted areas which had some 4D seismic response. The presence of a response confirms the presence of sands and oil and/or pressure connectivity, thereby reducing risk. The key is to learn how to read the 4D seismic response to identify areas which are not being efficiently swept.
- In summary: our experience is that those seeking a low-risk infill well might consider if areas of weak 4D response, indicating inefficient sweep, can provide attractive targets.

Discussion

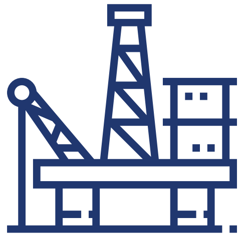
Thank you for your attention

I hope that this presentation was interesting and useful to you

Any feedback, questions or suggestions would be very welcome

Andrew.J.Wilson@intl.cnoocltd.com

THANKS



Discussion

- **Is there anything more vital to effective field development than understanding sweep style?**
- **Do we too often assume simple bottom-up sweep?**
- **If we look, will we find more cases of 4D seismic providing direct observations of sweep style?**

Dans les champs de l'observation le hasard ne favorise que les esprits préparés.

Louis Pasteur, Lecture, University of Lille 7 December 1854

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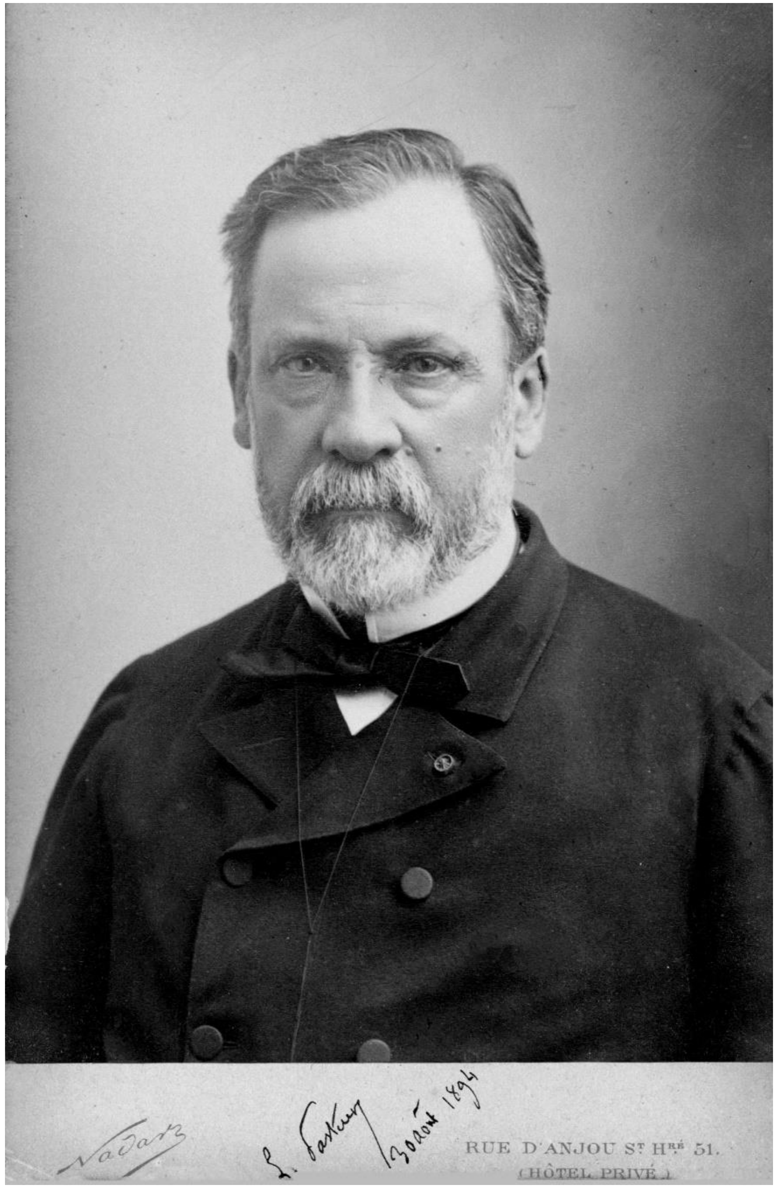

In the fields of observation chance favors only the prepared mind.

Louis Pasteur, Lecture, University of Lille 7 December 1854

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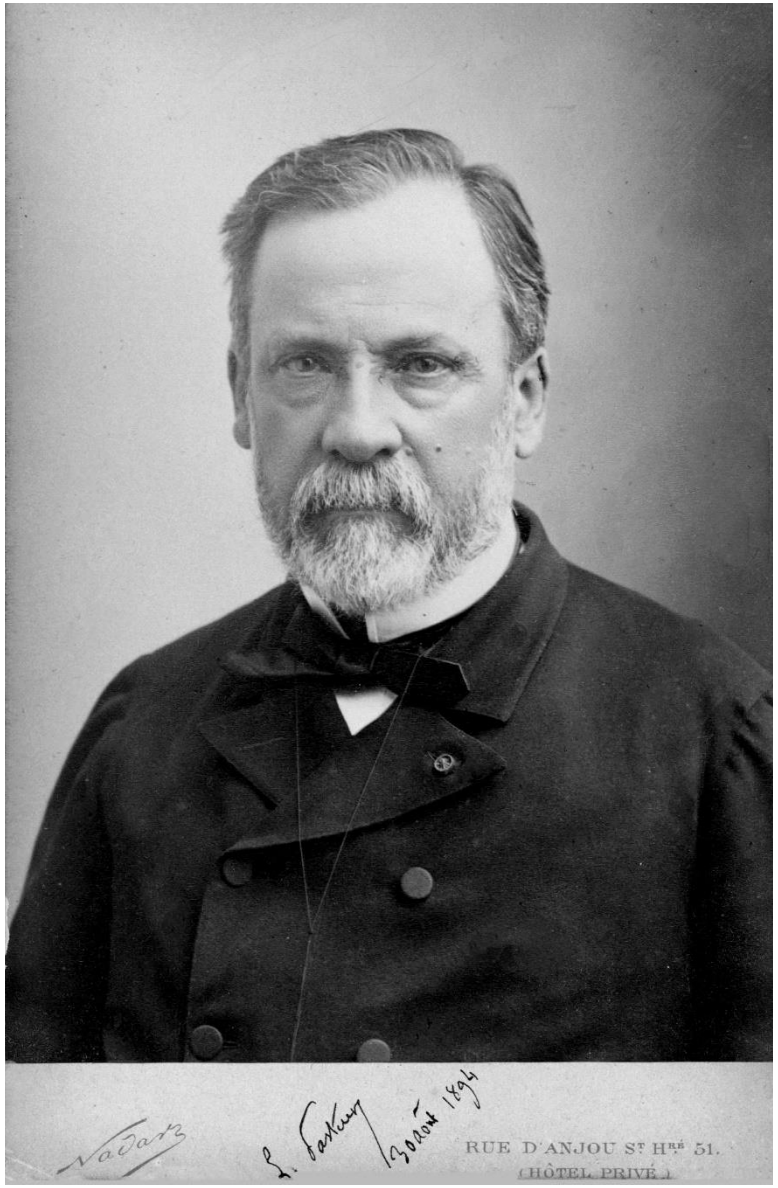

Extra Slides for Anticipated Questions

References

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- Wilson, A.J.S., McDonnell, P., Draper, C. and Tian, S. (2022) Improving 4D signal to noise and reducing depth uncertainty using 4D seismic wavefield harmony, Seismic 2022 Conference and Exhibition. https://www.spe-aberdeen.org/wp-content/uploads/2022/05/Golden-Eagle-presentation-to-Seismic-2022-improving-noise-and-reducing-depth-uncertainty-with-4D-seismic-wavefield-harmony.pdf

Golden Eagle: Timeline to First Infill Drilling

2006 — Golden Eagle Discovery

Original PreSTM

2009 — Golden Eagle Appraisal

PreSTM Reprocessing

Streamer Acquisition

2010 — Golden Eagle Sanction

PreSDM 1

PreSDM 2

2014 — Golden Eagle First Oil

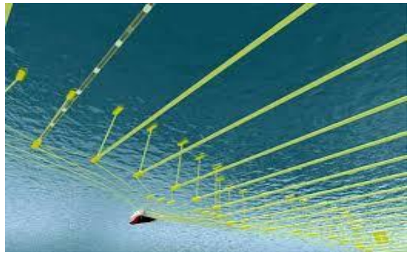
OBN acquisition

2016 — Development Drilling Finish

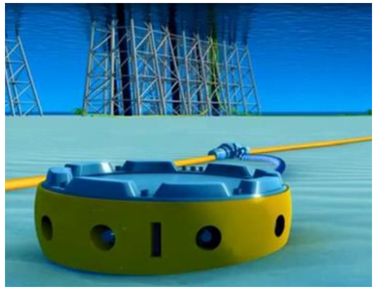
OBN PreSDM

4D OBN monitor

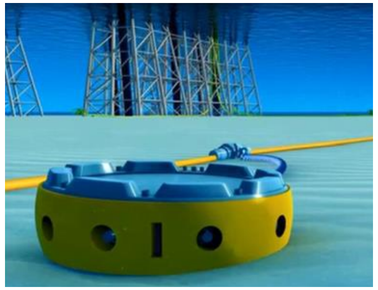
2020/21 — Platform Infill Drilling



Conventional Streamer



Ocean Bottom Nodes

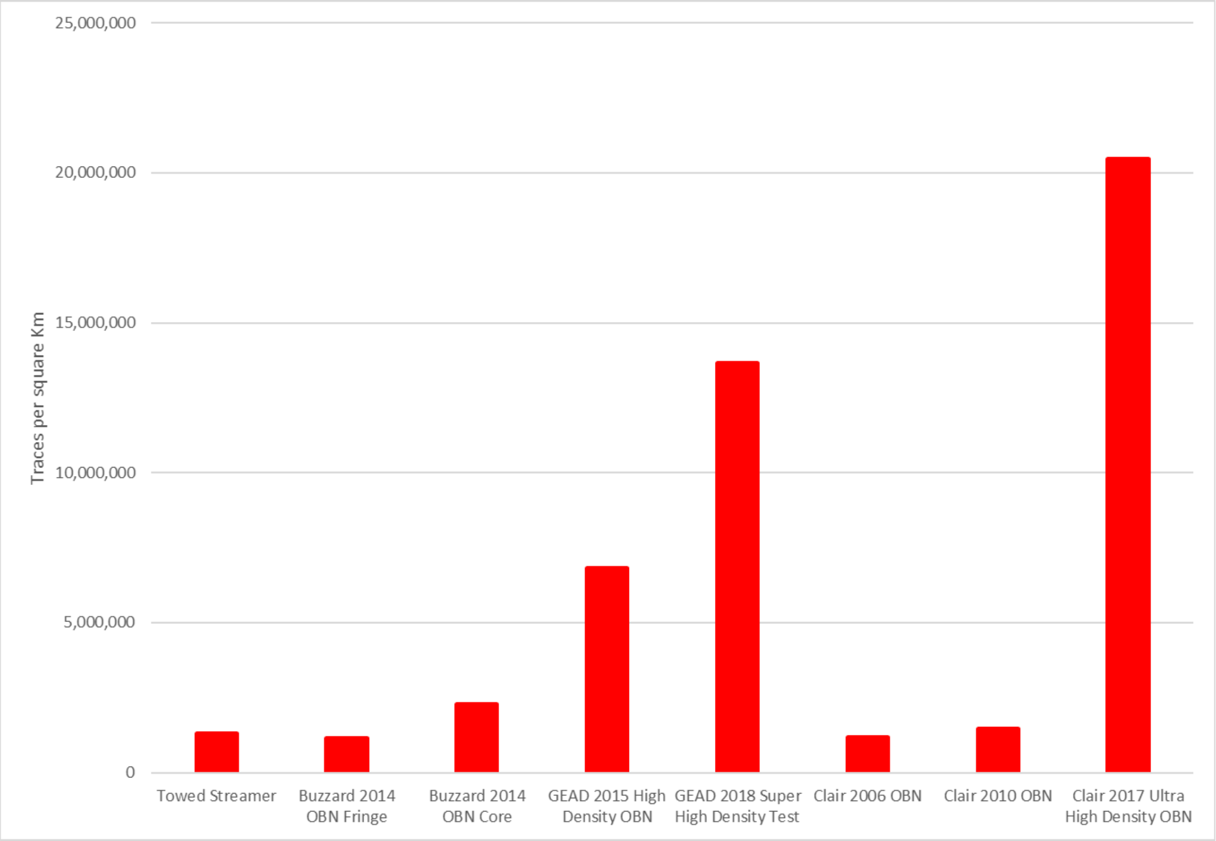


Ocean Bottom Nodes

Geowave Commander on close approach to Golden Eagle platform complex

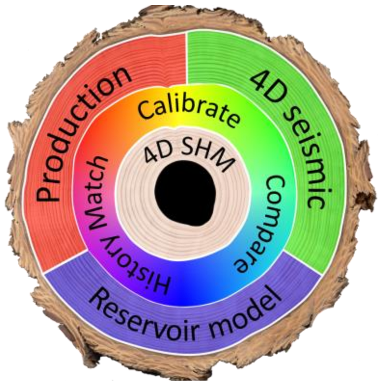
Golden Eagle: Summary

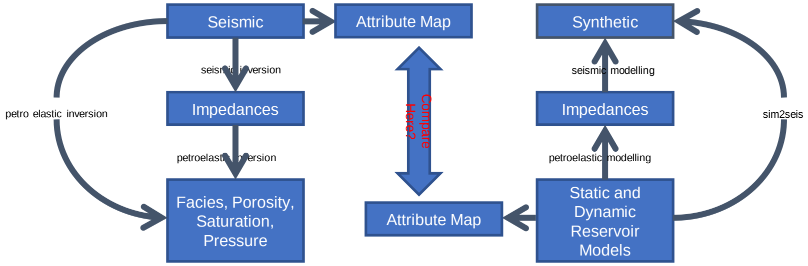
- The Golden Eagle area has a combination of an unusually challenging overburden and subtle reservoir seismic character.
- 3D and 4D seismic reservoir characterisation at GEAD requires an exceptionally high quality of seismic acquisition and processing.
- Golden Eagle is a low relief field and infill well planning requires super-accurate depth conversion.
- The high-density OBN seismic acquired for the 4D project enabled a step change improvement in 3D seismic image continuity and signal-to-noise compared to the best towed-streamer seismic.
- Having high-density OBN was also foundational to success of the 4D project.

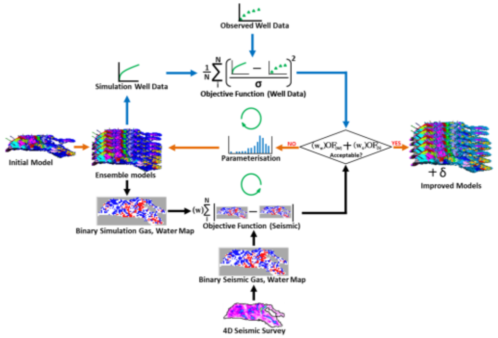


GEAD 4D Seismic Interpretation Strategy

- Follow the “tree trunk” tiered, structured approach to 4D seismic interpretation
- Explicit aim to make 4D interpretation consistent with geological and engineering observations
- Avoid premature “black box” optimisation of a single objective function
- Develop simple, robust meaningful 4D seismic attributes
- In model updating, first generate and apply simple, effective updates to get the models as close as possible to matching observations
- Then consider 4D assisted seismic history matching (ASHM)
    - Build on existing work with ensembles
    - Final “polish up” of models which are already a good match

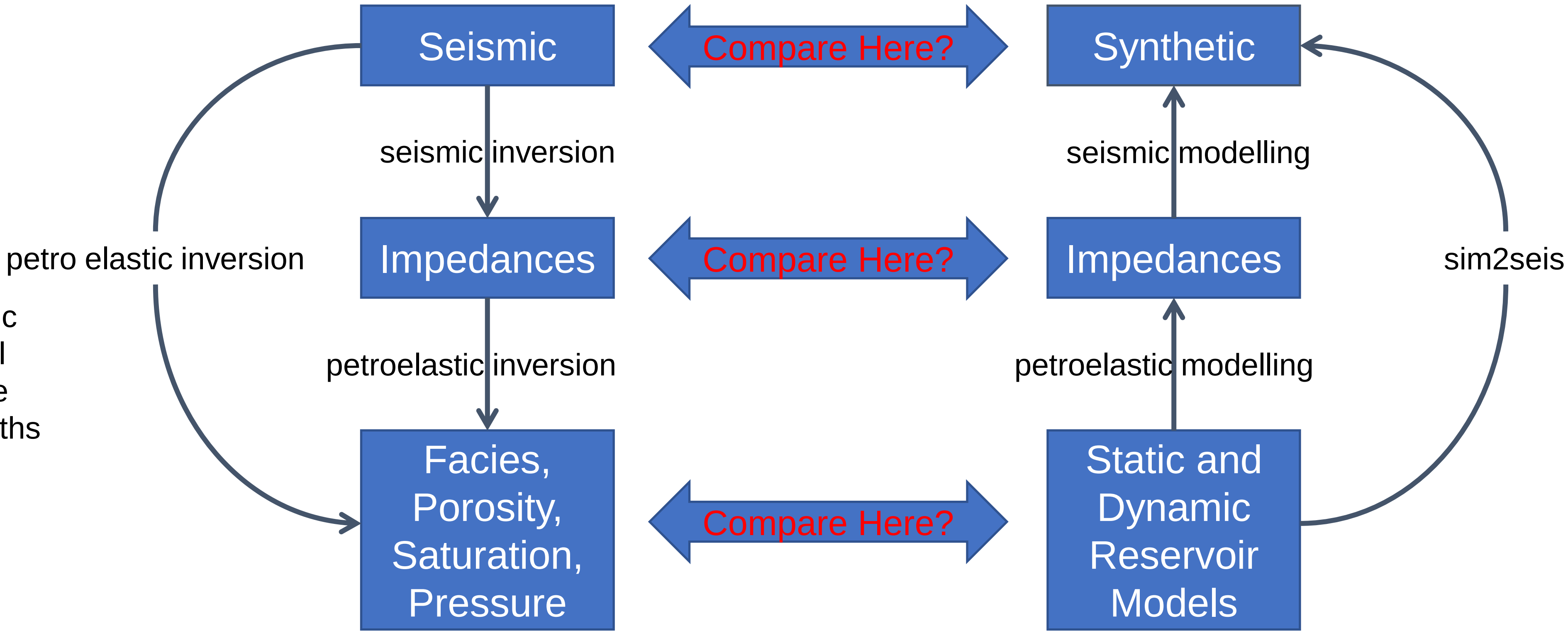






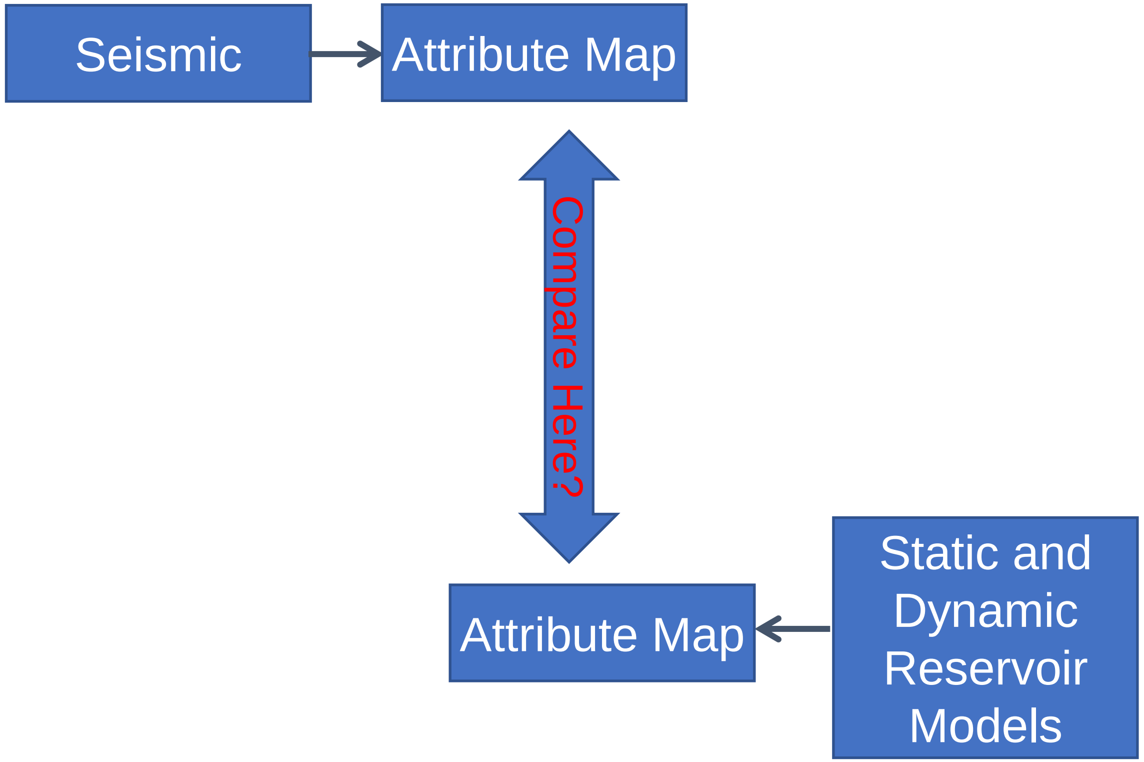
Relating Seismic and Reservoir Models

A petroelastic inversion will typically take several months



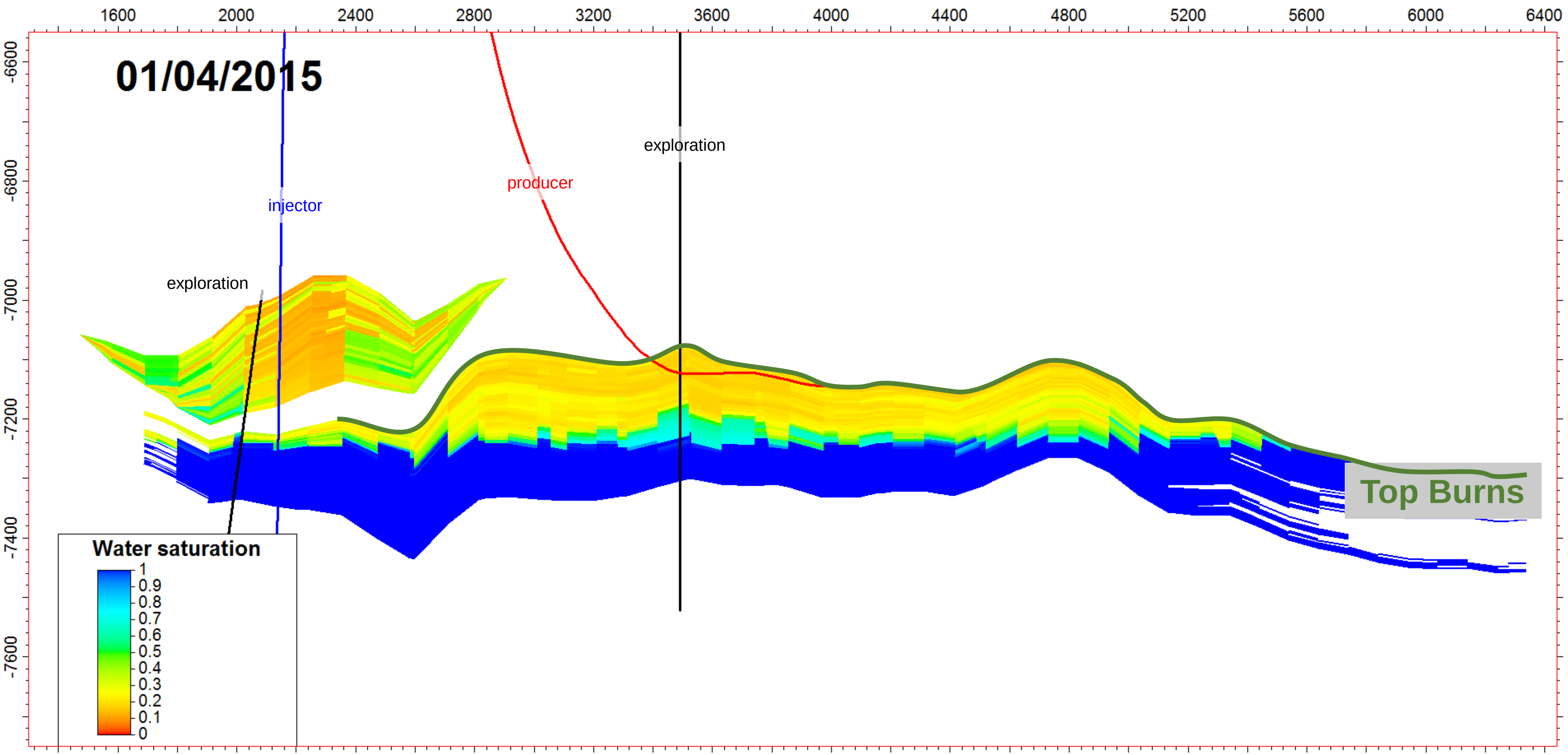
With NORSAR SeisRox this takes 2 days per Eclipse case

Relating Seismic and Reservoir Models

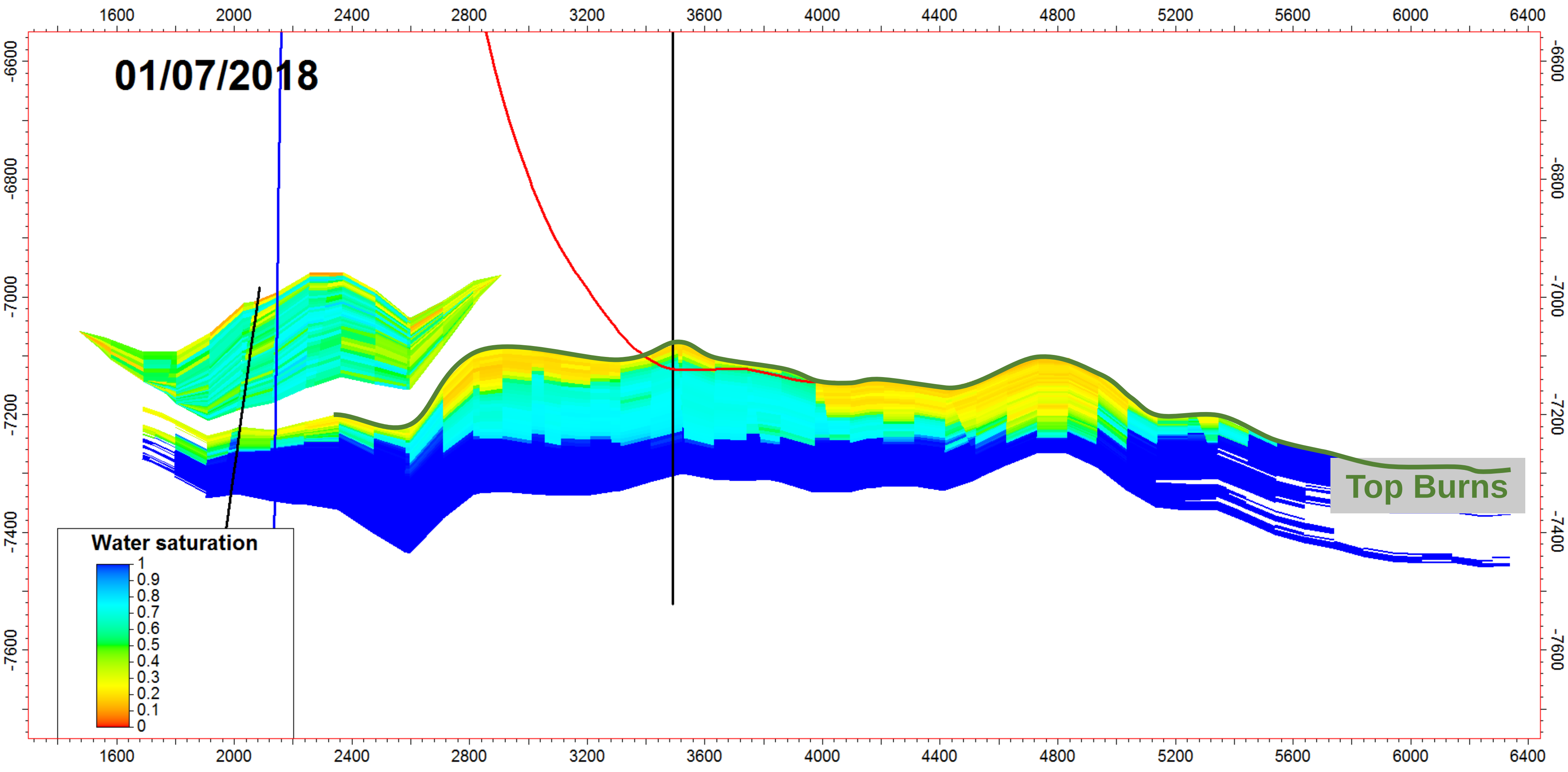


In the Burns the 4D response is dominated by water sweep and we have an effective 4D seismic attribute (max hardening on 4D quadrature) and an effective reservoir proxy attribute (swept oil volume).

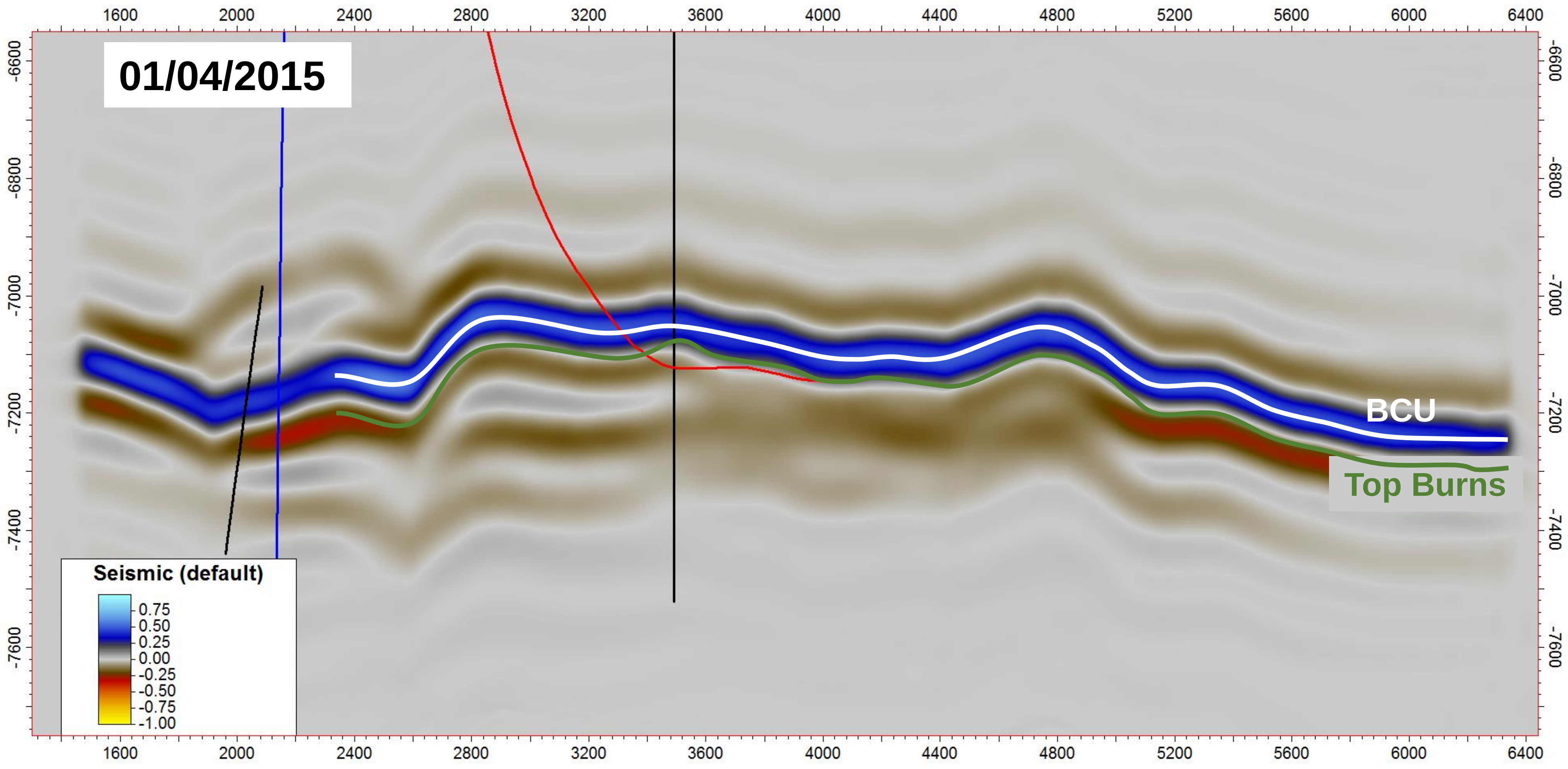
Saturation at time of baseline survey



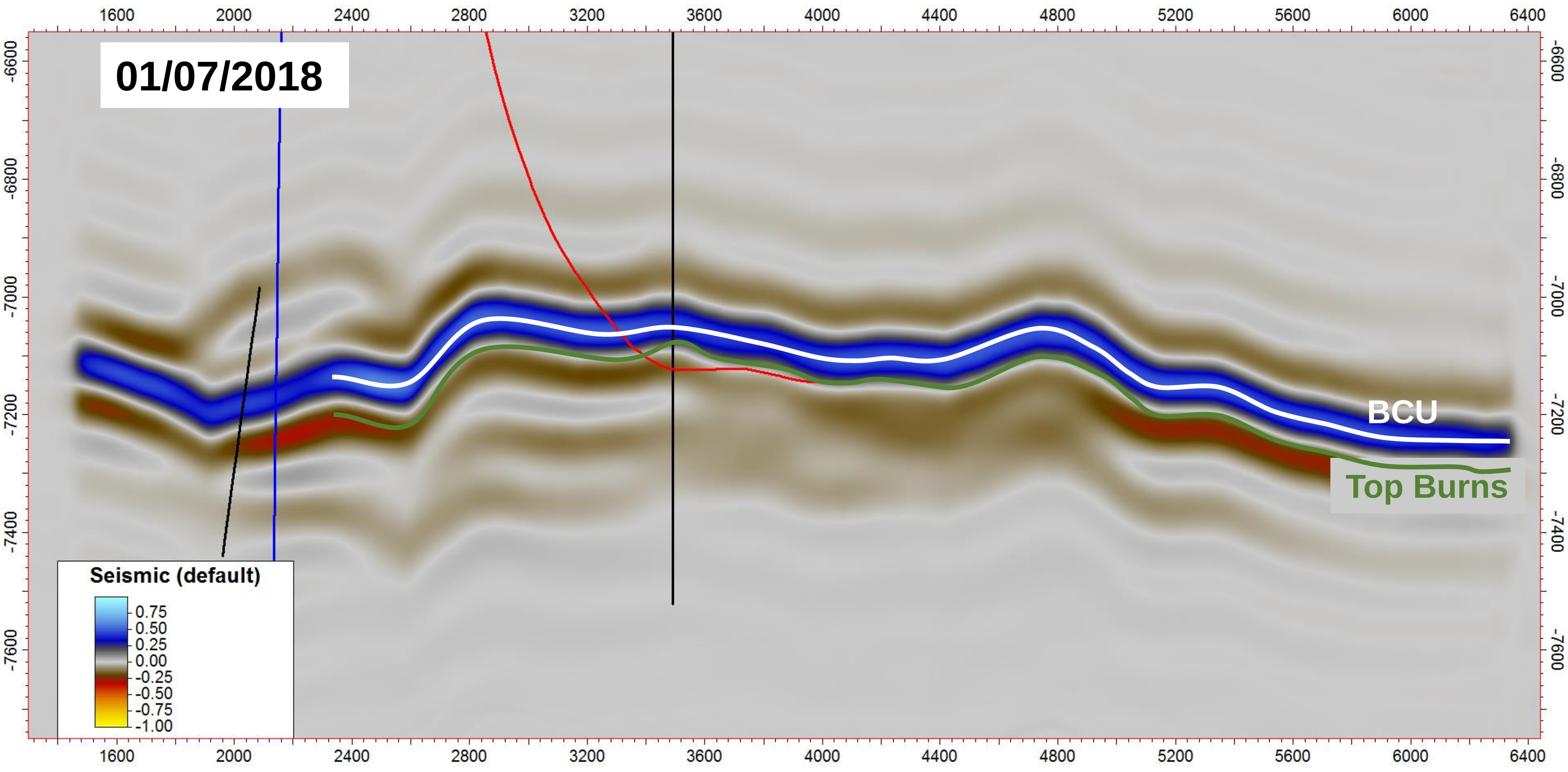
Saturation at time of monitor survey



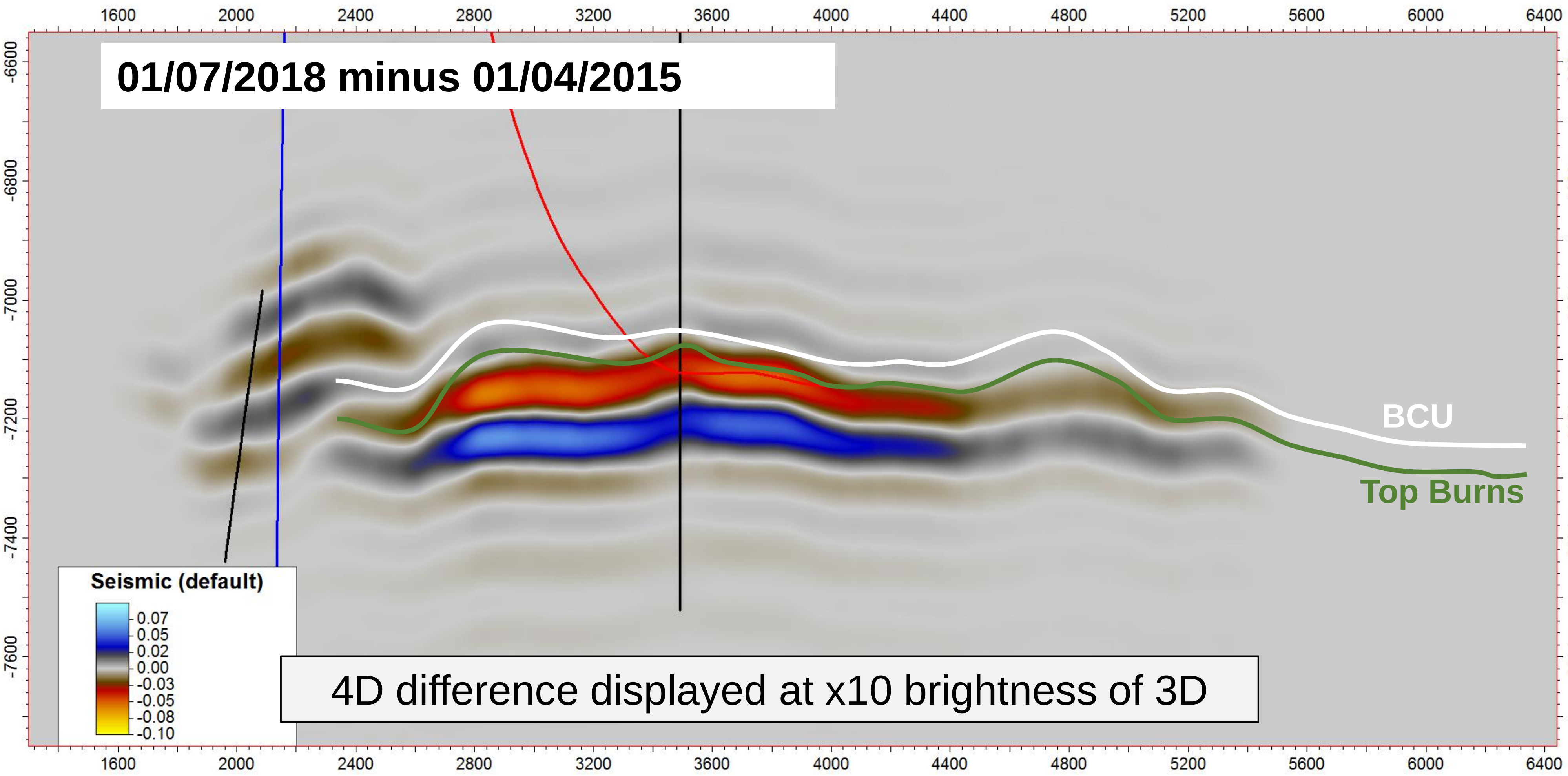
Synthetic seismic – baseline survey



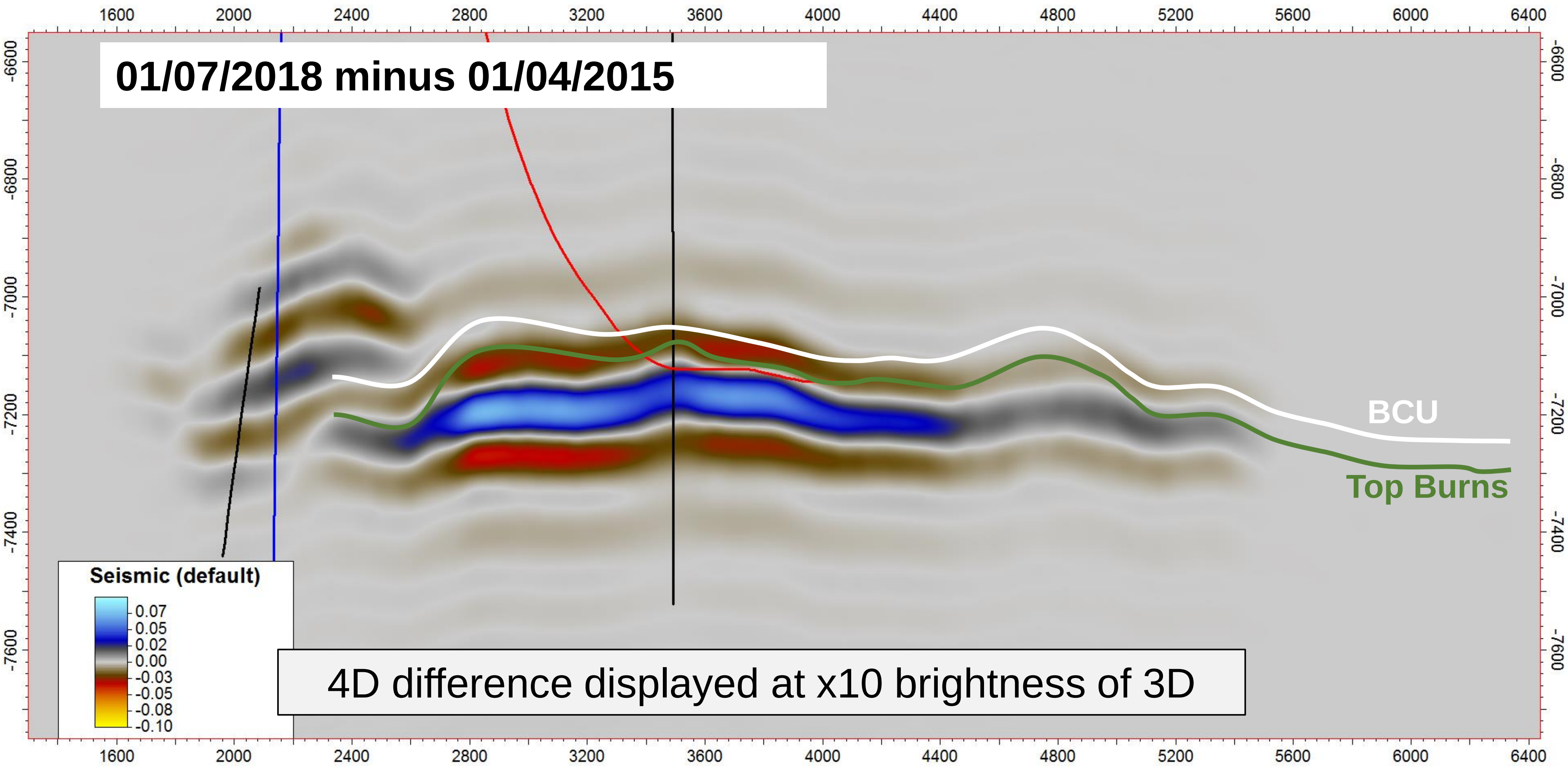
Synthetic seismic – monitor survey



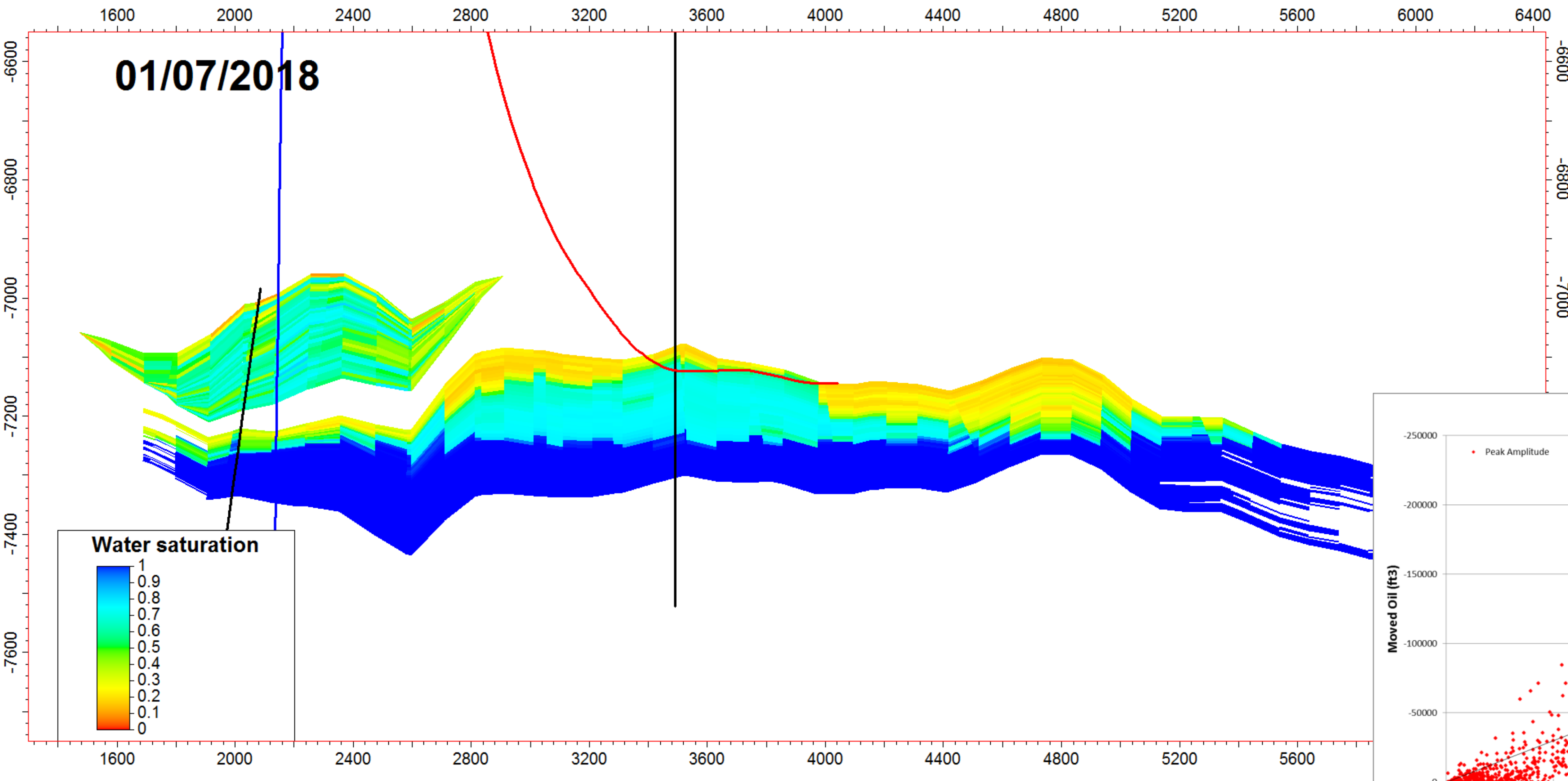
Synthetic seismic difference – monitor minus baseline

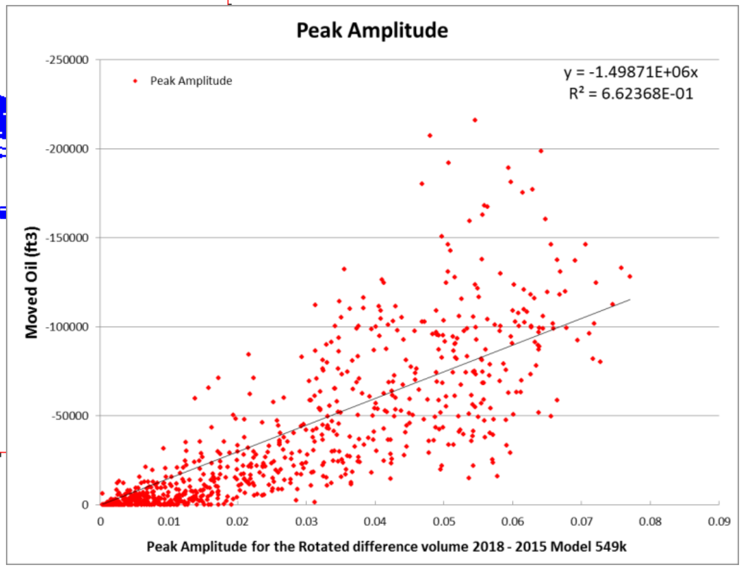


Synthetic seismic – quadrature of 4D difference

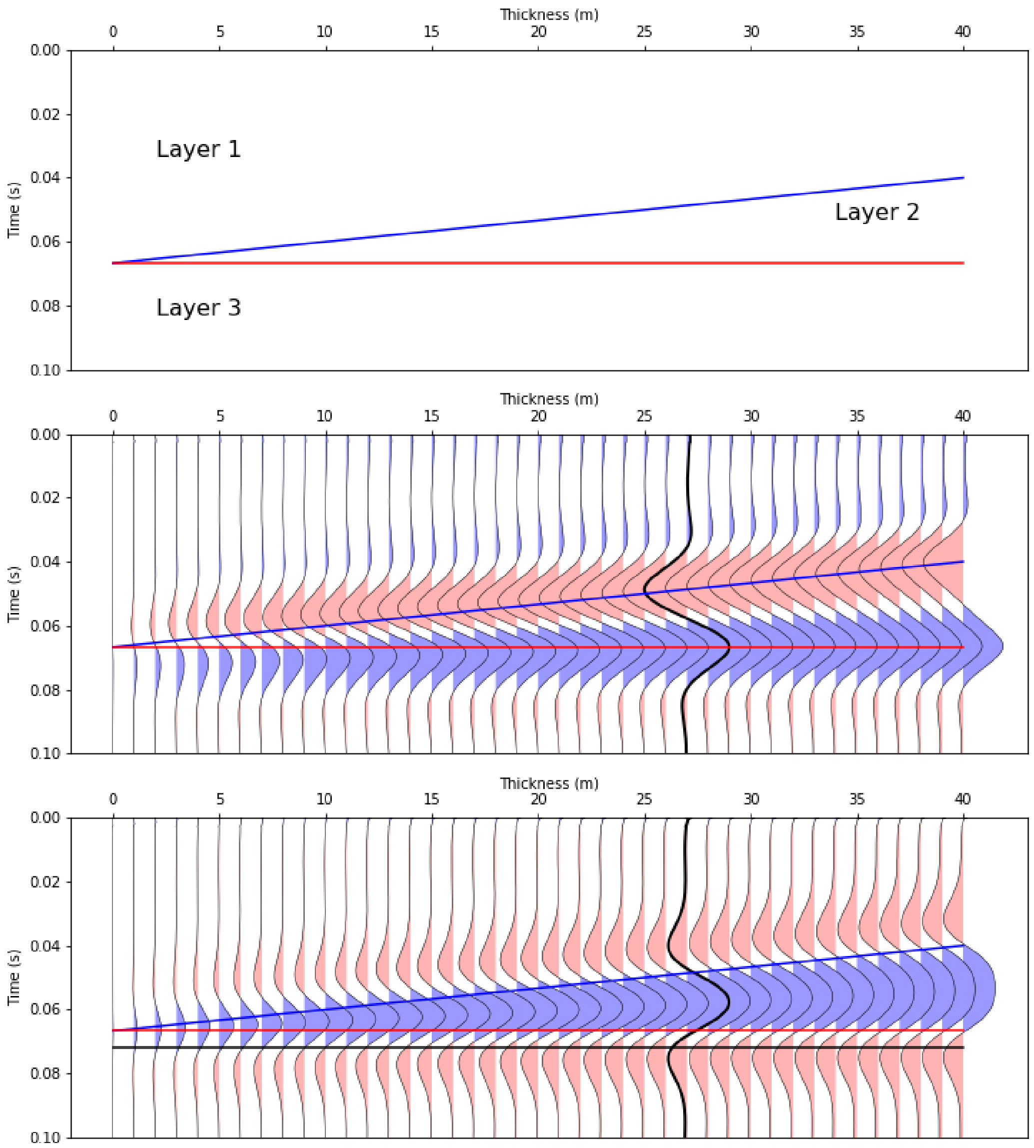


Robust correlation between amount of moved oil and maximum amplitude of the 4D quadrature in a window below BCU





4D-informed depth correction: some implementation details



20ms TWT ~ 100ft @ 3km/s

Thickness of swept layer

4D difference

Tuning thickness = 27m ~ 90ft

4D quadrature difference

Black line = Base + 5ms
(5ms ~ 25ft @ 3km/s)

Some simplifying assumptions:

- Homogeneous reservoir (NTG, POR, K)
- Uniform bottom-up sweep from initial to residual oil saturation
- Base of swept layer = OOWC = flat (equivalent to assuming that the base of our reservoir is always below the OOWC)
- Sharp saturation fronts
- Non-varying seismic wavelet
- Reservoir interval velocity not substantially affected by sweep

Observations:

- Base of swept layer correlates well to the lower zero crossing of the 4D quadrature, except when the swept layer is thin
- The lowermost image indicates that depth adjusting the 4D quadrature zero crossing to match the OOWC would incorrectly estimate the correction in the case of a thin swept interval

Application:

- Adjust the magnitude of the depth correction, using the amplitude of the 4D quadrature as a guide to the thickness of the swept interval

4D Seismic Noise Metrics

4D seismic noise levels are most commonly reported using the NRMS metric.

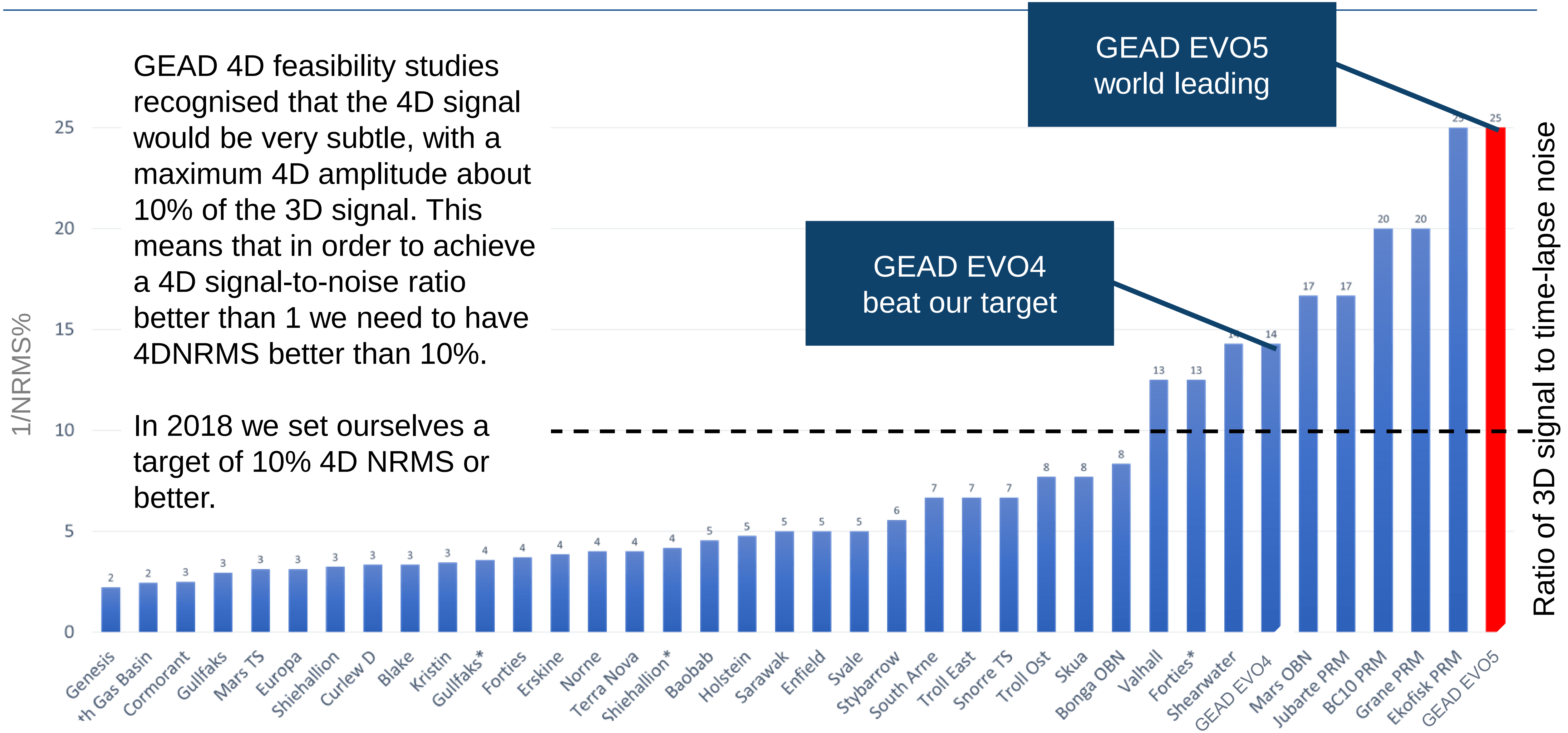
$$4D\ NRMS = \frac{RMS(monitor - base)}{0.5*[RMS(monitor) + RMS(base)]}$$

- Calculated over a window
- Displayed on a map
- Analysed in a histogram
- Summarised by one number (typically median)
- Reported numbers typically exclude noisy areas
  - for example the noisy area under a platform or a gas cloud could be excluded

Ratio of 3D signal to 4D noise

GEAD 4D feasibility studies recognised that the 4D signal would be very subtle, with a maximum 4D amplitude about 10% of the 3D signal. This means that in order to achieve a 4D signal-to-noise ratio better than 1 we need to have 4DNRMS better than 10%.

In 2018 we set ourselves a target of 10% 4D NRMS or better.



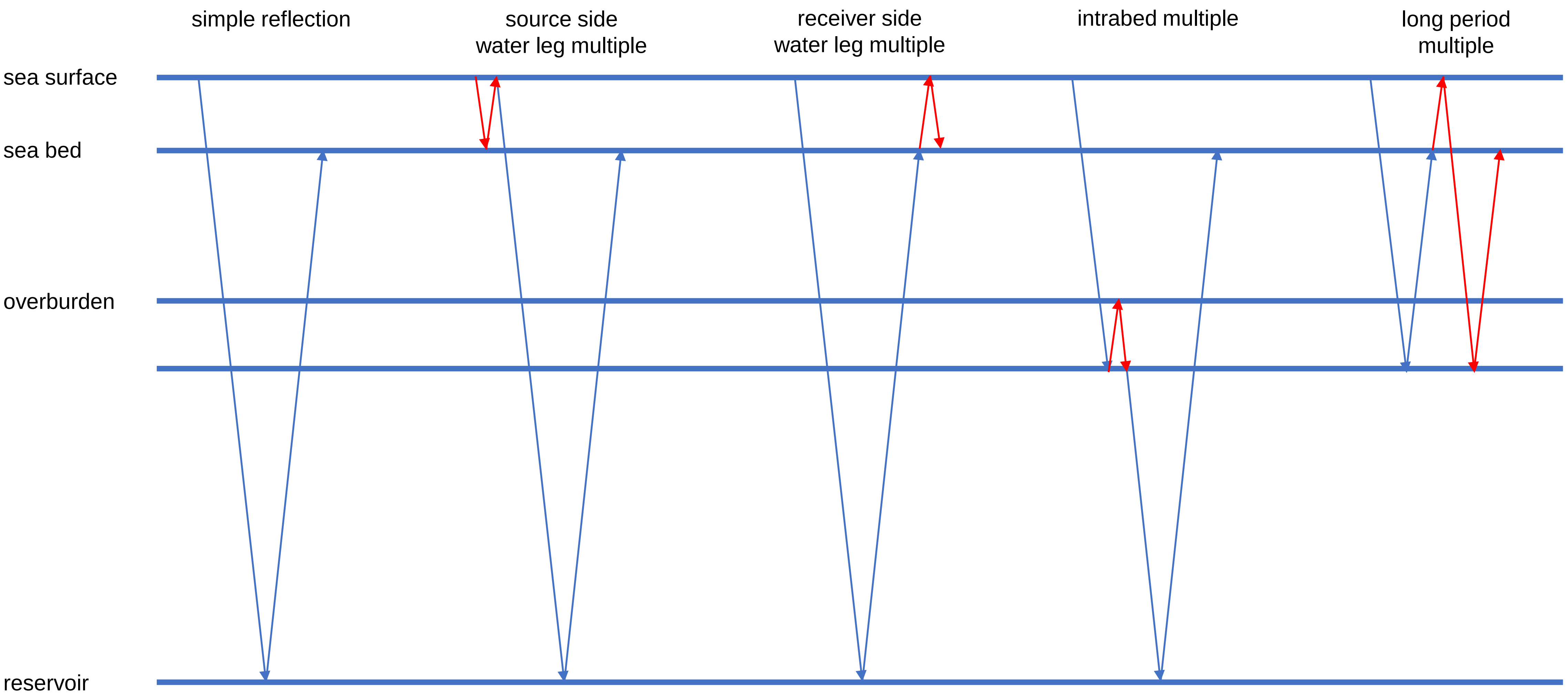
The following slides summarise the wavefield harmony "trick" that took us from EVO4 to EVO5, improving 4D noise levels from 8% to 4.4% 4DNRMS, a world-leading outcome.

Edited based on V.Omofoma 2017

Improving 4D Noise Levels Using 4D Wavefield Harmony

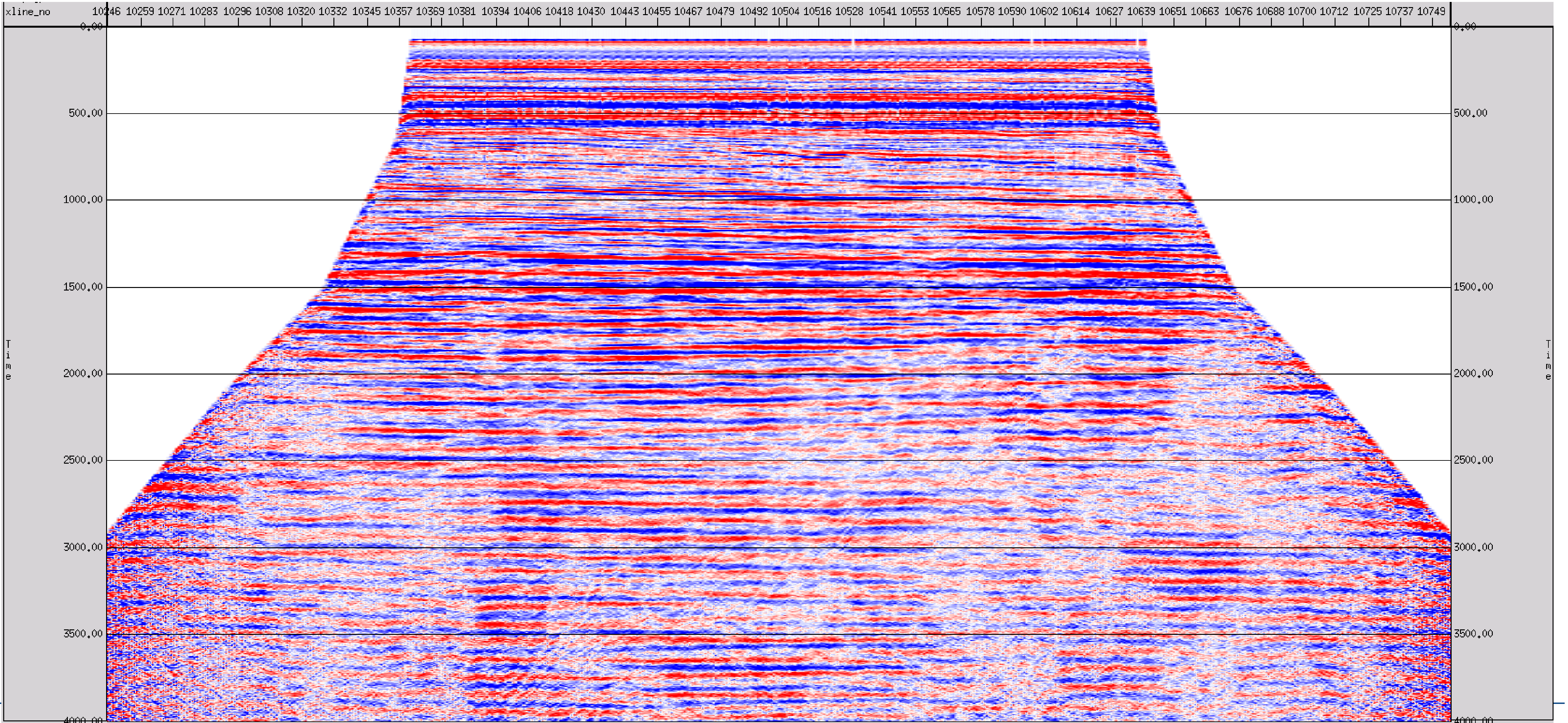
- What are seismic “multiples” and why do they matter to GEAD?
- What is special about OBN seismic that helps us tackle multiples?
- What is PZ summation (essential concept only)?
- What are these wavefields and what are the implications for GEAD 4D?
  - upgoing
  - downgoing
  - reflectivity
- What do we have to do to achieve harmony between wavefields?
- What are the key advantages of achieving 4D wavefield harmony for GEAD?

What are seismic multiples?



Why do multiples matter to GEAD?

This is a brute stack seismic line from onboard processing during the 2018 GEAD seismic acquisition. Almost all of the energy on this plot is water leg multiple.



Ocean Bottom Nodes contain both hydrophones and geophones

Hydrophones

- A hydrophone is a **pressure** sensor designed to be used underwater.
- The measurement of pressure is **insensitive to the direction of propagation** of the seismic energy.
- Hydrophones **detect only P waves**.

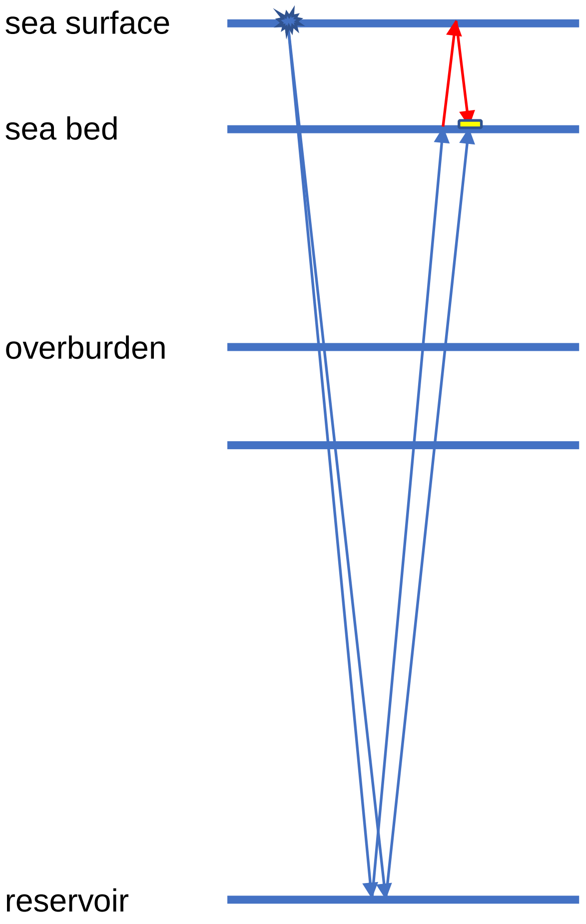
Geophones

- A geophone measures movement – either **velocity** or **acceleration**.
- A 3-component geophone measurement is **directional** – delivers a **vector** with (x, y, z) component.
- Geophones **detect P-waves, S-waves and surface waves**.

Why is this important?

- One of the key advantages of OBN seismic is that we can identify and remove certain modes of seismic multiple energy by exploiting the different characteristics of hydrophones and geophones.

The essence of PZ summation



The primary reflection is recorded as a positive value on both the hydrophone and geophone.

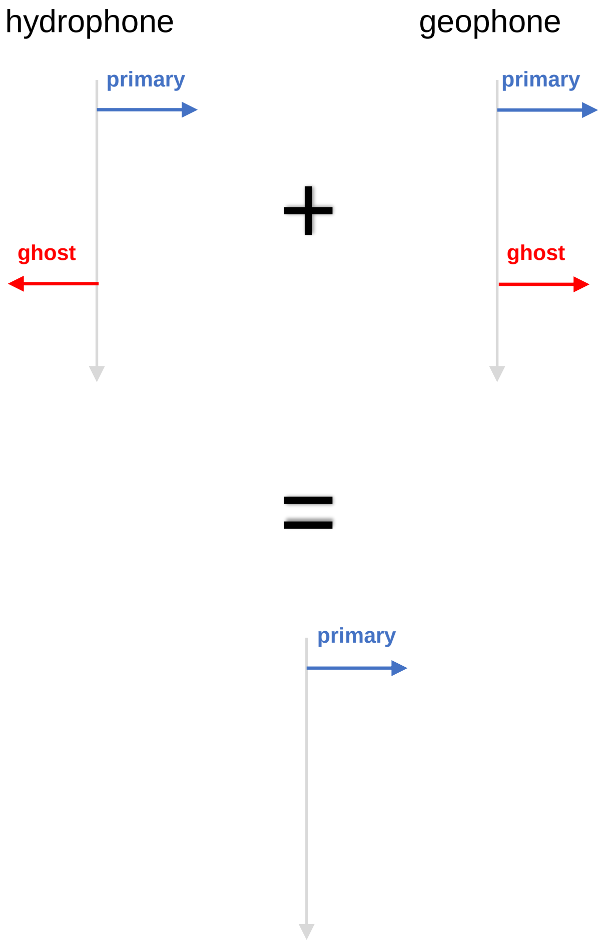
The receiver side water leg multiple (also known as the receiver ghost) is reflected off the sea-surface (which has a reflection coefficient of -1) so has opposite polarity to the primary reflection.

The hydrophone therefore records a negative value.

However the geophone records a positive value because although the polarity is reversed the ghost arrives as a downward motion.

If we add the hydrophone and geophone and then divide this summed trace amplitude by 2 we are left with a trace where the primary has been preserved but the receiver ghost has been eliminated.

This is the essence of PZ summation.

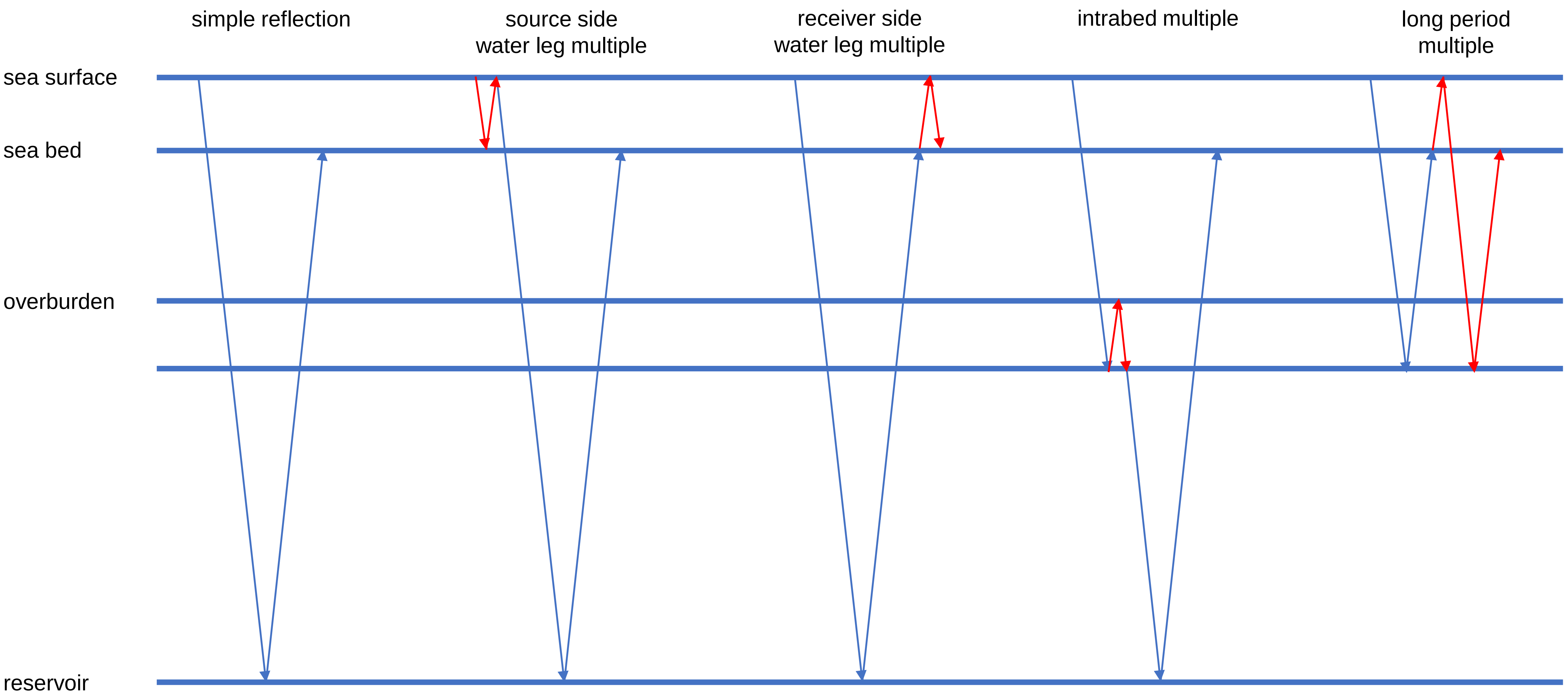


One step beyond the conceptual essence

- The previous explanation of the conceptual essence of PZ summation does not include some physical behaviour which is important in the real world
- Explaining these details is beyond the scope of this presentation
- However, in essence
  - upgoing wavefield = P + Z
  - downgoing wavefield = P – Z

- It is important to recognise that the upgoing and downgoing wavefields still contain many multiples
- For example, the upgoing wavefield includes source-side water-leg multiples and interbed multiples

After PZ sum the upgoing wavefield still contains many multiples



One step further

- Having calculated upgoing and downgoing wavefields we can go one step further to calculate a reflectivity wavefield
- In summary U = D ⊗ R

  Where the operator ⊗ represents convolution

  U is the upgoing wavefield

  D is the downgoing wavefield

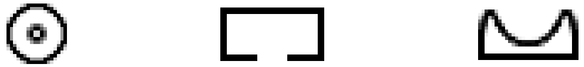
  R is the reflectivity
- In order to estimate the reflectivity we need to run a deconvolution process
- Successful PZ summation and up-down decon requires very careful processing, for example
  - calibration of geophone-to-hydrophone response
  - estimation of seabed reflectivity
  - handling of different noise character on hydrophone and geophone

The steps to 4D wavefield harmony

- PZ summation allows separation into upgoing and downgoing wavefields
- Reflectivity can be estimated using up-down deconvolution
  - removes all water leg multiples
  - provides a model of multiple energy which can be used in de-multiple processing of the upgoing wavefield
  - has several other advantages for 4D processing
- After separation into upgoing, downgoing & reflectivity wavefields we still need to perform demultiple processing, de-noise, migration, residual demultiple, gather flattening, waveform shaping etc
- It is not usual to take all three wavefields through the full processing sequence, but if done it would be standard to adjust the processing flow for each wavefield until it was judged optimal for that wavefield. Such optimisation causes subtle differences between wavefields, so they cannot be simply combined to reinforce 4D signal and cancel noise.
- We processed all three wavefields ensuring consistent frequency content between the 4D upgoing, downgoing and reflectivity wavefields and consistent event timing with the 3D imaging result.
- Harmony among our wavefields enabled two innovations. Firstly, pre-stack co-denoise and summation of the 4D response from the upgoing, downgoing and reflectivity wavefields. This improved 4D noise levels from 8% to 4.4% 4DNRMS, a world-leading outcome. Secondly, we updated our depth conversion of the 3D image by relating the amplitude and vertical position of the 4D response to the OOWC.

The Rosetta Stone – Learning to Read Egyptian Glyphs

- Around 2,000 years ago a message was carved into the Rosetta Stone using both Egyptian hieroglyphs and Greek
- When the Rosetta Stone was found in Egypt in 1799 the meaning of the Egyptian hieroglyphs had been lost
- Because the stone shows the same message in two different languages it was possible to learn the translation from hieroglyphs to Greek



sun **house** **mountain**

- With the learning from this one stone it was then possible to translate thousands of other ancient Egyptian inscriptions

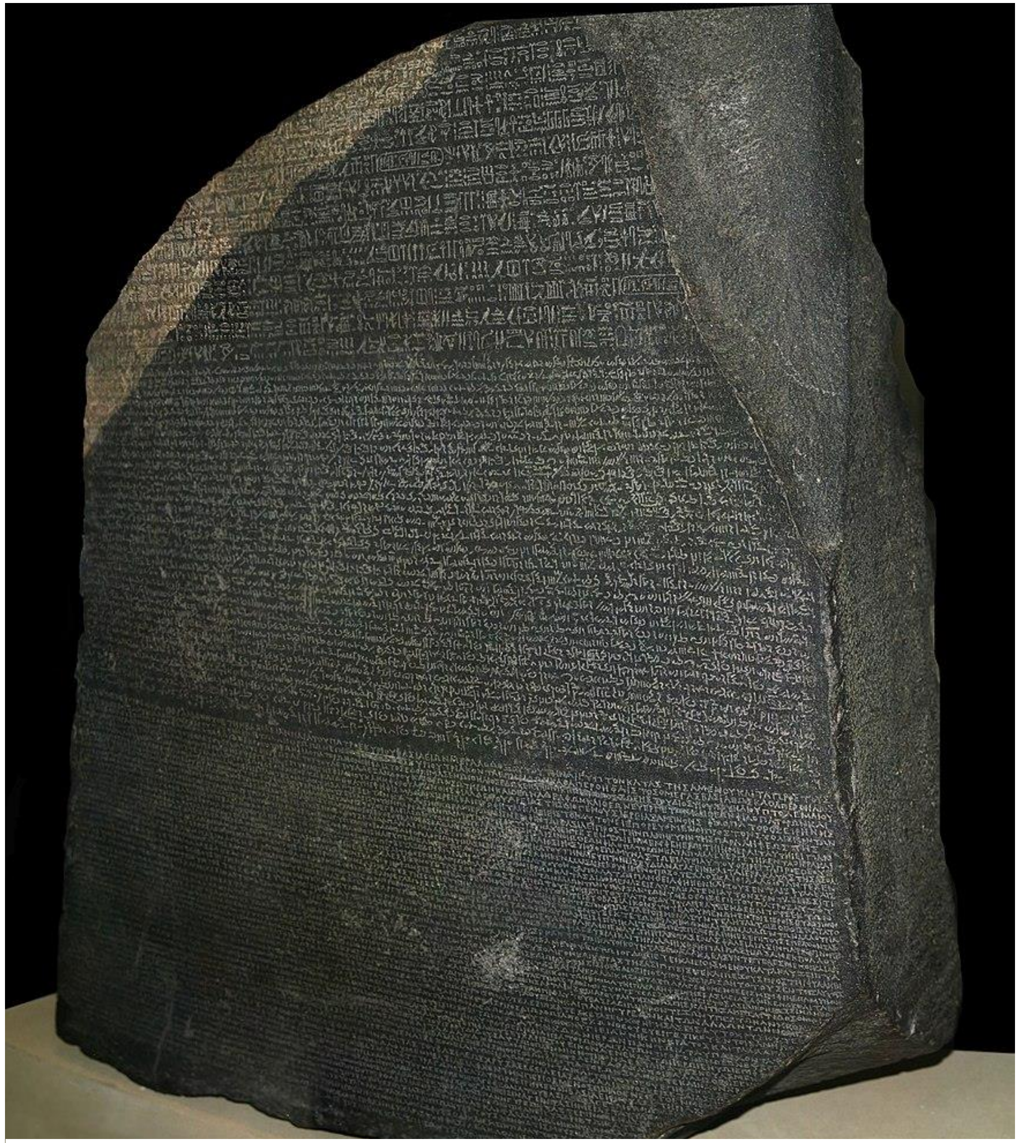
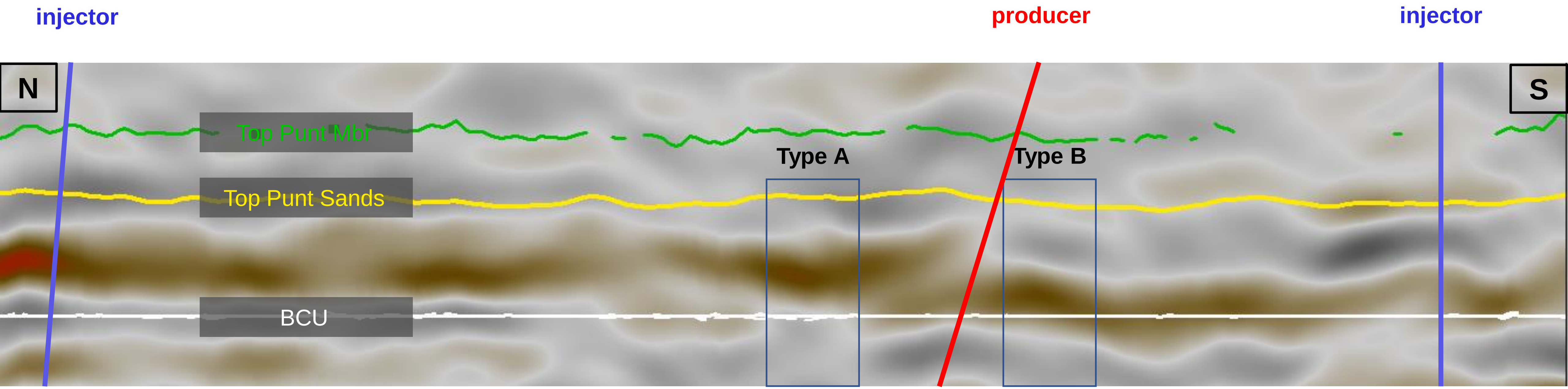


Image credits: © Hans Hillewaert https://commons.wikimedia.org/wiki/File:Rosetta_Stone.JPG

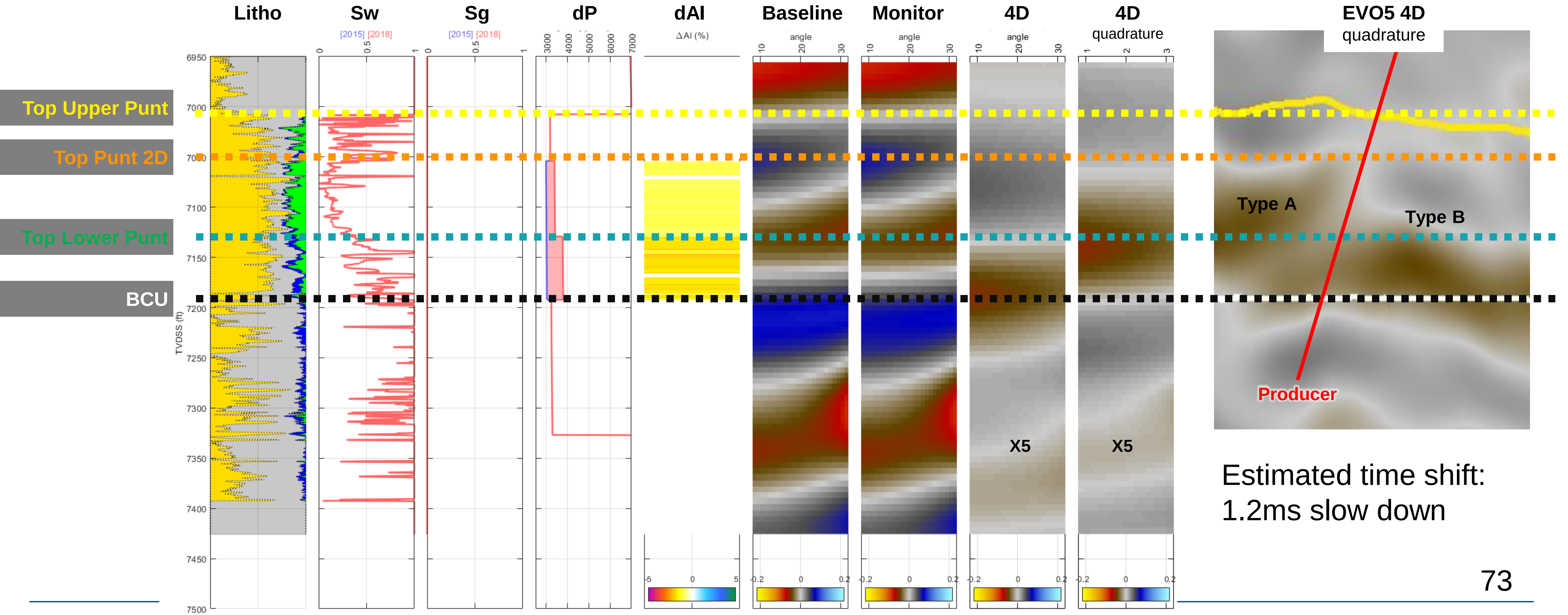
Learning to Read 4D Seismic Glyphs

- This seismic section shows the observed GEAD 4D difference quadrature on a line along the Punt channel sands which lie between Top Upper Punt (yellow horizon) and the BCU (white horizon)
  - the section has been flattened on the BCU
  - red indicates a softening, associated with pressure increase in the Punt
- In this area the Golden Eagle Punt has consistent 3D seismic character but there is a change in the 4D seismic character which happens from the North to South sides of the Producer
  - North of the producer, the 4D quadrature shows broad red (Type A)
  - South of the producer, the 4D quadrature shows blue-over-red (Type B)
- We need a "4D seismic Rosetta Stone" to help us learn what these 4D seismic characters mean



"No Sweep" Scenario

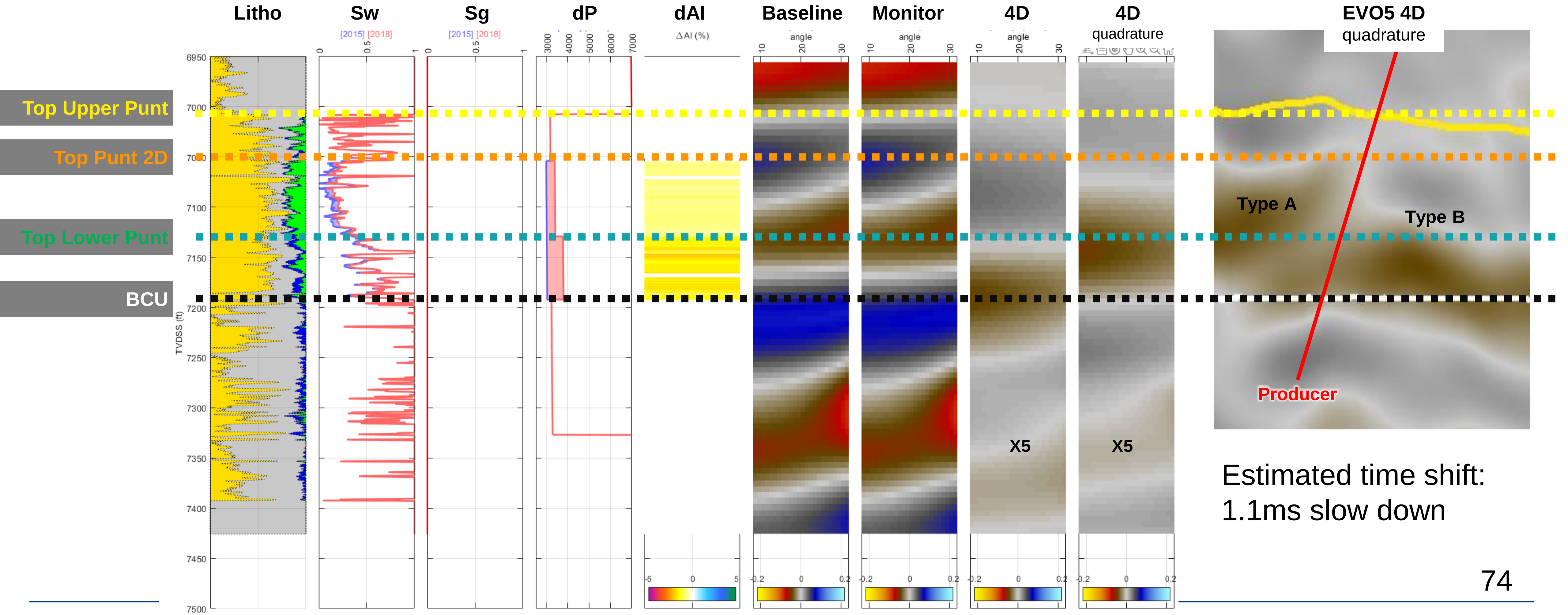
- In this scenario there is no water sweep. The 4D synthetic character is a good match to the "Type A" character, with 4D quadrature showing a broad red (soft) loop positioned quite centrally in the Punt. However the estimated time shift is significantly larger than observed.



Estimated time shift:
1.2ms slow down

“Sweep 10% of movable oil” Scenario

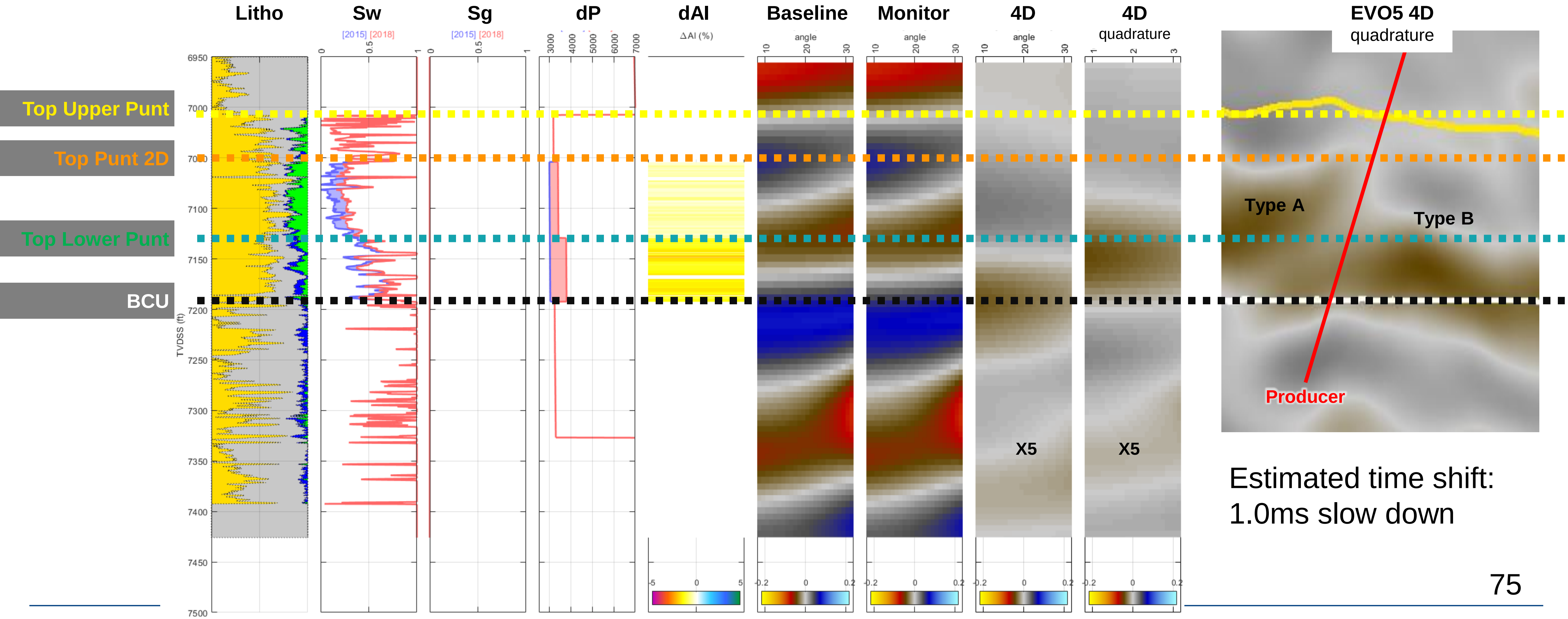
- In 10% water sweep scenario the 4D synthetic character is a good match to the “Type A” character on the northern side of on the northern side of the producer. However the estimated time shift is larger than observed.



Estimated time shift:
1.1ms slow down

“Sweep 20% of movable oil” Scenario

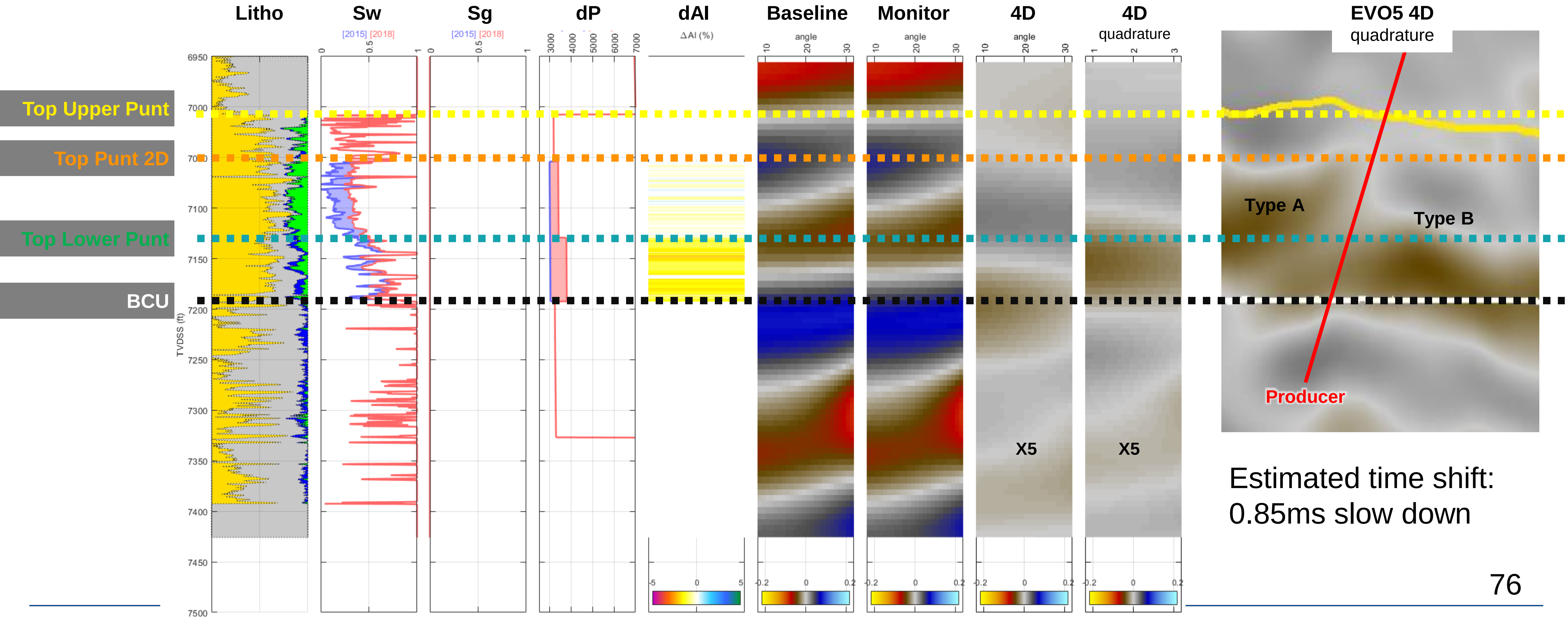
- In the 20% sweep scenario the 4D synthetic character is dominated by a red (soft) response but that response sits deeper in the section than observed on the northern side of the producer. The estimated time shift is larger than observed.



Estimated time shift:
1.0ms slow down

“Sweep 30% of movable oil” Scenario

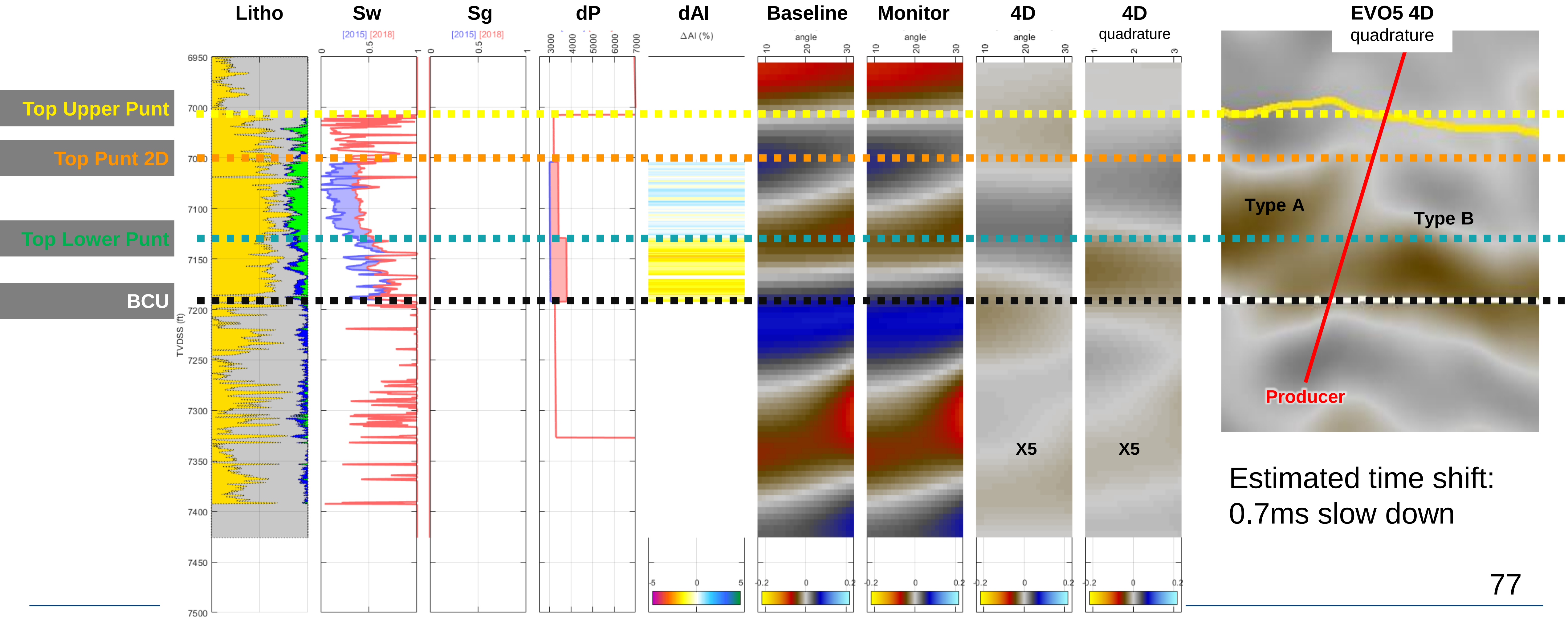
- In the 30% sweep scenario the 4D synthetic character is dominated by a red (soft) response but an upper blue (hard) loop is starting to develop. The estimated time shift is a little larger than observed.



Estimated time shift: 0.85ms slow down

“Sweep 40% of movable oil” Scenario

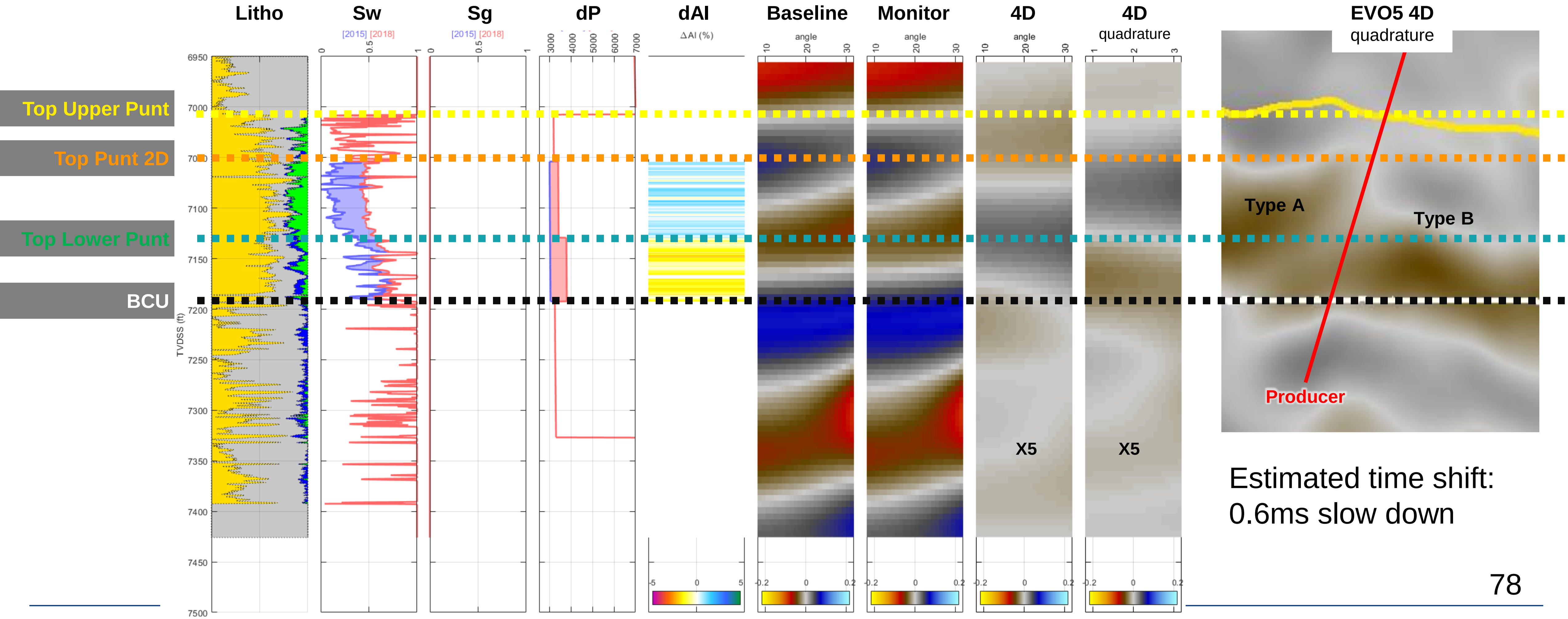
- In the 40% sweep scenario the 4D synthetic character is a good match for the “Type B” character, showing an upper blue (hard) above a slightly brighter red (soft). The estimated time shift is similar to the maximum observed near the producer.



Estimated time shift:
0.7ms slow down

"Sweep 50% of movable oil" Scenario

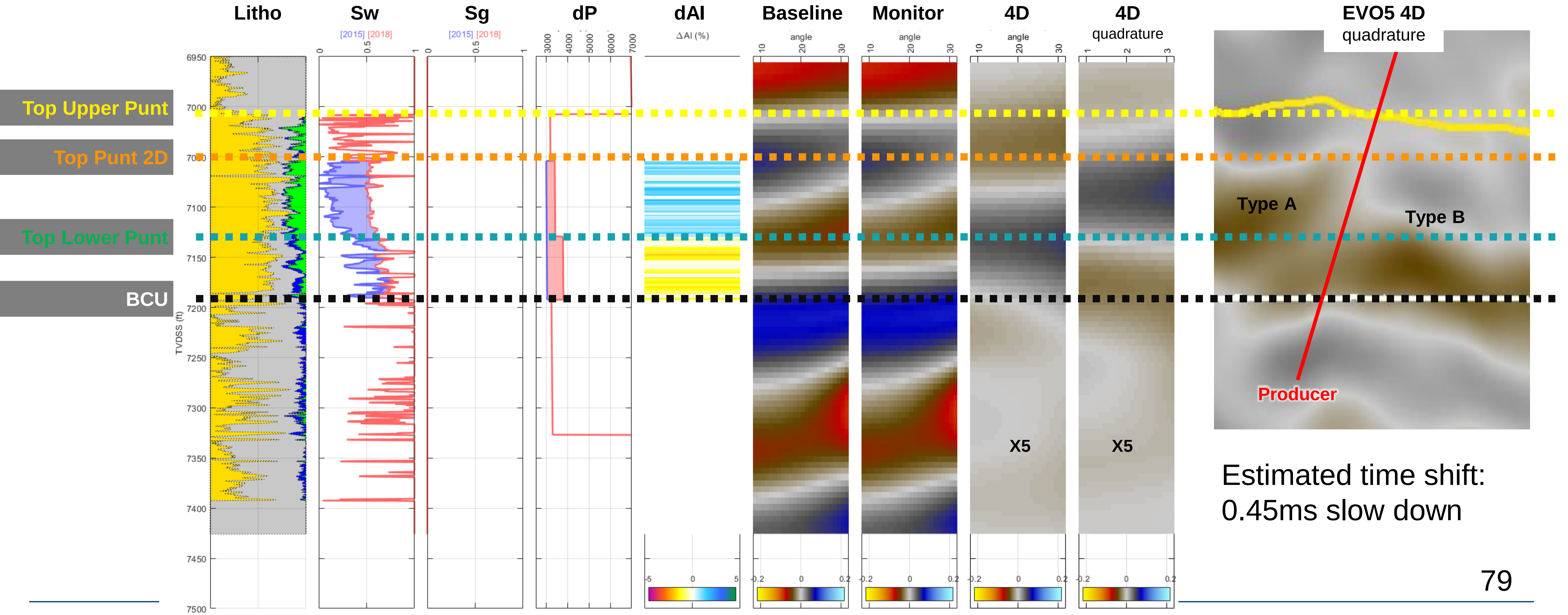
- In the 50% sweep scenario the 4D synthetic character is a fair match for the "Type B" character, showing an upper blue (hard) above a red (soft) of similar amplitude. The estimated time shift is similar to some observations near the producer.



Estimated time shift:
0.6ms slow down

“Sweep 60% of movable oil” Scenario

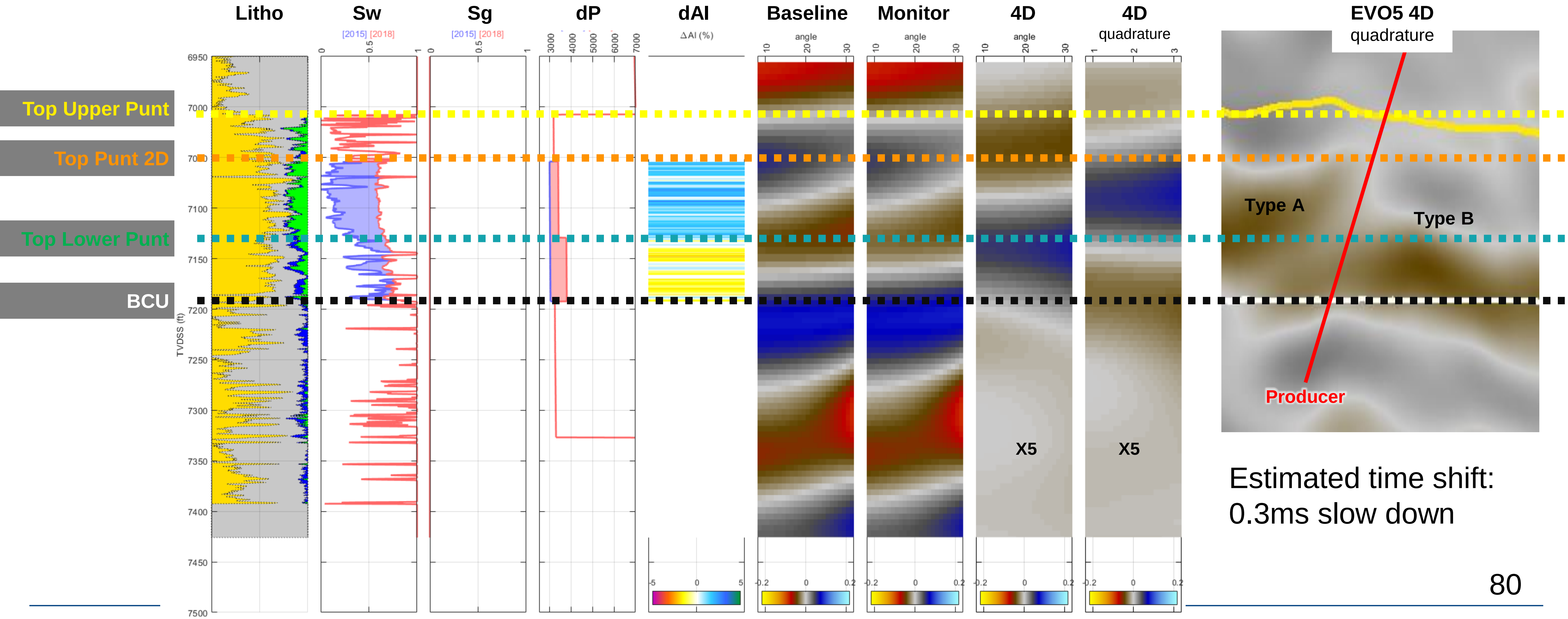
- In the 60% sweep scenario the 4D synthetic character shows a fair match for the “Type B” character, although the upper blue (hard) is becoming brighter than the underlying red (soft). The estimated time shift is similar to observations near the producer.



Estimated time shift:
0.45ms slow down

“Sweep 70% of movable oil” Scenario

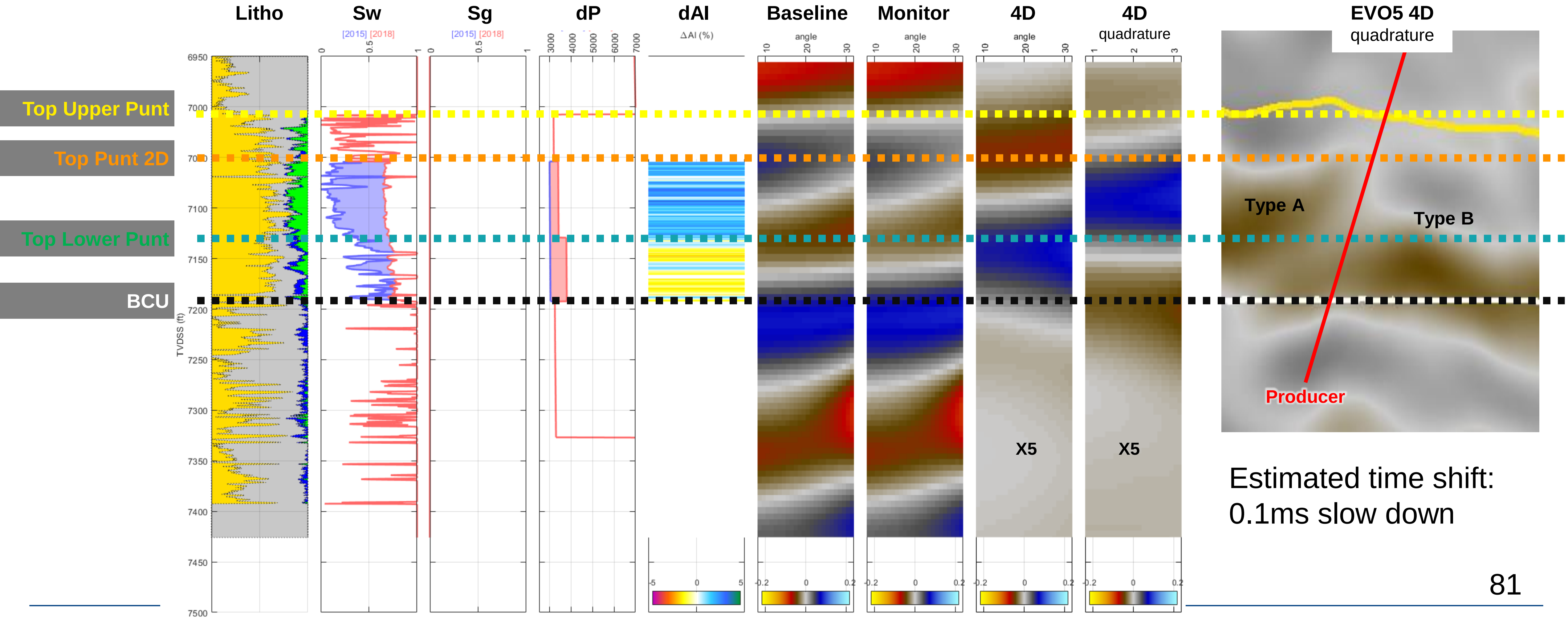
- In the 70% sweep scenario the 4D synthetic character shows a poor match for the “Type B” character and is generally too bright. The estimated time shift is smaller than most observations near the producer.



Estimated time shift:
0.3ms slow down

“Sweep 80% of movable oil” Scenario

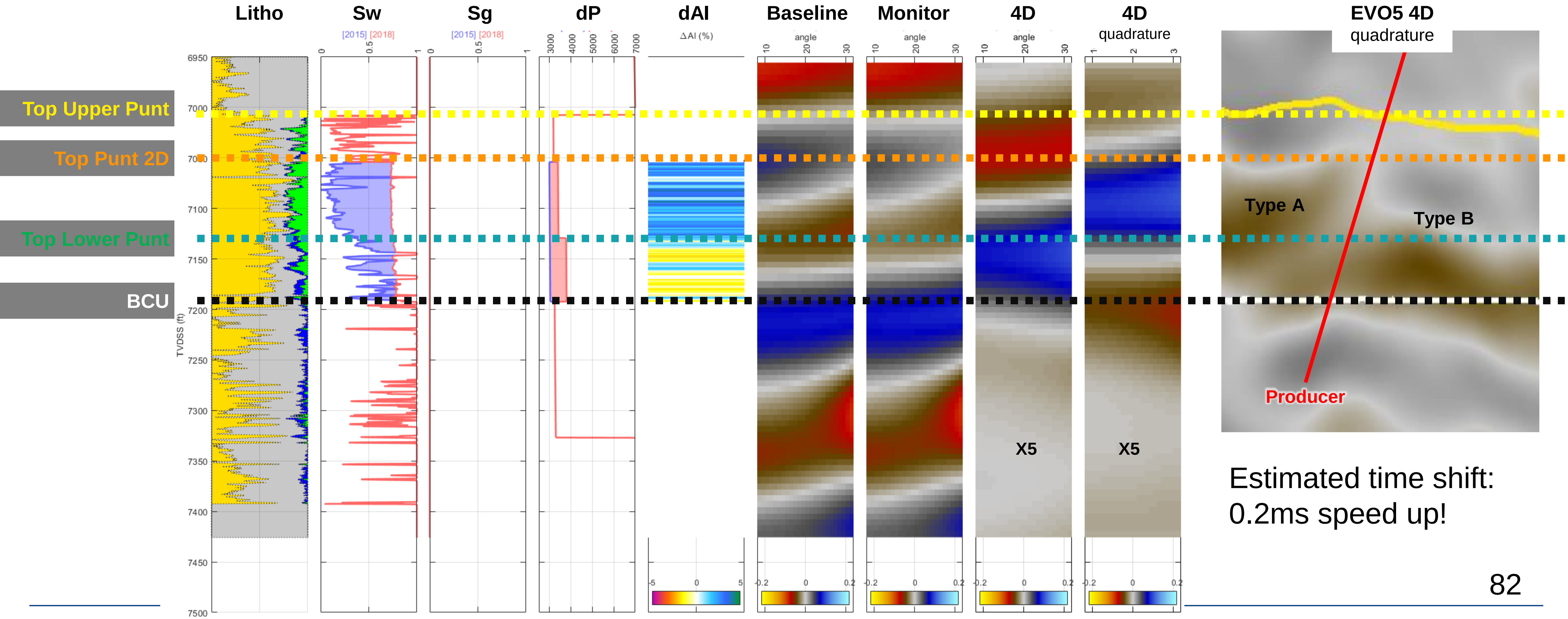
- The 80% water sweep scenario does not match observations. The modelled response is very bright and predicted time shift is almost zero.



Estimated time shift:
0.1ms slow down

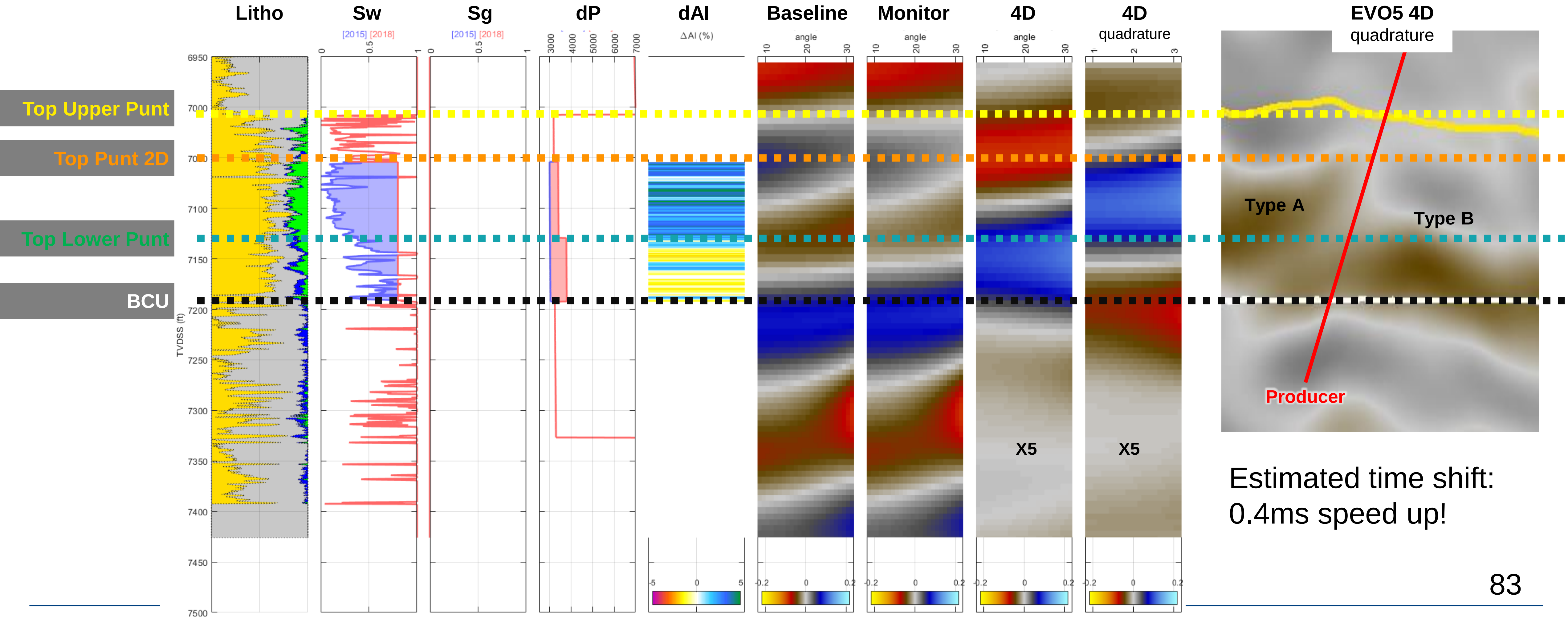
"Sweep 90% of movable oil" Scenario

- The 90% water sweep scenario does not match observations. The modelled response is very bright and results in a time shift which is a speed up, rather than a slow down.



"Sweep 100% of movable oil" Scenario

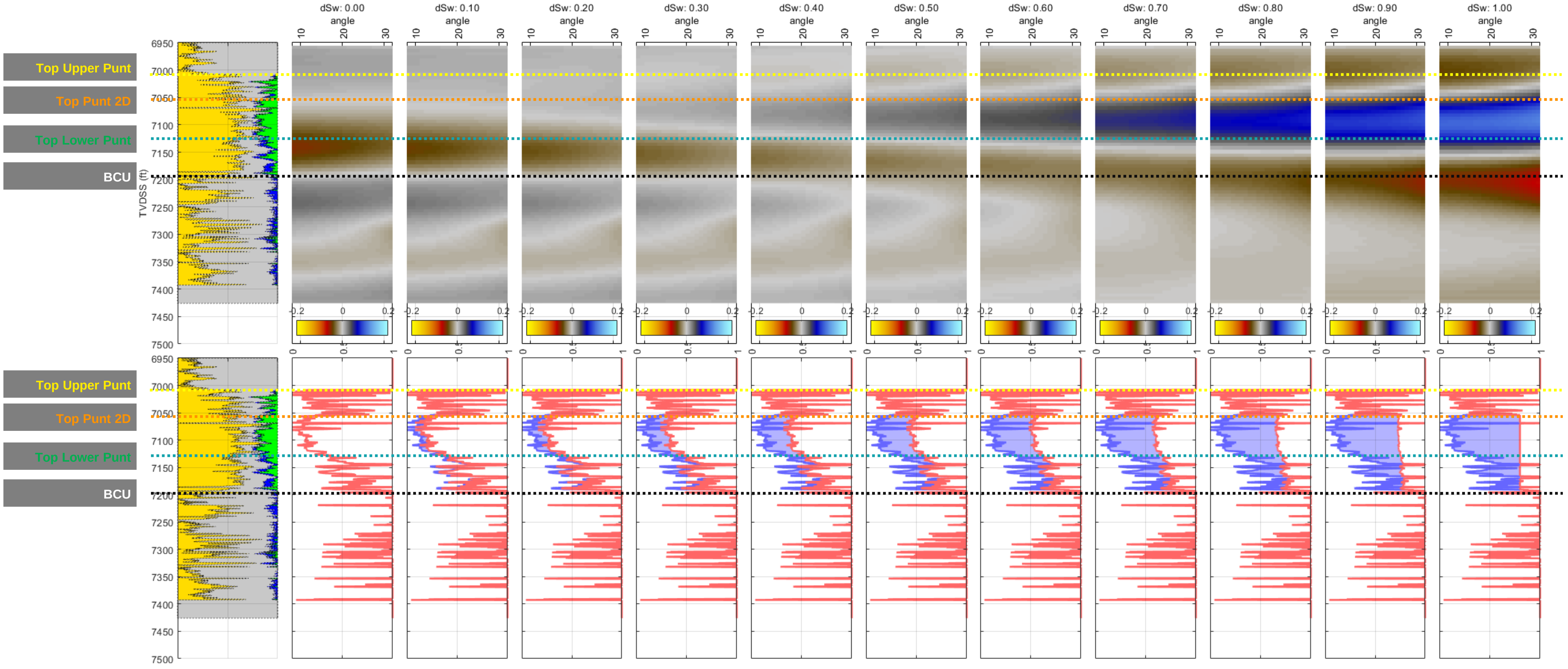
- The 100% water sweep scenario does not match observations. The modelled response is extremely bright and results in a time shift which is a speed up, rather than a slow down.



Estimated time shift:
0.4ms speed up!

4D Response Panel: Edge Drive From the Southern Injector

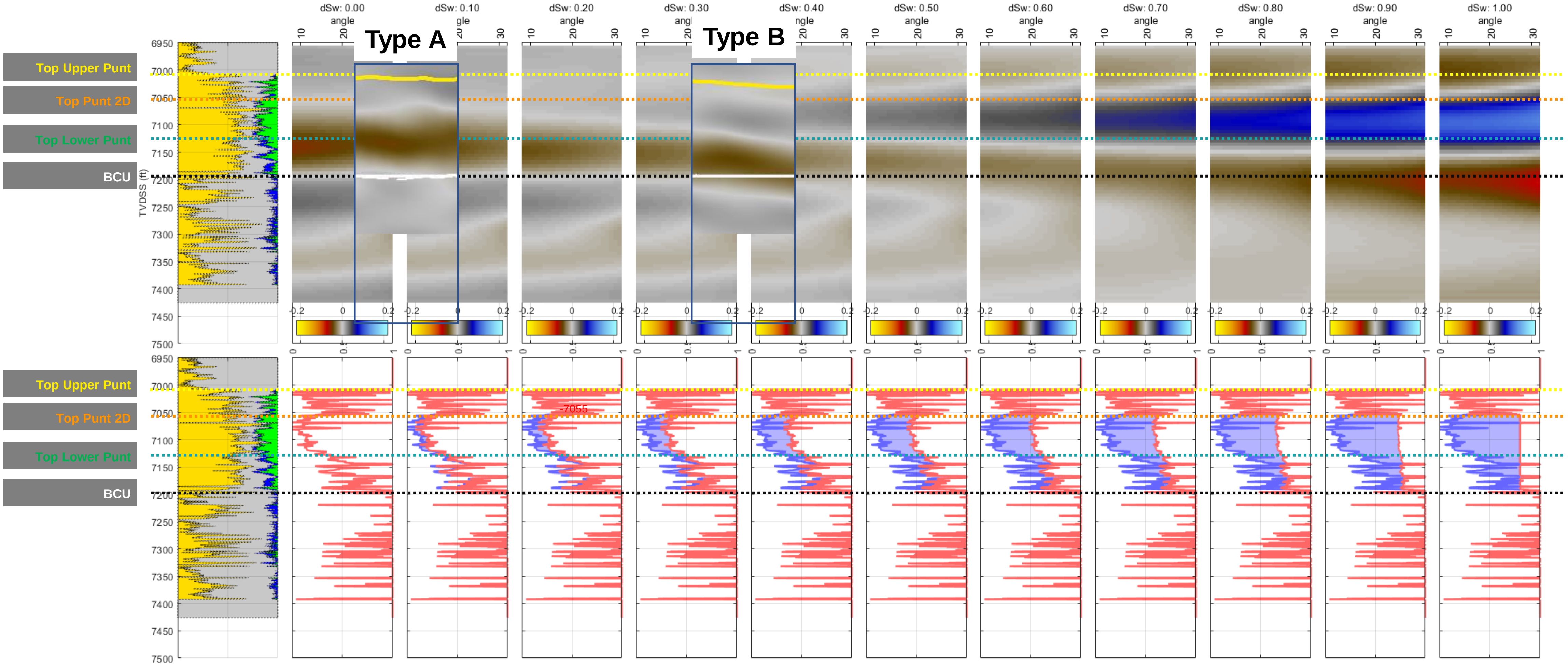
This response panel is our "Rosetta Stone". It connects the languages of geology, petrophysics, reservoir engineering and 4D seismic. The upper panel shows the synthetic 4D seismic character while the lower panel shows the equivalent sweep pattern. The same pressure changes are used in each track.



4D Response Panel: Edge Drive From the Southern Injector

Type A seismic character matches 0 to 10% sweep.

Type B seismic character matches 30 to 40% sweep.



4D Response Panel: Edge Drive From the Southern Injector

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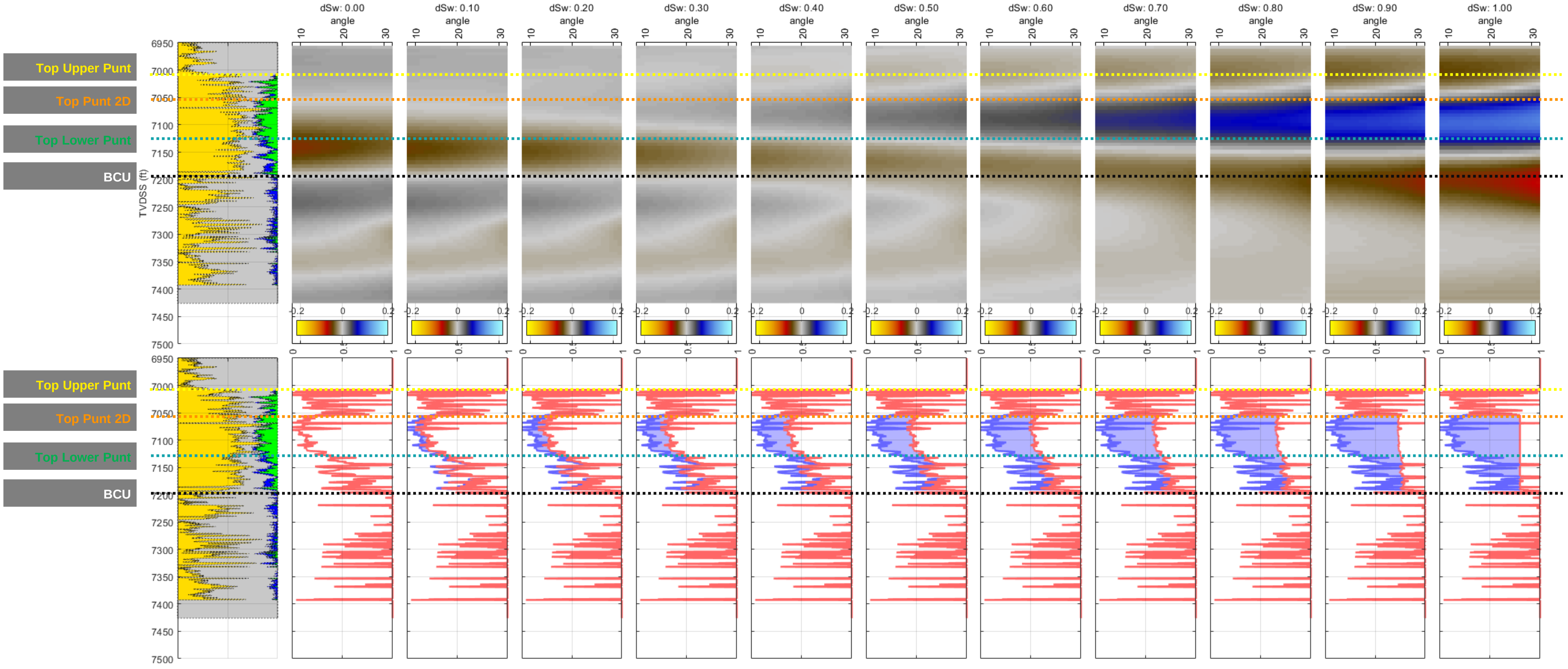
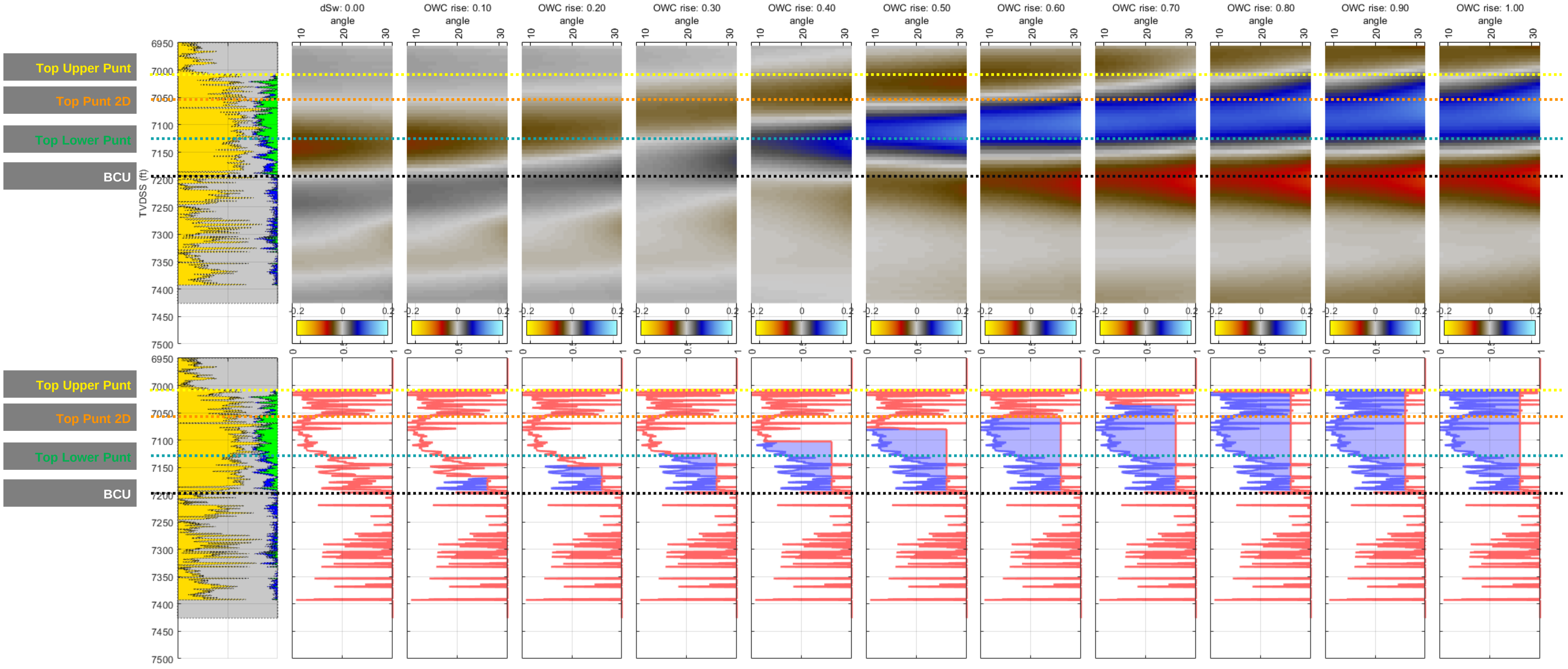


4D Response Panel: Bottom Up Sweep in Punt

These cases with ΔP but little ΔS still match Type A seismic character.

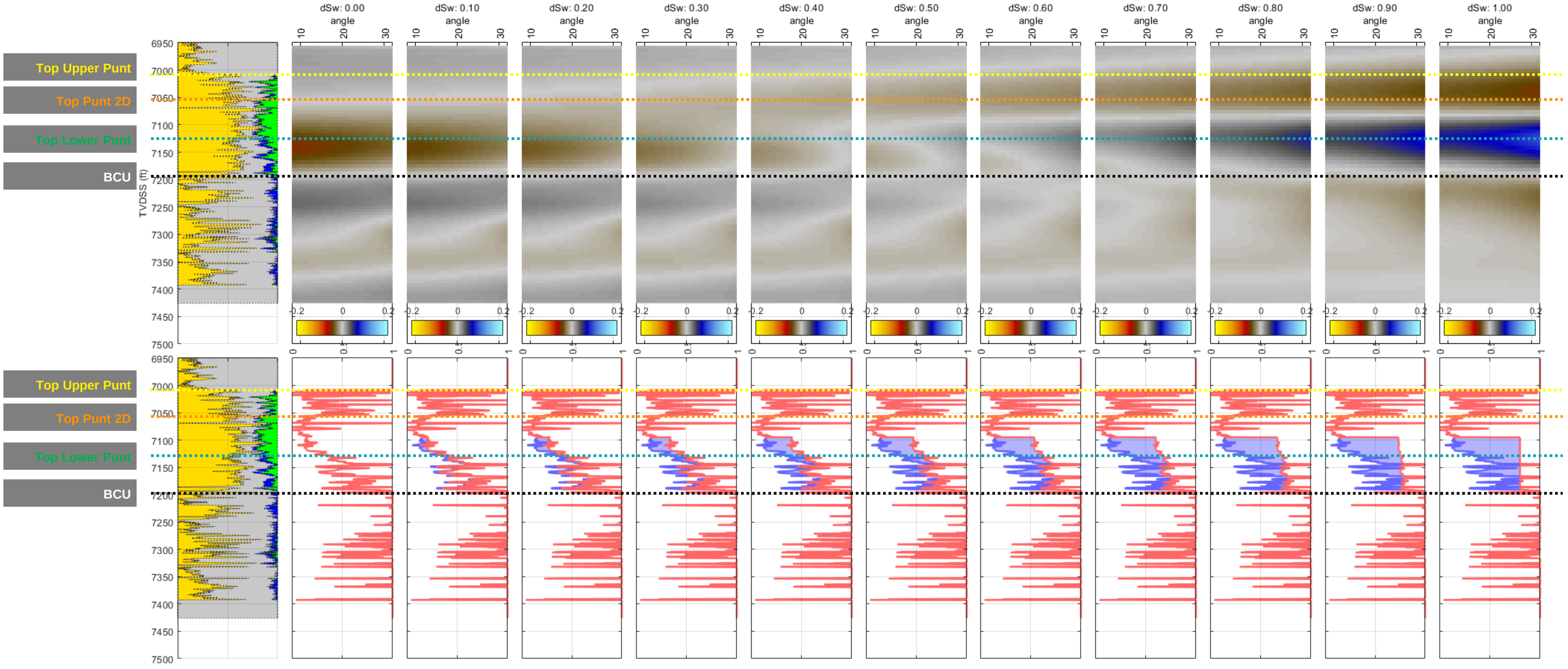
This response panel does not have a good match to a Type B seismic character. If we model bottom-up sweep in the Punt we cannot match the observed 4D.



4D Response Panel: Only Lower Half of Punt Is Swept

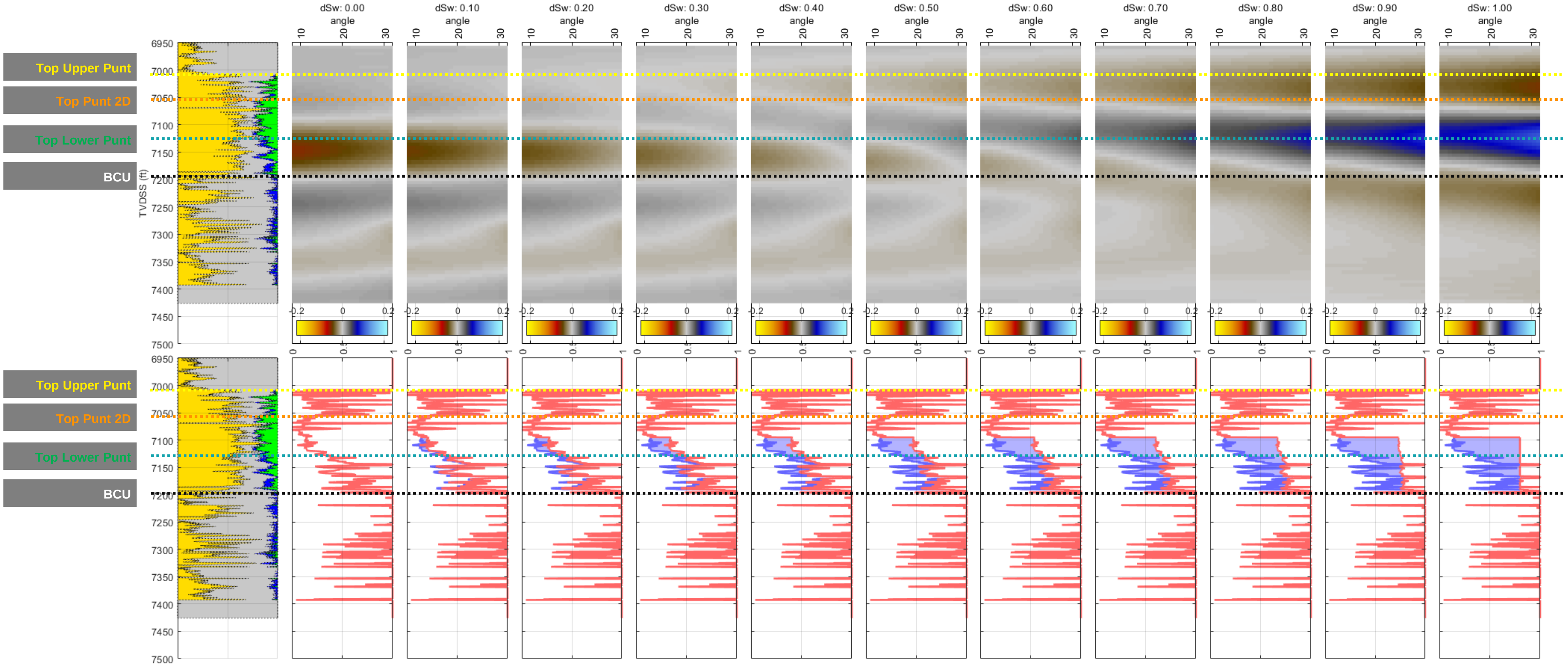
These cases with ΔP but little ΔS still match Type A seismic character.

This response panel does not have a good match to a Type B seismic character. If we model bottom-up sweep in the Punt we cannot match the observed 4D.



4D Response Panel: Only Lower Half of Punt has ΔS ΔP

In this response panel pressure and sweep are only applied to the lower half of the Punt sand.
This response panel does not contain a good match to either Type A or Type B character.



Summary Observations

- In the area around this production well the Golden Eagle Punt has consistent 3D seismic character but there is a change in the 4D seismic character at the production well
  - North of the producer 4D quadrature shows broad red (4D seismic character type A)
  - South of the producer 4D quadrature shows blue-over-red (4D seismic character type B)
- Modelling of the 4D seismic response using pressure changes estimated from well data demonstrates that
  - broad red 4D quadrature signature (type A) is consistent with pressure increase but little to no sweep on the northern side of the producer
  - blue-over-red 4D quadrature character (type B) is consistent with pressure increase and edge-drive sweep from G10 on the southern side of the producer
- Sensitivity testing indicates that
  - type B character is best-matched by ~40% sweep in Punt 2D, which is consistent with observed water cut
  - bottom-up sweep in Punt does not reproduce type B character
  - unrealistic pressure change scenarios do not reproduce type A or type B

Summary Conclusions

- We have developed a new way of presenting pressure and saturation responses which enables an easy visual connection between different sweep scenarios and 4D seismic responses
- Our 4D response panels act as a "Rosetta Stone" allowing a translation between the languages of reservoir engineering and 4D seismic
- Learning how to translate this language allows semi-quantitative interpretation of pressure and saturation signals around this Punt production well
- This 4D seismic analysis supports the interpretation of efficient edge-drive sweep from the southern injector to this producer and inefficient sweep on the "lazy side" north side, at the time of the monitor survey (Sep 2018)
- The analysis also allows us to identify some sweep patterns that do not match observations
  - for example, bottom-up sweep in the Punt 2D does not match observed 4D seismic response

Further Work

- In this "Rosetta Stone" approach we are making a visual judgement of the match between observed 4D seismic character and synthetic results made from modelling just a few sensitivities for just two highly simplified sweep style scenarios
- This is significantly more cases than we had modelled before and the results were valuable
- However our colleagues immediately thought of more scenarios and more sensitivities to run
- We could very quickly move into a world where we have hundreds of response panels to compare with our observed 4D
- This motivates a change from human-performed comparisons to machine-performed comparisons following the "Physics-driven machine learning" paradigm