Improving 4D signal to noise and reducing depth uncertainty using 4D seismic wavefield harmony

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Acknowledgements

- Golden Eagle coventurer group
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  - Craig Lawrie for encouragement to process all three wavefields which ultimately led us to seismic harmony
- Many, many helpful contacts in the wider 4D seismic community and in particular from the Edinburgh Time Lapse Project at Heriot Watt University

Outline

Part One: Assuring 4D success without excessive cost

- Some metrics to help get the cost vs quality balance right for your project

Part Two: Achieving exceptional 4D signal to noise in a difficult data area

- There is no “free lunch” and the basics still apply
- But using a new “wavefield harmony” method delivered a breakthrough improvement in signal to noise

Part Three: Impact on Golden Eagle

- Reservoir model update example
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- Our most successful infill well

Assuring 4D seismic success without excessive cost

- Several case studies demonstrate that in difficult data areas the quality of 3D and 4D seismic images can be improved by using high density OBN seismic acquisition
- However, increasing acquisition density comes at a cost
- Assuring 4D success without excessive cost is a priority for any 4D project
- Carbon sequestration projects can expect the regulator to require assurance that their seismic measurement, monitoring and verification (MMV) programme will detect 4D signals with confidence

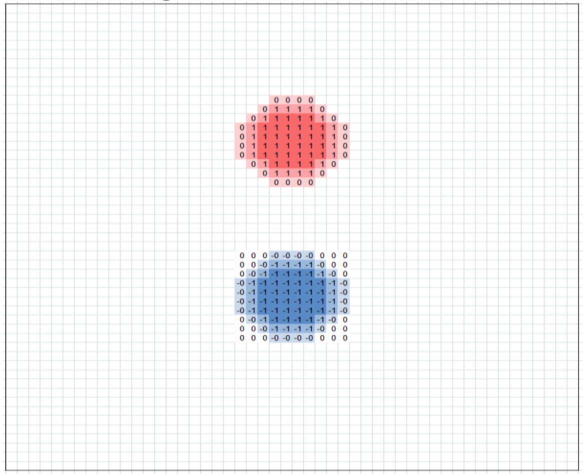
- Some metrics to help get the cost vs quality balance right for your project
  - Ratio of 4D signal to 4D noise
  - Ratio of 4D signal to 3D amplitude
  - Ratio of 3D amplitude to 4D noise

Ratio of 4D signal to 4D noise

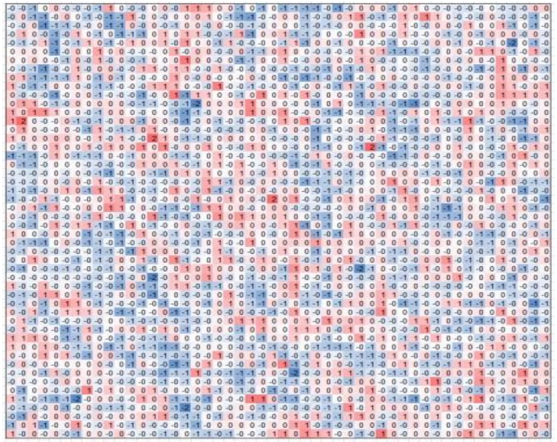
- To observe a signal with confidence, what ratio of 4D signal to 4D noise do we need?

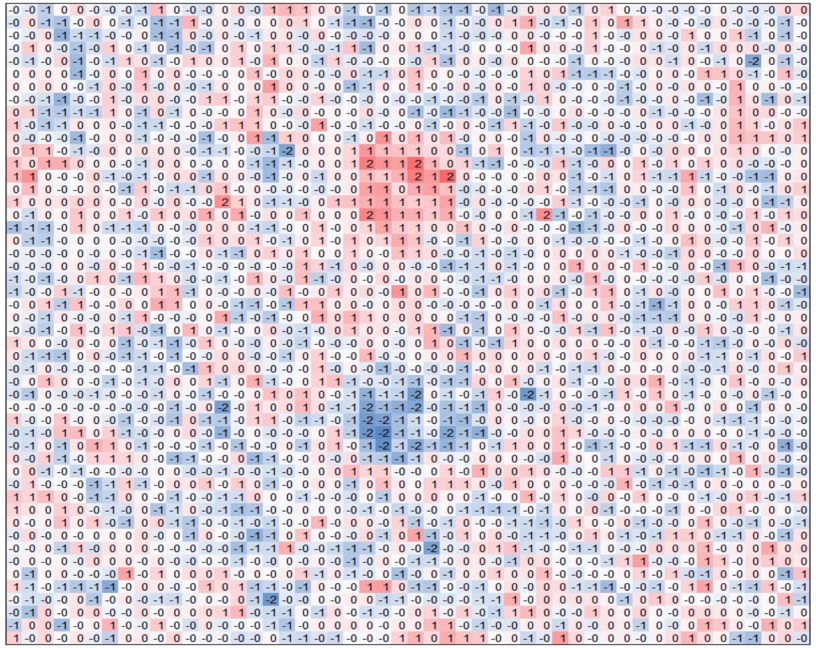
- What is the impact of the coherency of noise?

4D Signal



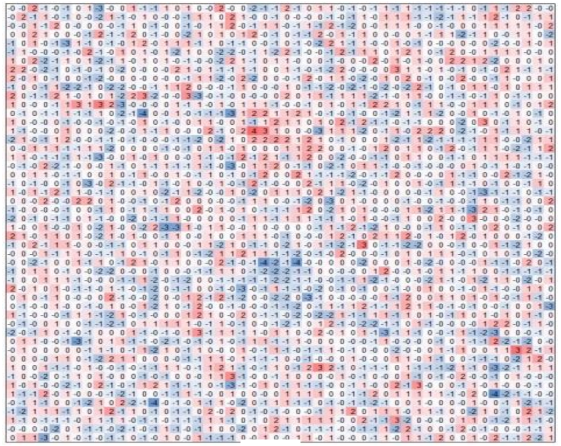
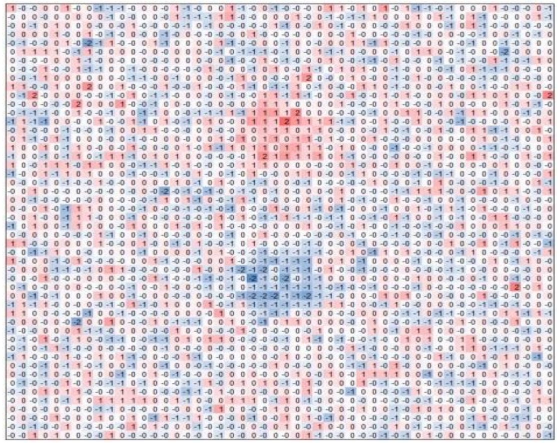
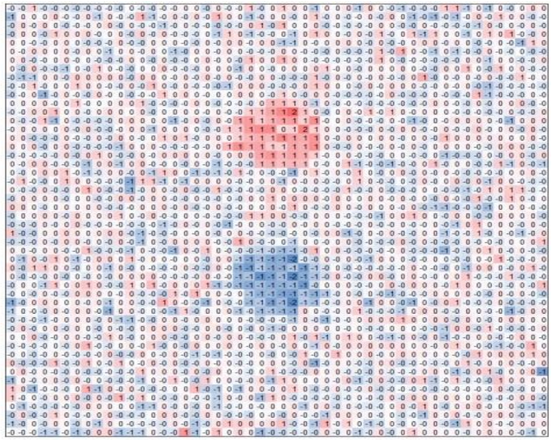
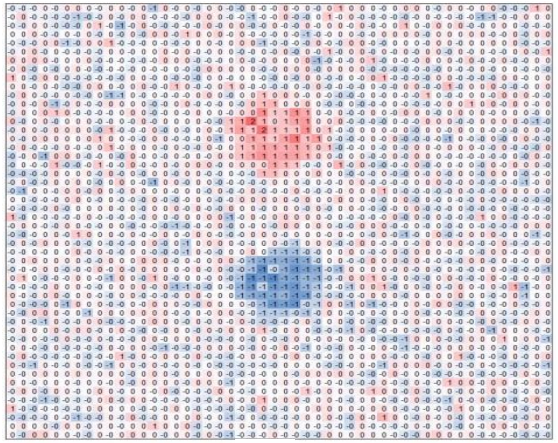
4D Noise



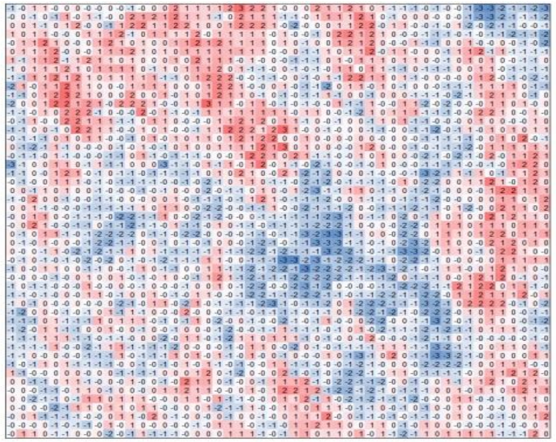
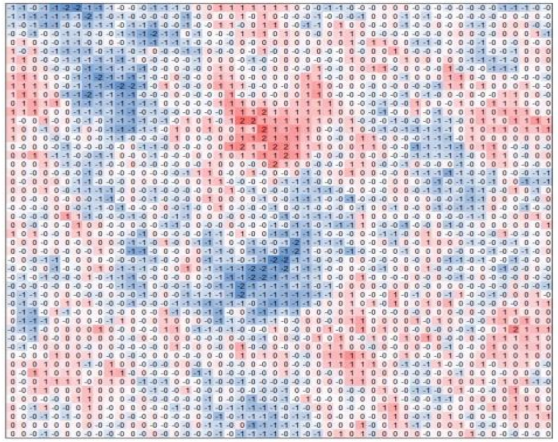
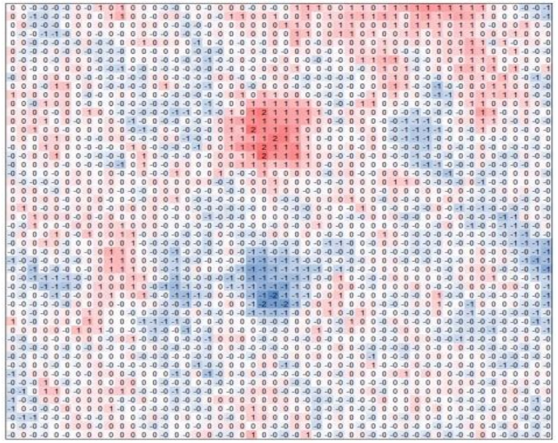
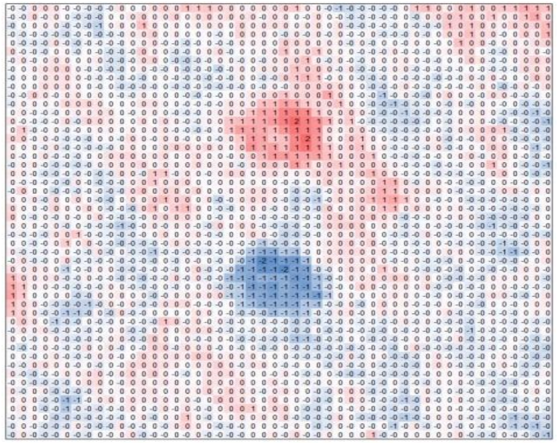


Ratio of 4D signal to 4D noise

With incoherent Gaussian noise, signal is weakly discernible at S:N=1

1 2 3 4

With coherent Gaussian noise, signal is only discernible at S:N=2, and becomes clear with S:N>4

Very few case studies report the ratio of 4D signal to 4D noise

Ratio of 4D signal to 3D signal

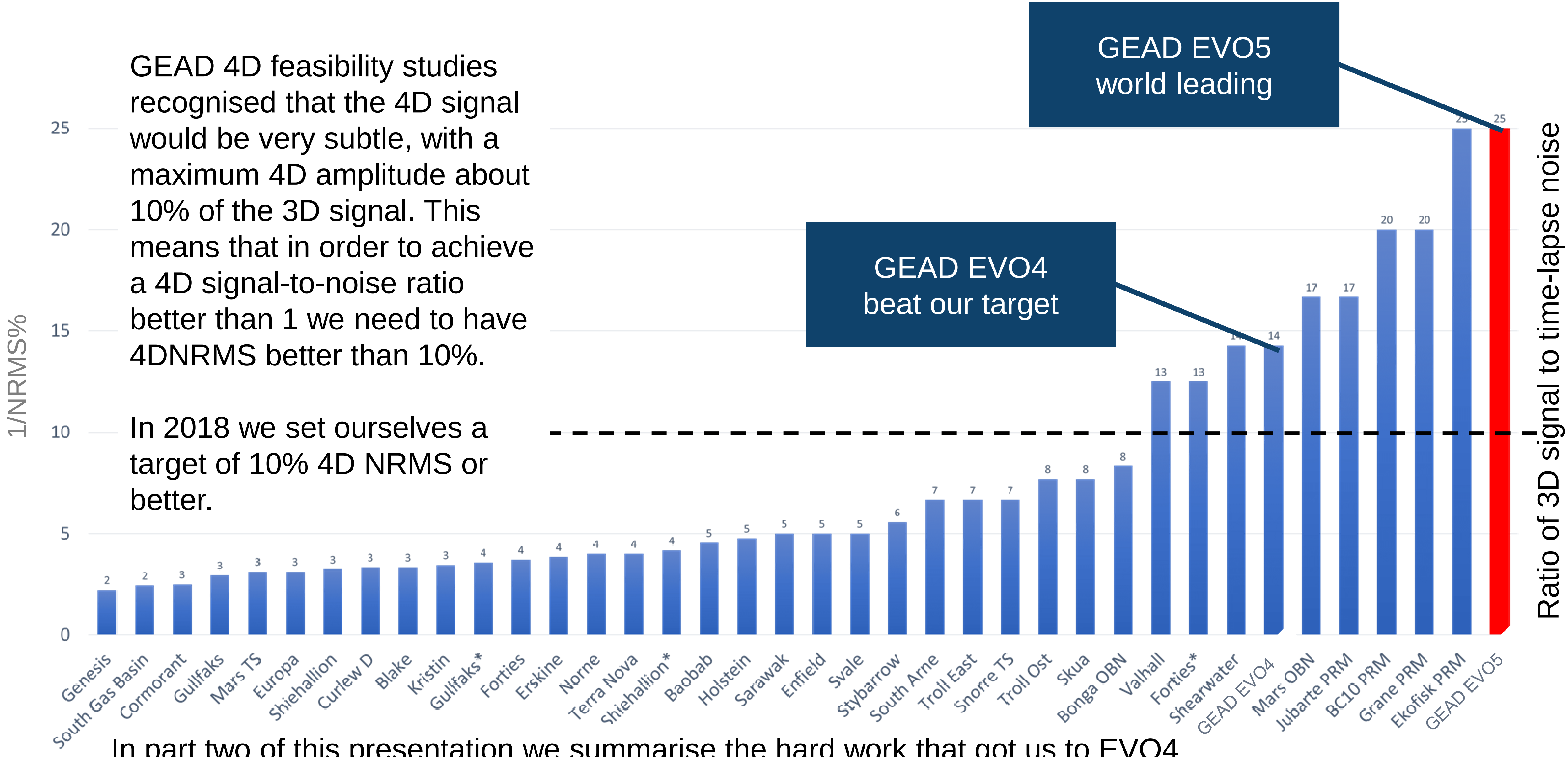
- As with the ratio of 4D signal to 4D noise, very few case studies report the ratio of 4D signal to 3D signal.
- The metric which is most widely reported is the ratio of 4D noise to 3D signal, or “4DNRMS”.
- For Golden Eagle our 4D feasibility studies recognised that the 4D signal would be very subtle, 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 needed to have 4DNRMS better than 10%.
- Which is to say we needed the ratio of 3D signal to 4D noise to be greater than 10.

- How challenging is it to achieve a ratio of 3D signal to 4D noise greater than 10?

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.



In part two of this presentation we summarise the hard work that got us to EVO4 and the wavefield harmony “trick” that took us from EVO4 to EVO5.

Edited based on V.Omofoma 2017

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- Some metrics to help get the cost vs quality balance right for your project

Part Two: Achieving exceptional 4D signal to noise in a difficult data area

- **There is no “free lunch” and the basics still apply**
- **But using a new “wavefield harmony” method delivered a breakthrough improvement in signal to noise**

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Part Two: Achieving Exceptional 4D Seismic Quality

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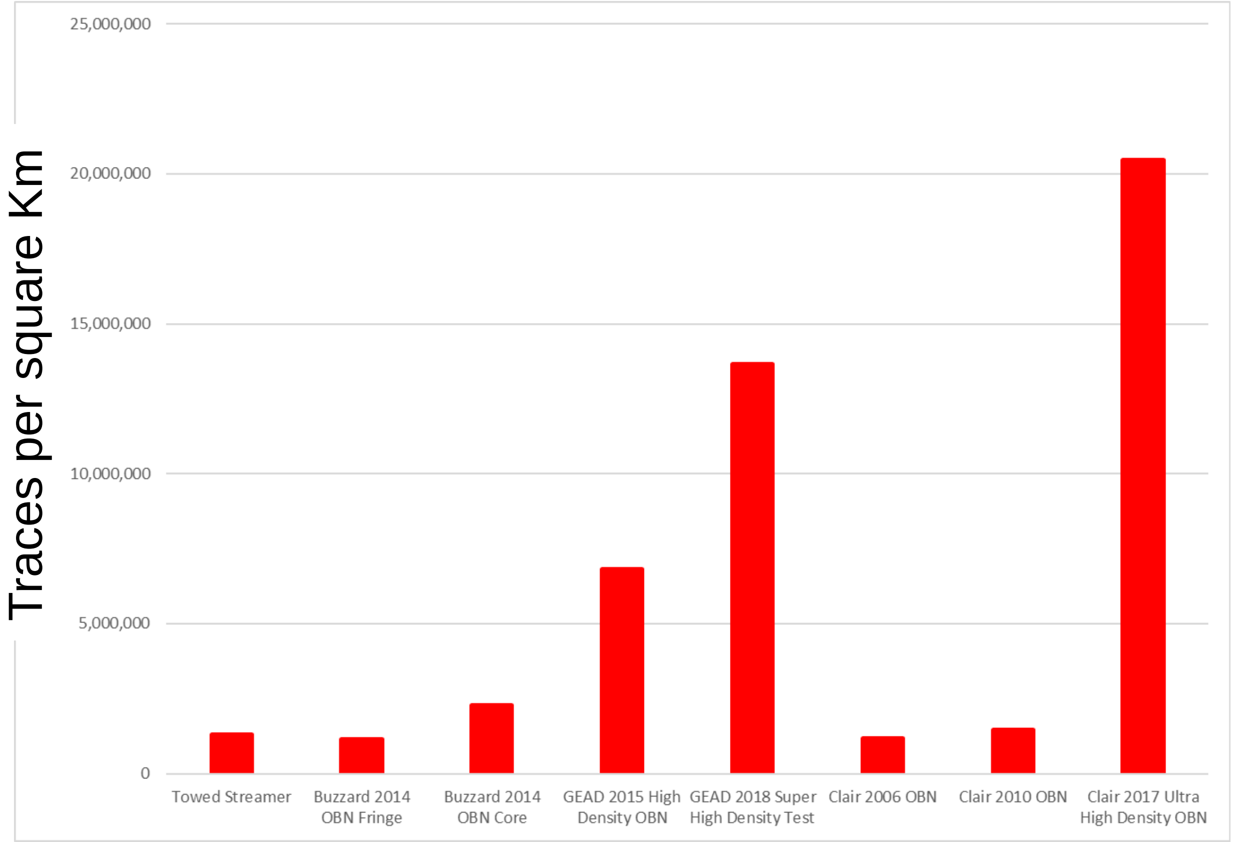
- The Golden Eagle area has a combination of an unusually challenging overburden and subtle reservoir seismic character.
- 3D and 4D seismic reservoir characterisation at GEAD requires an exceptionally high quality of seismic acquisition and processing.
- Golden Eagle is a low relief field and infill 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.

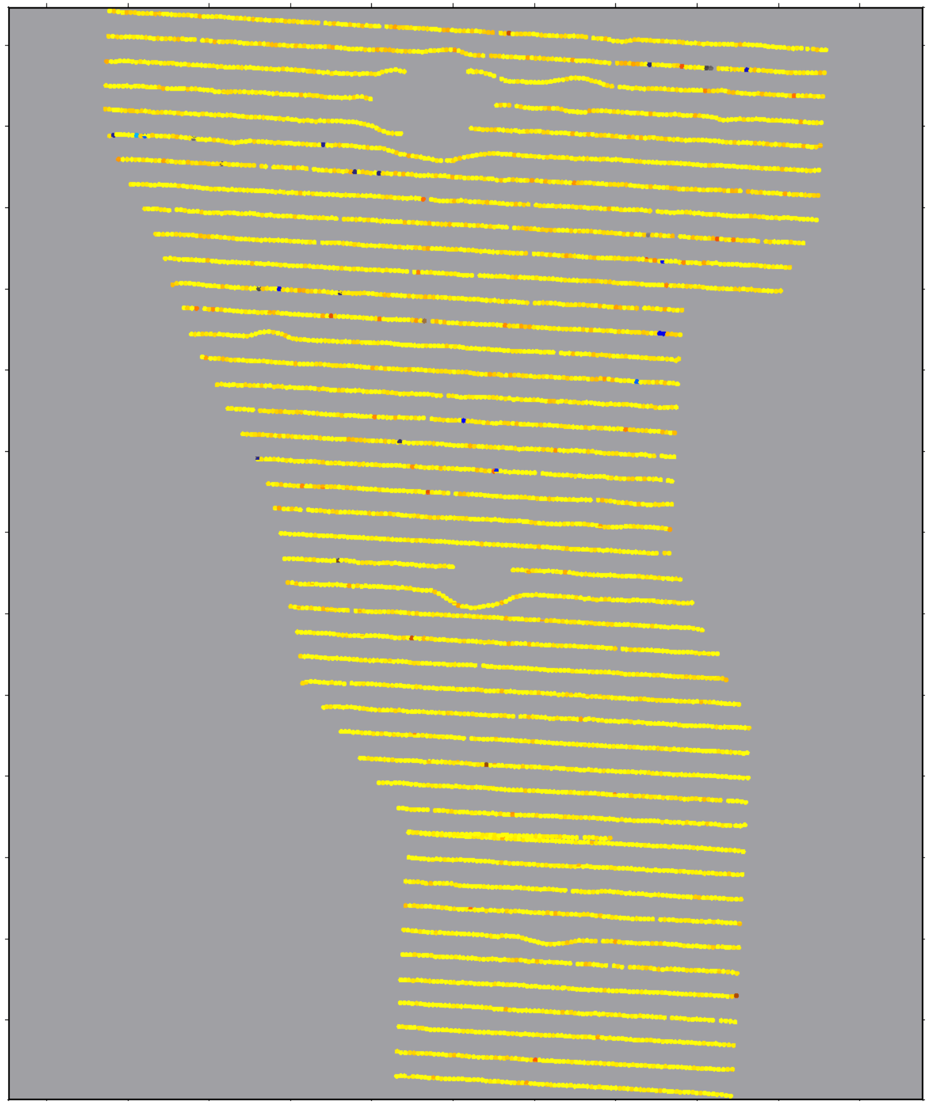


Part Two: Achieving Exceptional 4D Seismic Quality

Relentless Marginal Gains During Processing

- Q: When is 99.995% Not Good Enough?
- A: When you're aiming for world class 4D noise levels
- There are around 400 steps in our 4D seismic processing and many of these processes were run with quality standards that are exceptional
- When applied over several hundred processing steps the resulting marginal improvements accumulate to provide a significant improvement in 4D signal-to-noise ratio.

Example Node QC Plot



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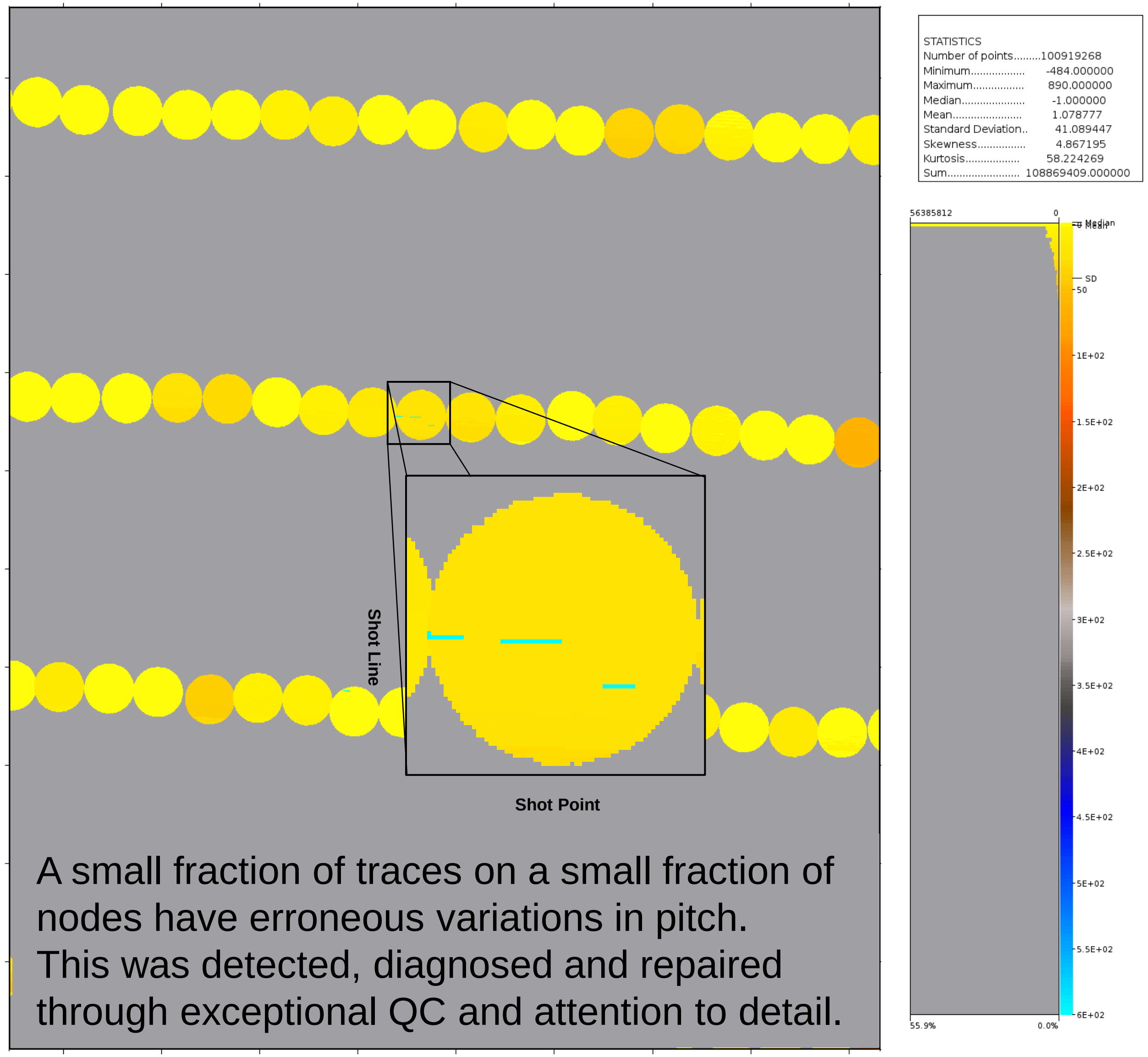

A small fraction of traces on a small fraction of nodes have erroneous variations in pitch. This was detected, diagnosed and repaired through exceptional QC and attention to detail.

Part Two: Achieving Exceptional 4D Seismic Quality

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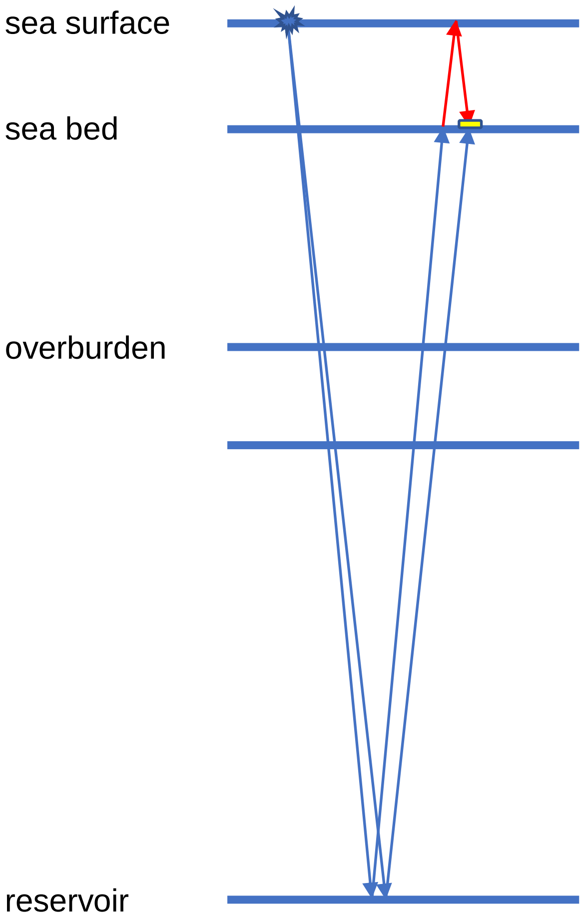
Top Seven Step Change Breakthroughs

- Breakthrough performance of acquisition contractor when accurately re-positioning OBN on the seabed using a node-on-rope deployment system
- Tidally-matched source shooting
- QC during seismic processing using full-field 4D QC maps informed by sim2seis
- Achieving speed and quality by delivering a series of incrementally improving versions of the seismic: EVO2, EVO3, EVO4, EVO5
- Vz denoise in the common shot domain
- Targeted filtering of noise associated with the velocity contrast at Top Chalk
- 4D seismic wavefield harmonisation

What are these seismic wavefields?

Ocean bottom nodes contain both hydrophones and geophones



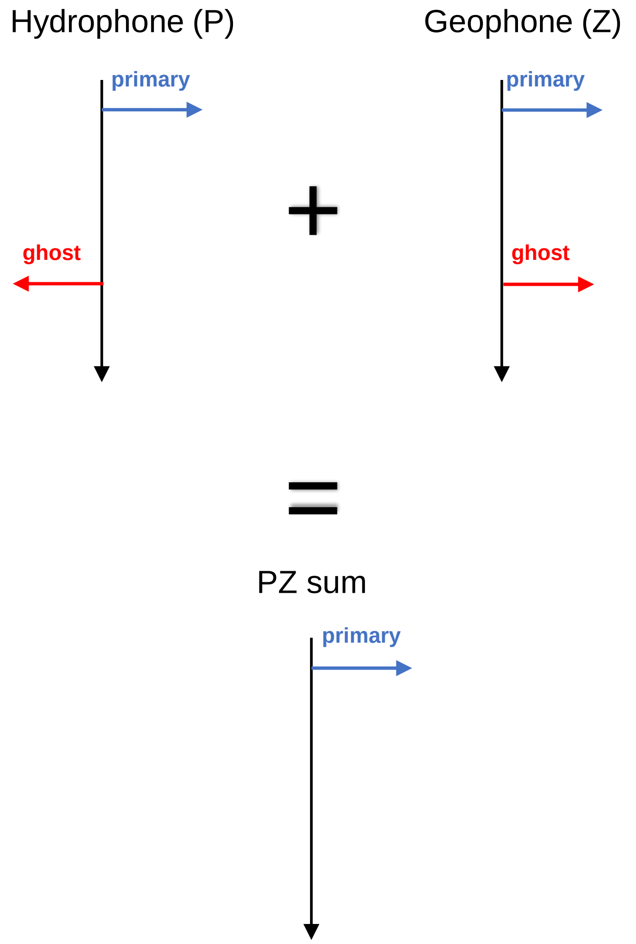
A hydrophone is a **pressure** sensor designed to be used underwater. The measurement of pressure is **insensitive to the direction of propagation** of the seismic energy.

A 3-component geophone measurement is **directional** – delivers a **vector** with (x, y, z) component.

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.

We separate the recorded signal into **upgoing** and **downgoing** wavefields from which a third wavefield, the **reflectivity**, can be estimated by up-down deconvolution.

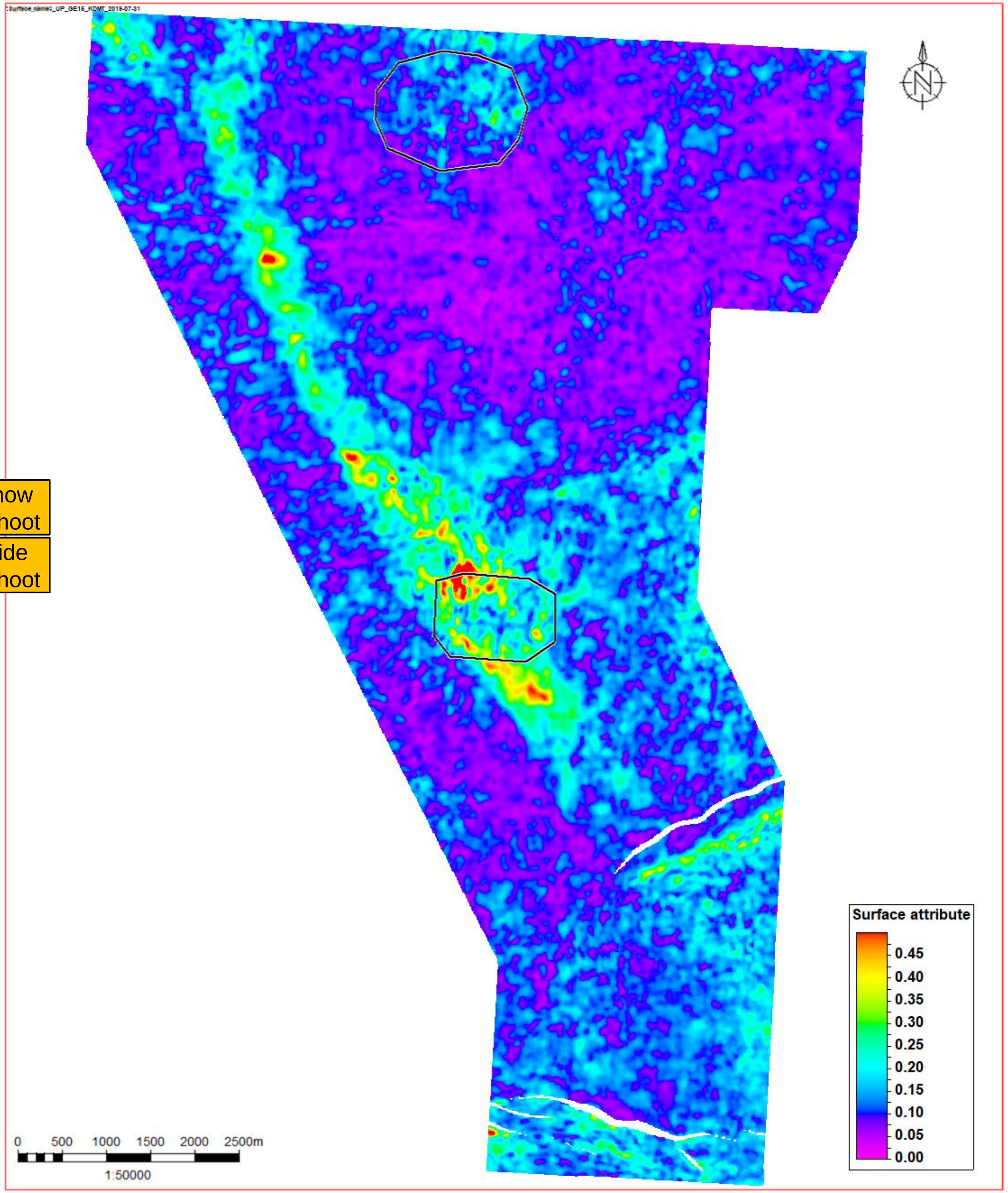
At Golden Eagle we observed that while the 4D signal was similar on all three wavefields, the 4D noise was different; we set out to exploit this observation.



EVO2 Fast Track

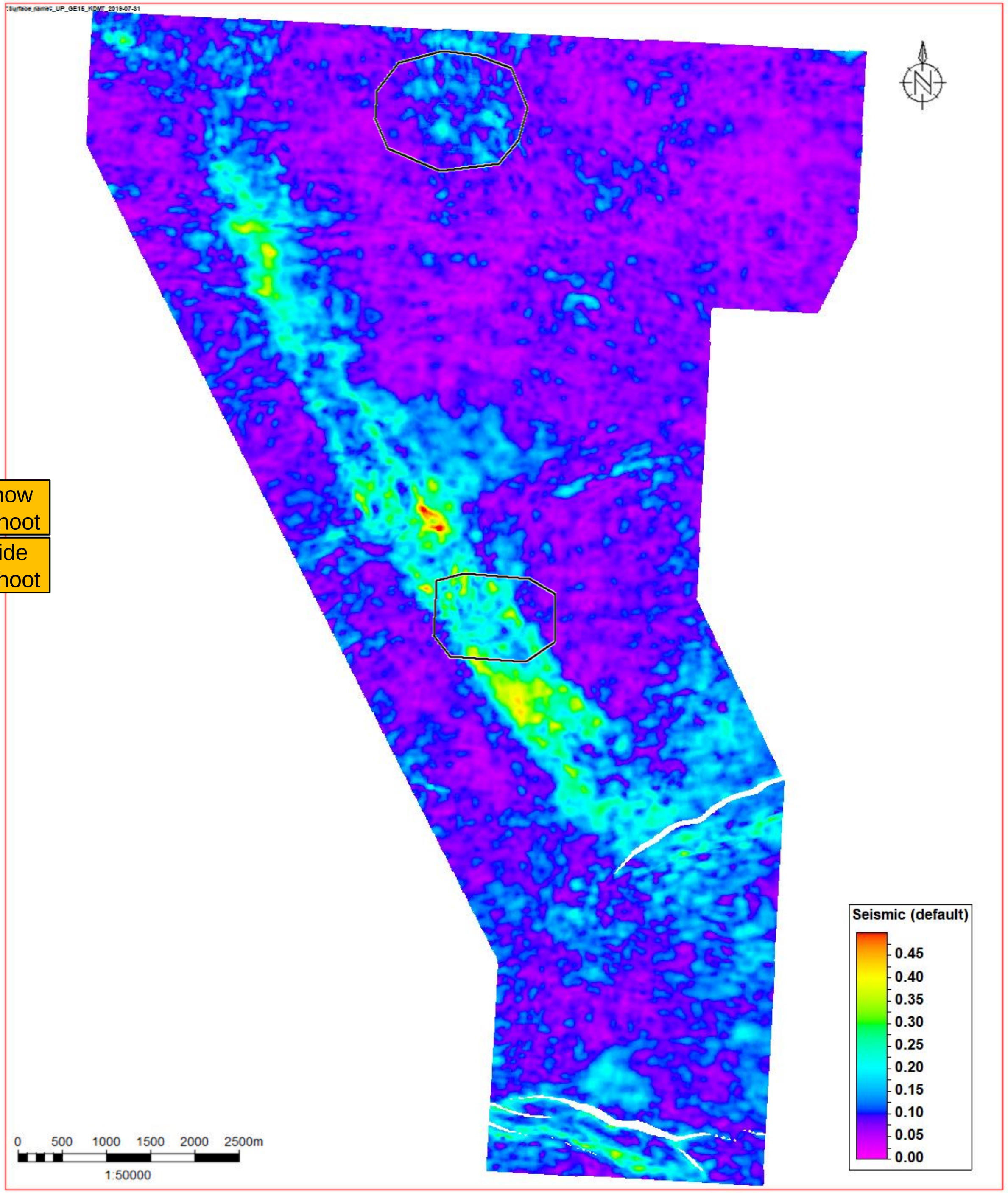
Show Ushoot

Hide Ushoot



- 4D NRMS calculated in a window 100ms wide centred on the BCU
- The Punt channel has a clear expression on this 4D NRMS map
- In addition we can see heightened noise
  - in the undershoot beneath the Northern subsea drill centre where there was a semisub during the baseline seismic acquisition
  - in the undershoot beneath the GEAD platform complex
  - in some areas of steep dip

EVO4 Upgoing

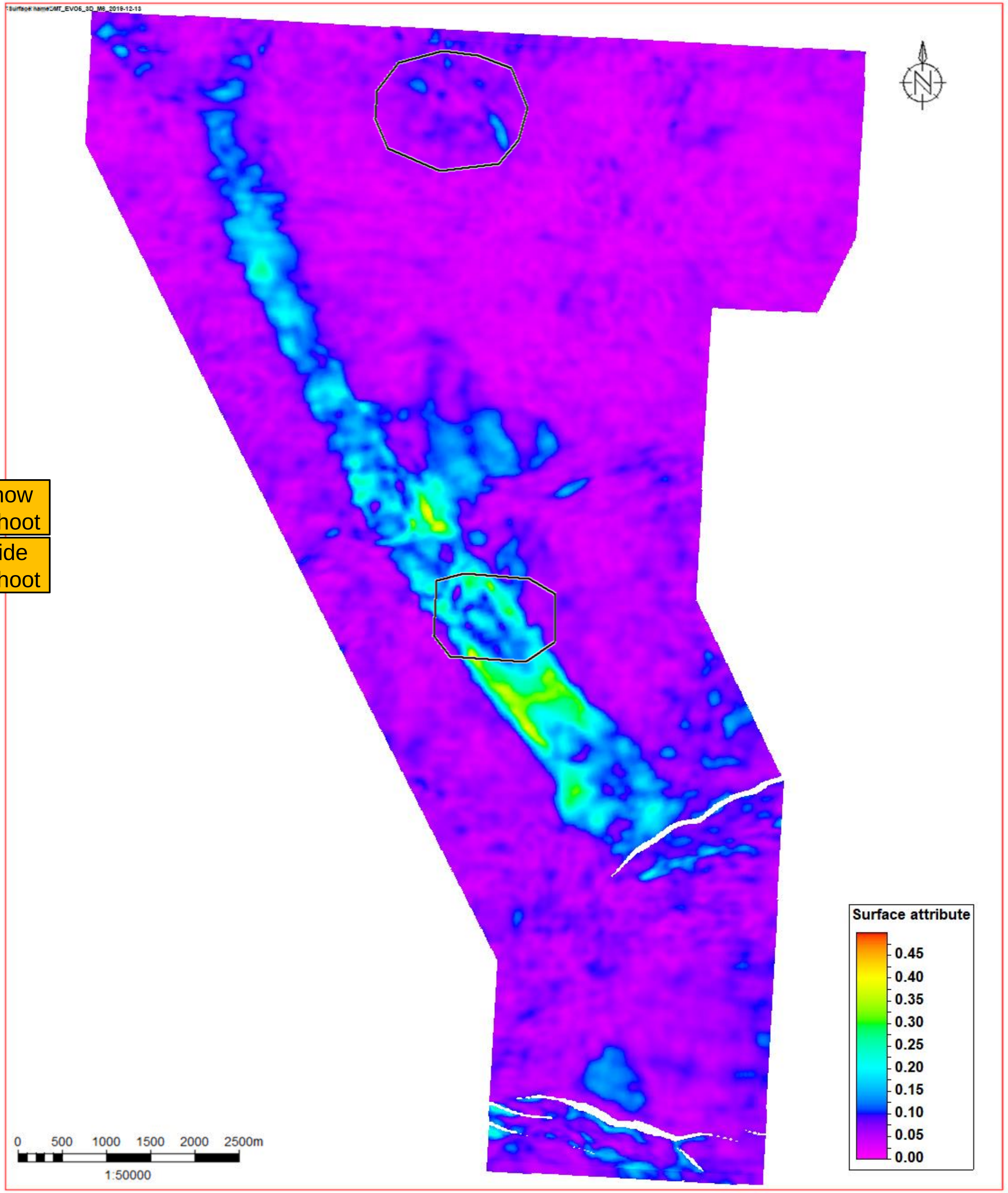


Show Ushoot

Hide Ushoot

- 4D NRMS calculated in a window 100ms wide centred on the BCU
- Significant reduction in noise levels from EVO2 fast-track to EVO4
  - undershoot areas still show noise levels higher than background
  - Peregrine and Golden Eagle Burns 4D now much more evident on this map, compared with EVO2

EVO5 WS-CDN



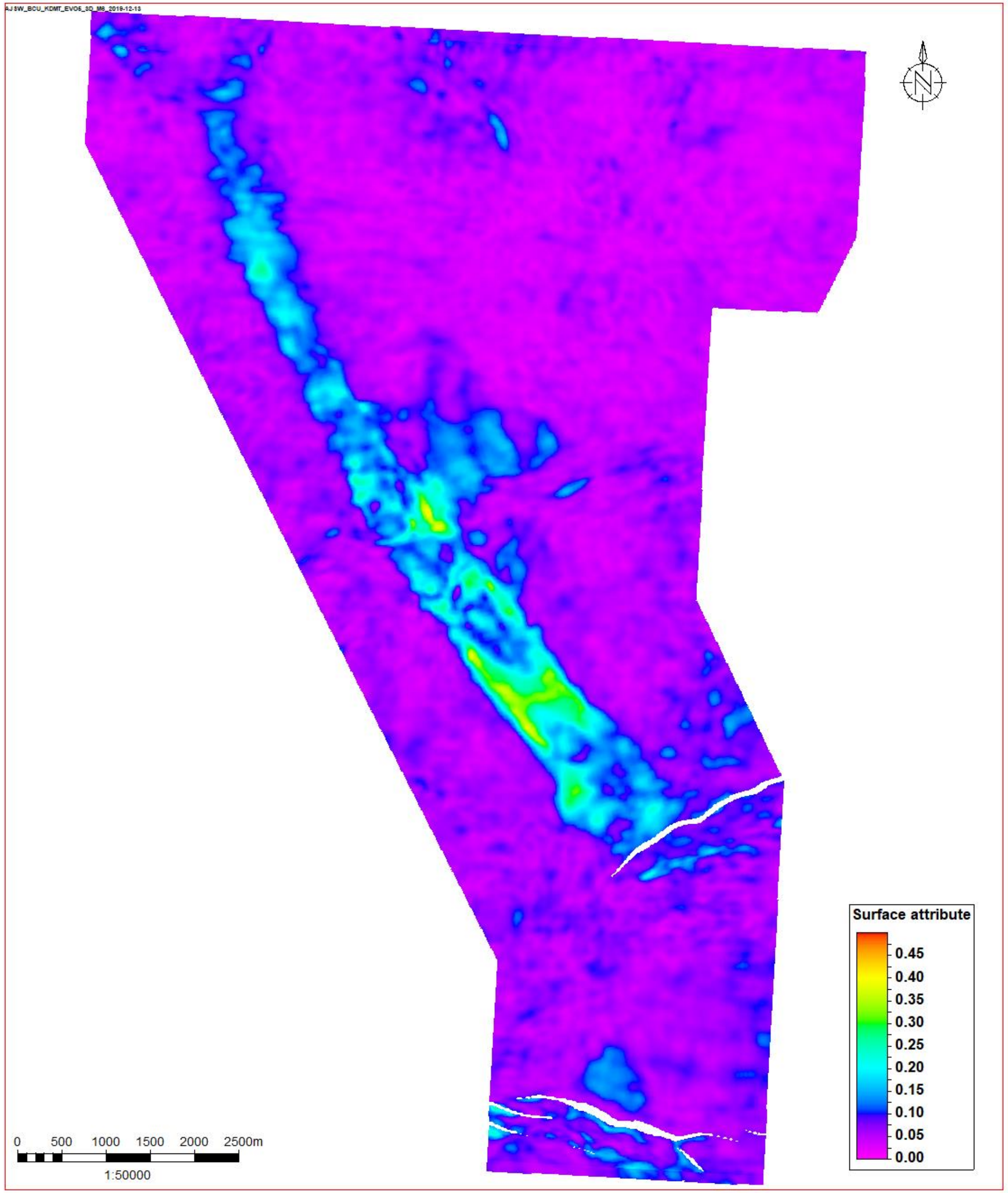
Show Ushoot

Hide Ushoot

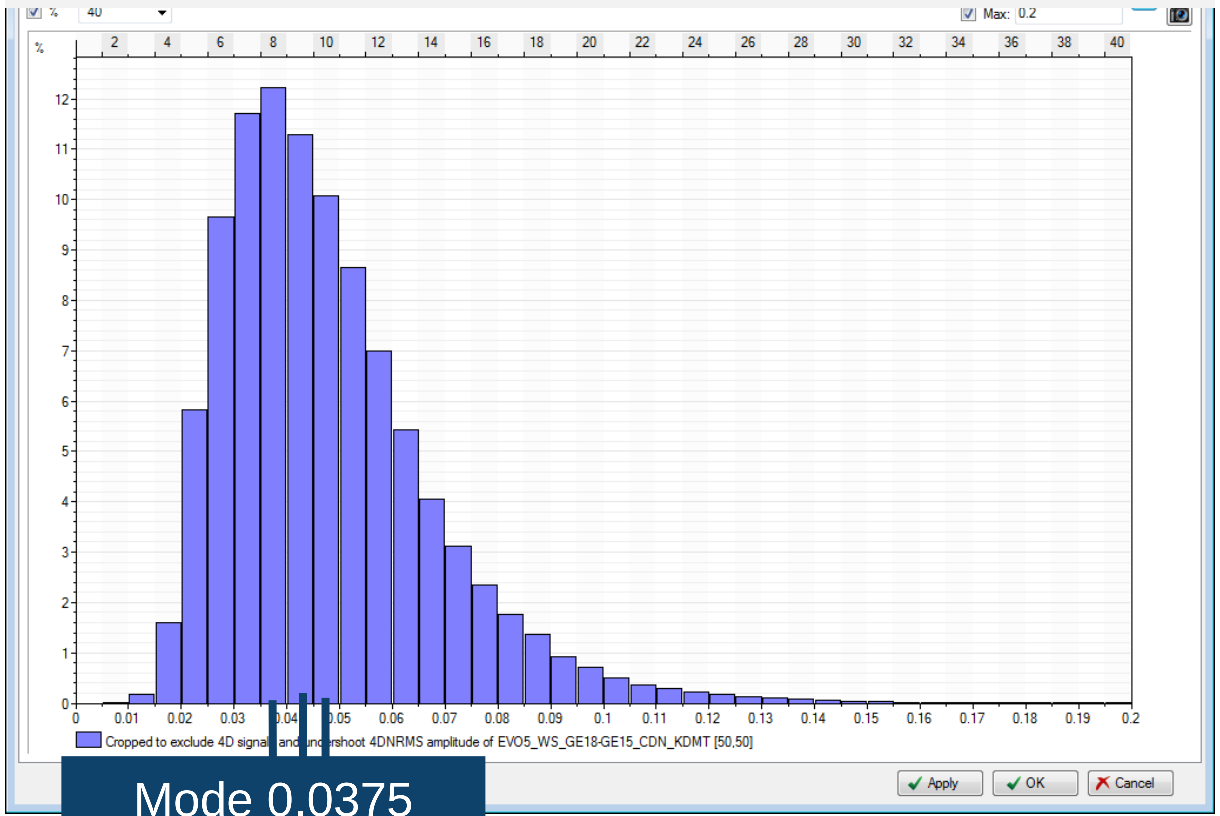
- 4D NRMS calculated in a window 100ms wide centred on the BCU
- Significant reduction in 4D noise levels from EVO4 to EVO5
  - undershoot areas still show noise levels higher than background
  - Peregrine and Golden Eagle Burns 4D have a very clear outline

- WS = Wavefield Sum
  - Summation of upgoing, downgoing and reflectivity wavefields
- WS-CDN = Wavefield Sum Co De-Noise
  - Pre-stack 4D de-noise applied to each wavefield using the WS as a prior model for the curvelet domain matching

EVO5 WS-CDN



Away from areas of 4D signal and undershoot for EVO5_WS_CDN the overall median 4DNRMS is 4.4%



Mode 0.0375

Median 0.0438

Mean 0.0477

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CNOOC

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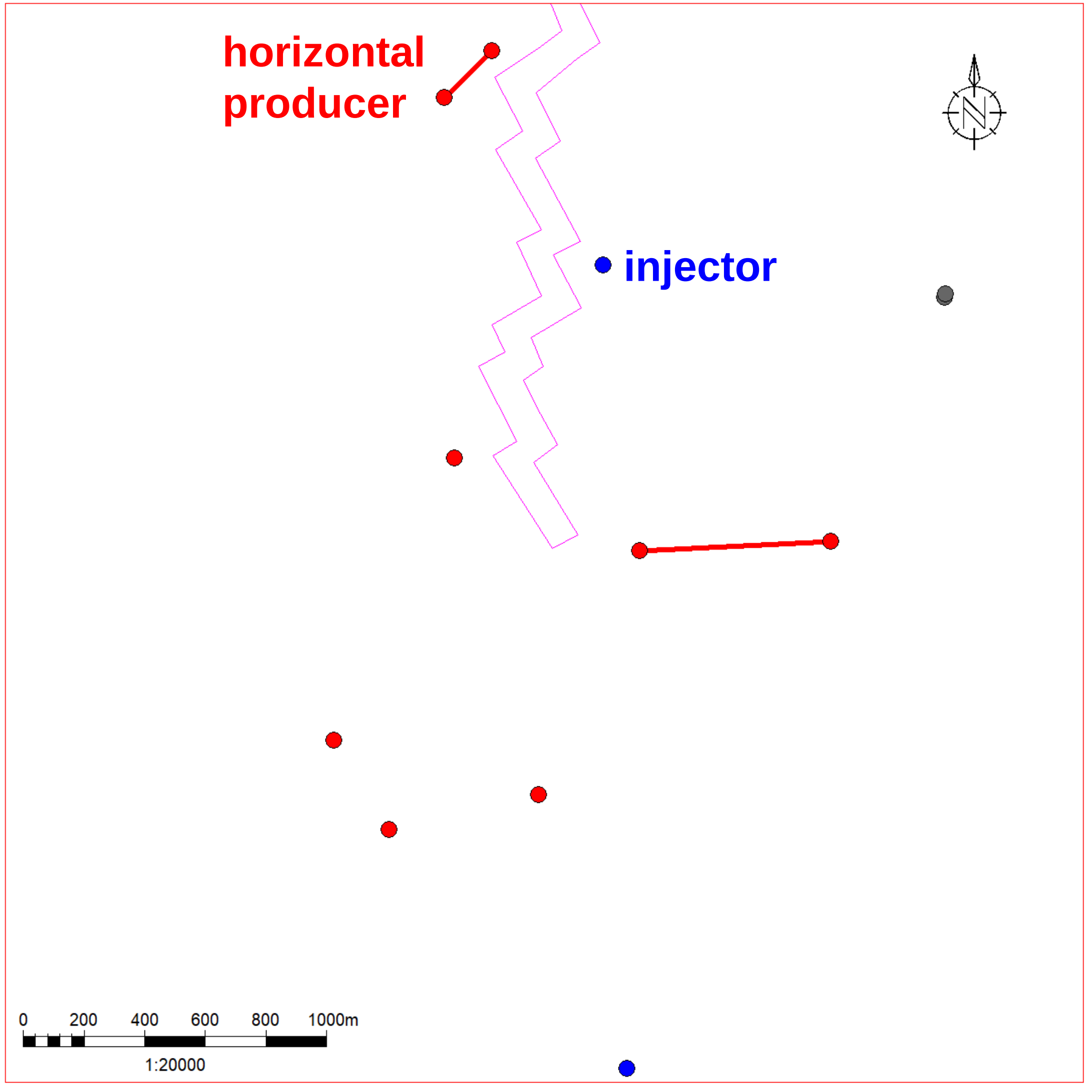
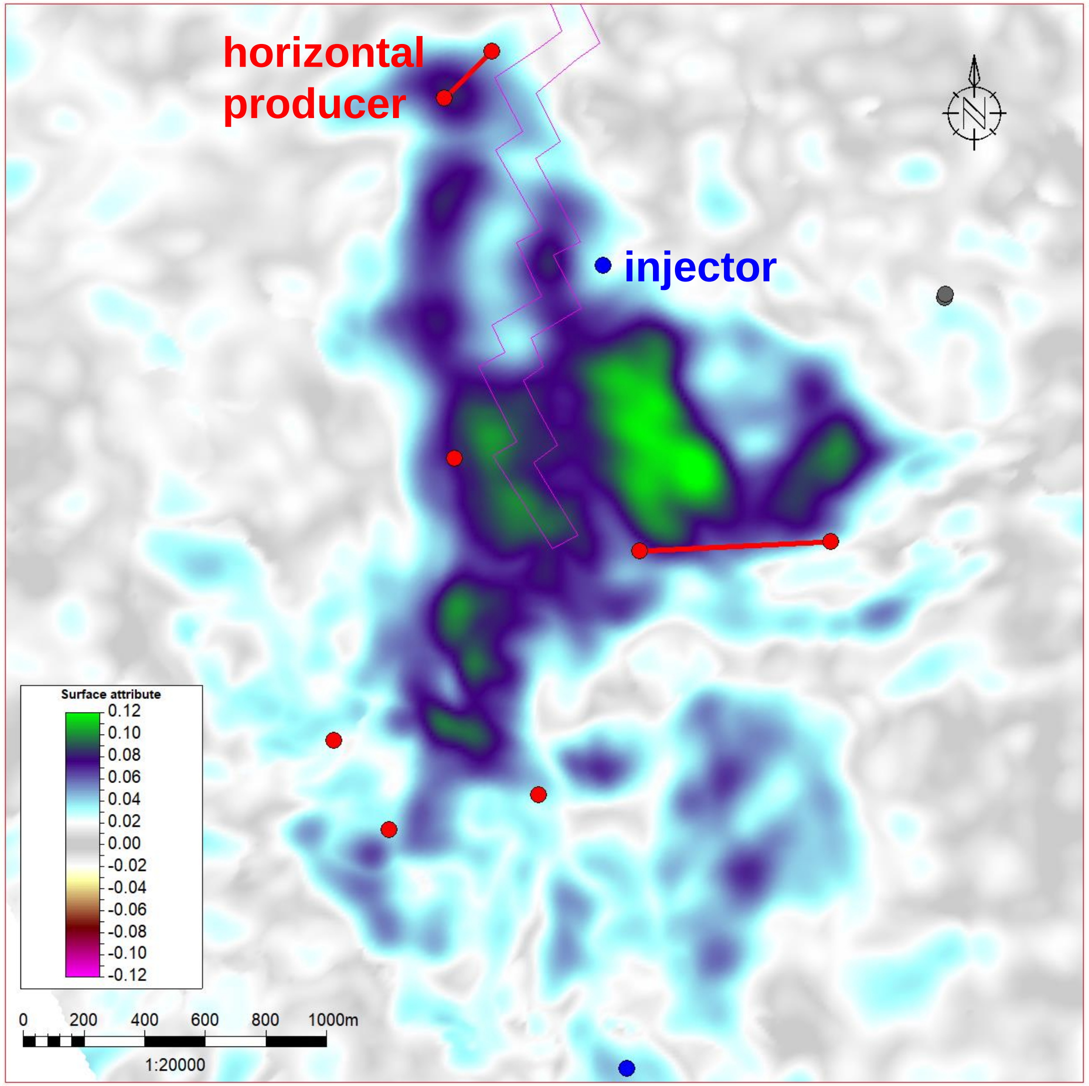
- **Reservoir model update example**
- **Reduction in depth uncertainty using 4D-informed depth conversion**
- **Our most successful infill well**

Before 4D



- Dynamic data indicate that the water injector is providing some pressure support to the horizontal producer but that produced water is aquifer water not injected water
- To capture this dynamic effect the geomodeller adds a polygon between the injector and horizontal producer inside which the NTG of the reservoir is reduced
- Before 4D seismic the geomodeller must use judgement to decide where to place this polygon

Comparing model and 4D



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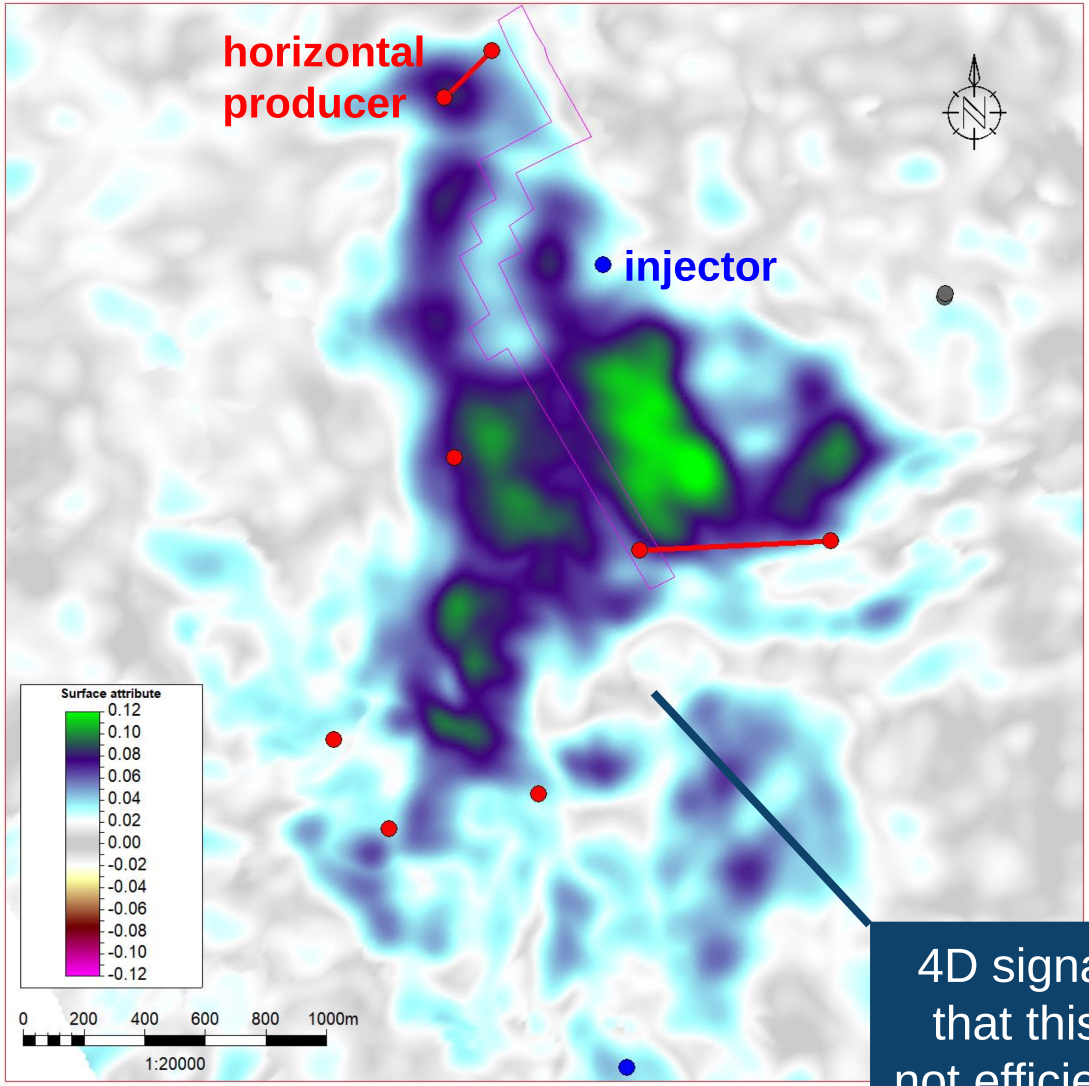
- Reviewing 4D seismic is it now clear where to place the polygon

After 4D



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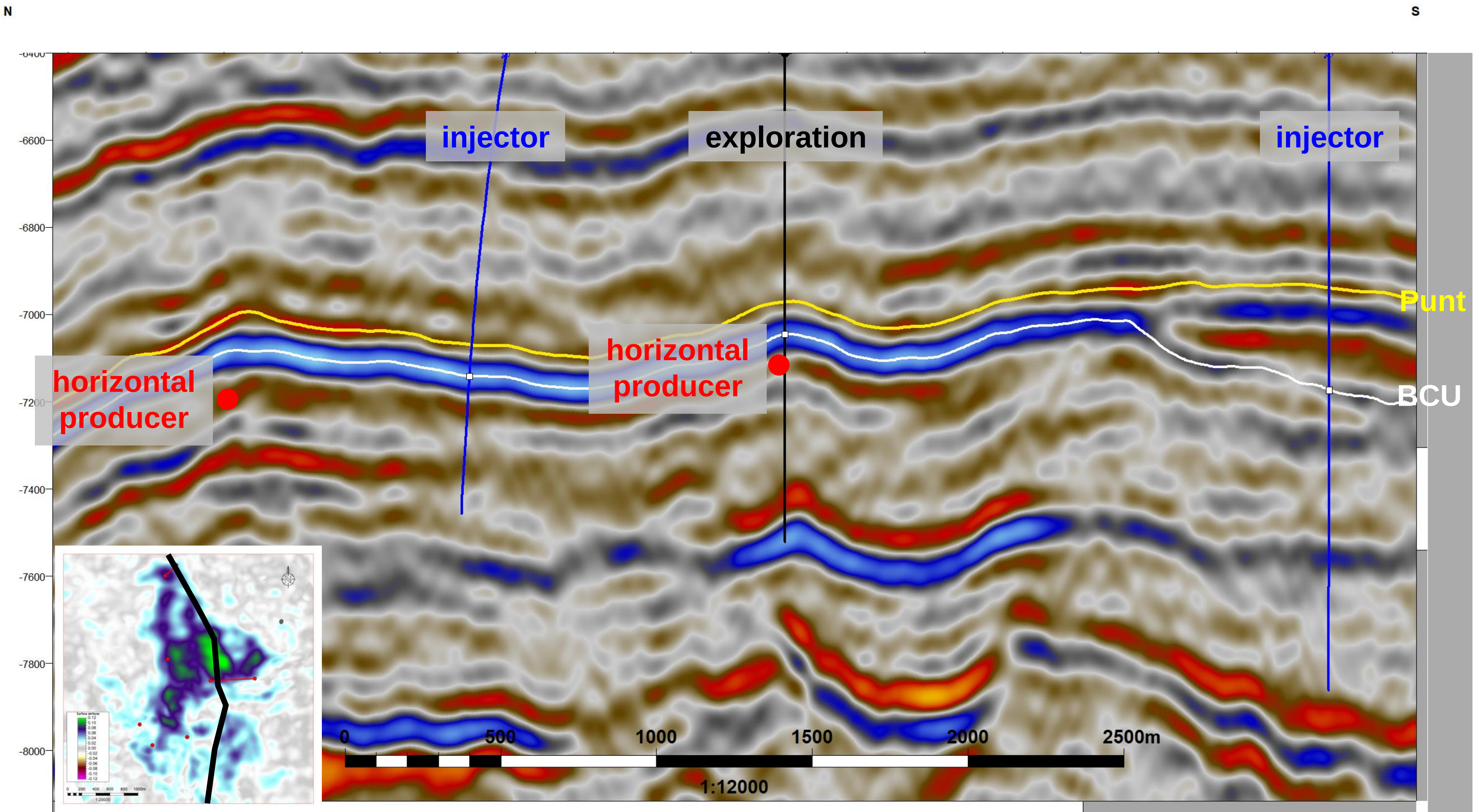
- Before 4D seismic the geomodeller must use judgement to decide where to place this polygon
- Reviewing 4D seismic is it now clear where to place the polygon
- Polygon updated to match 4D seismic

4D signal indicated that this area was not efficiently drained

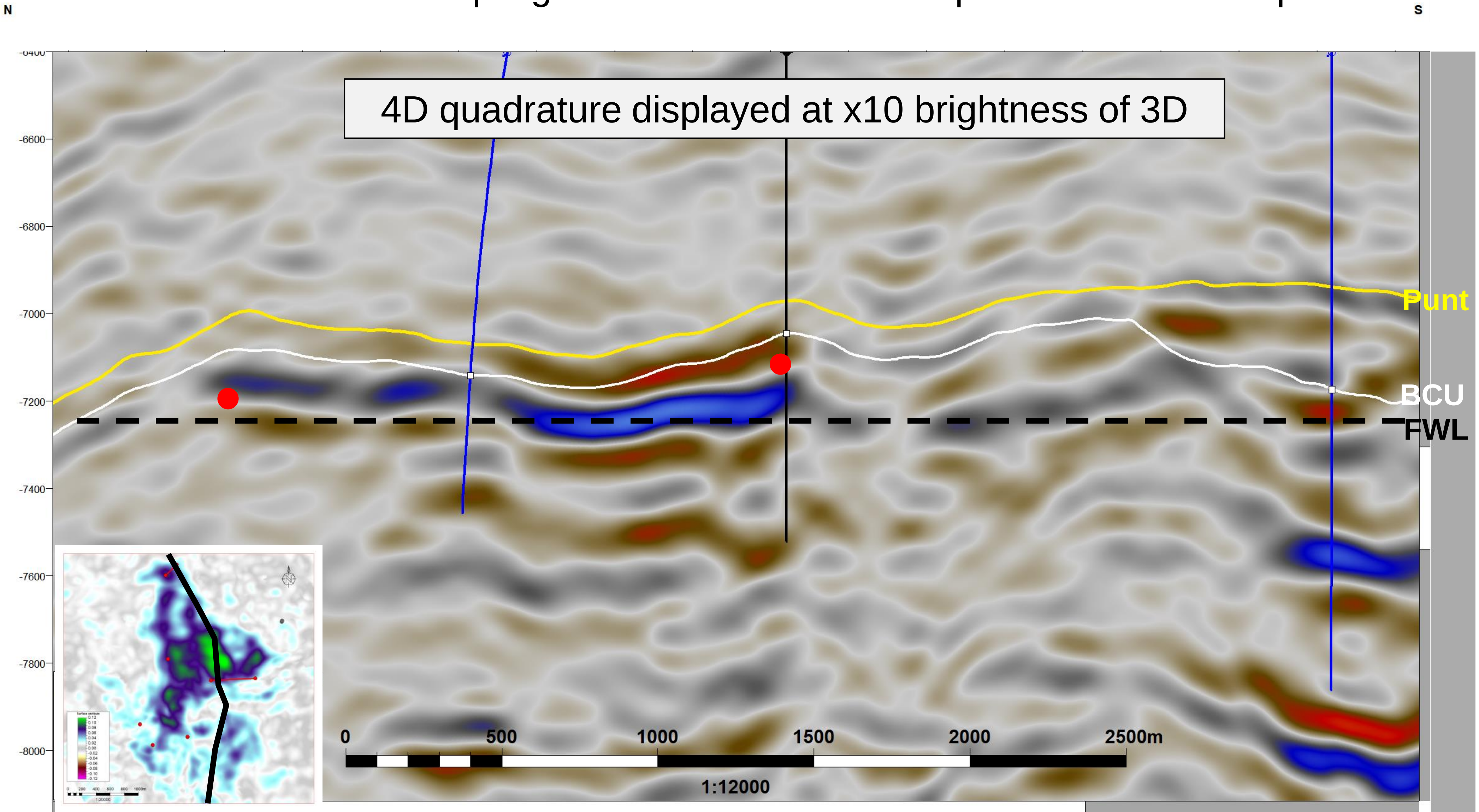
Before 4D-informed depth correction

EVO5 3D seismic image after depth conversion including tie to wells



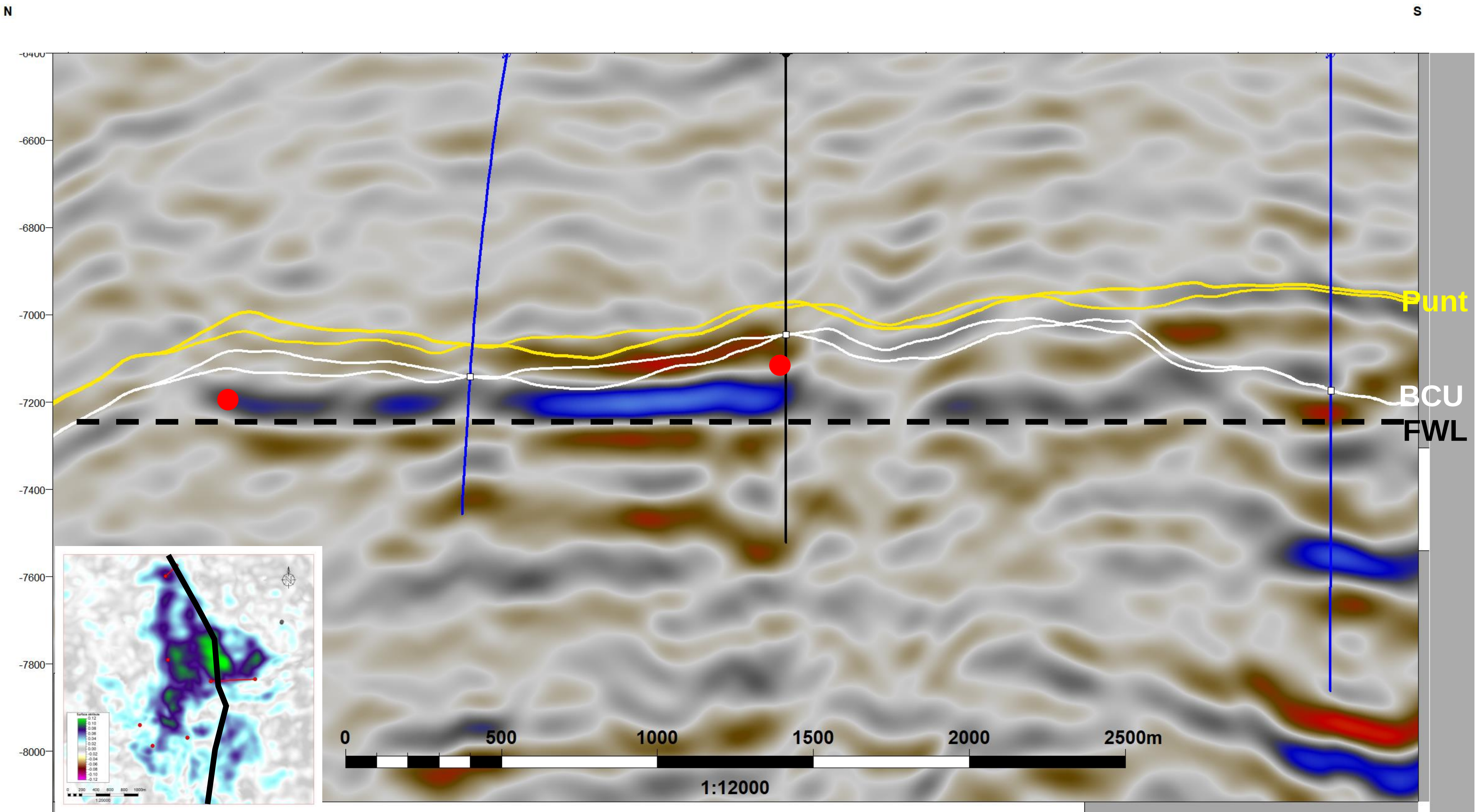
Before 4D-informed depth correction

EVO5 4D seismic quadrature after depth conversion including tie to wells
imperfect conformance of sweep signal & FWL indicates scope for a residual depth correction



Before 4D-informed depth correction

EVO5 4D seismic quadrature after 4D-informed depth correction



After 4D-informed depth correction

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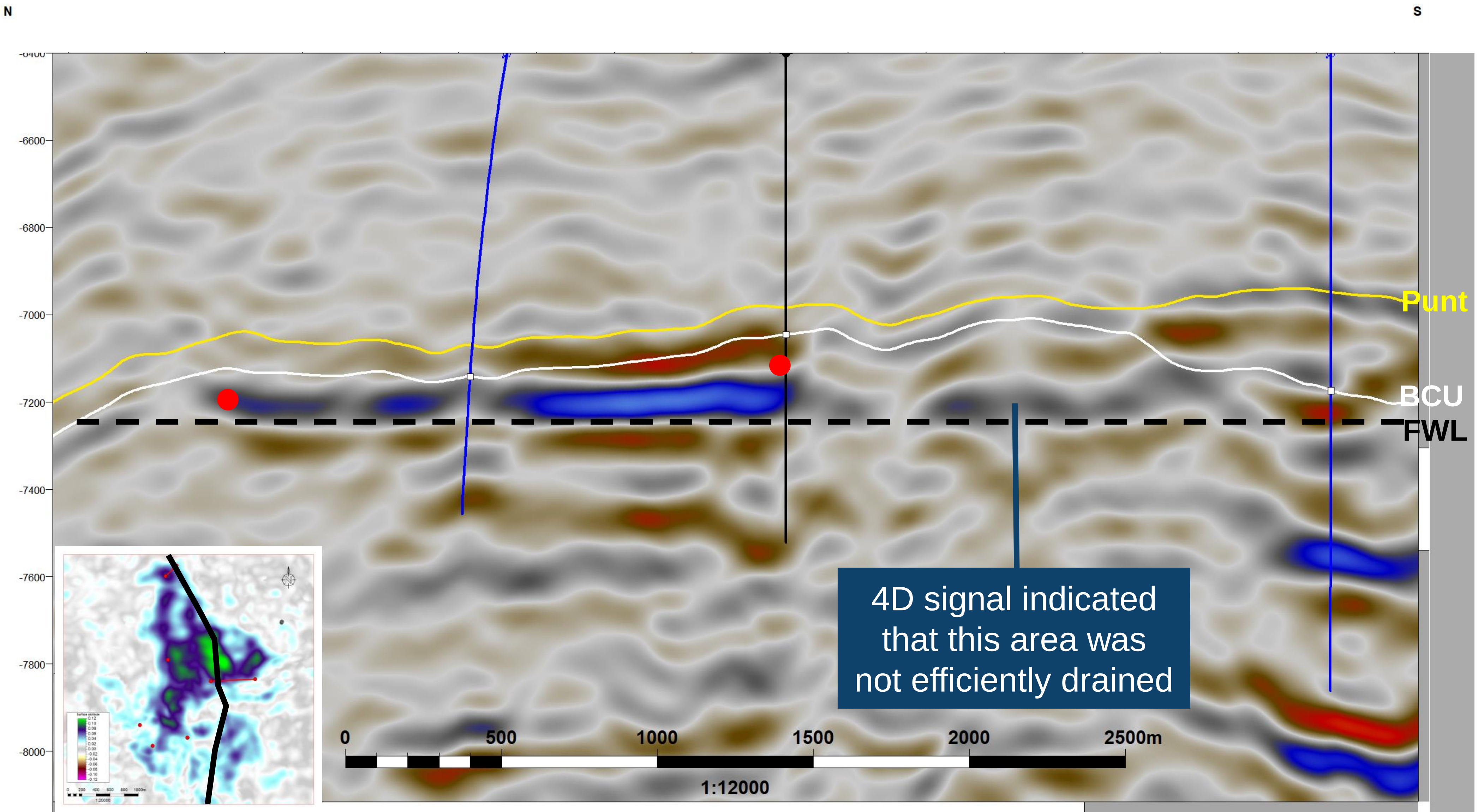
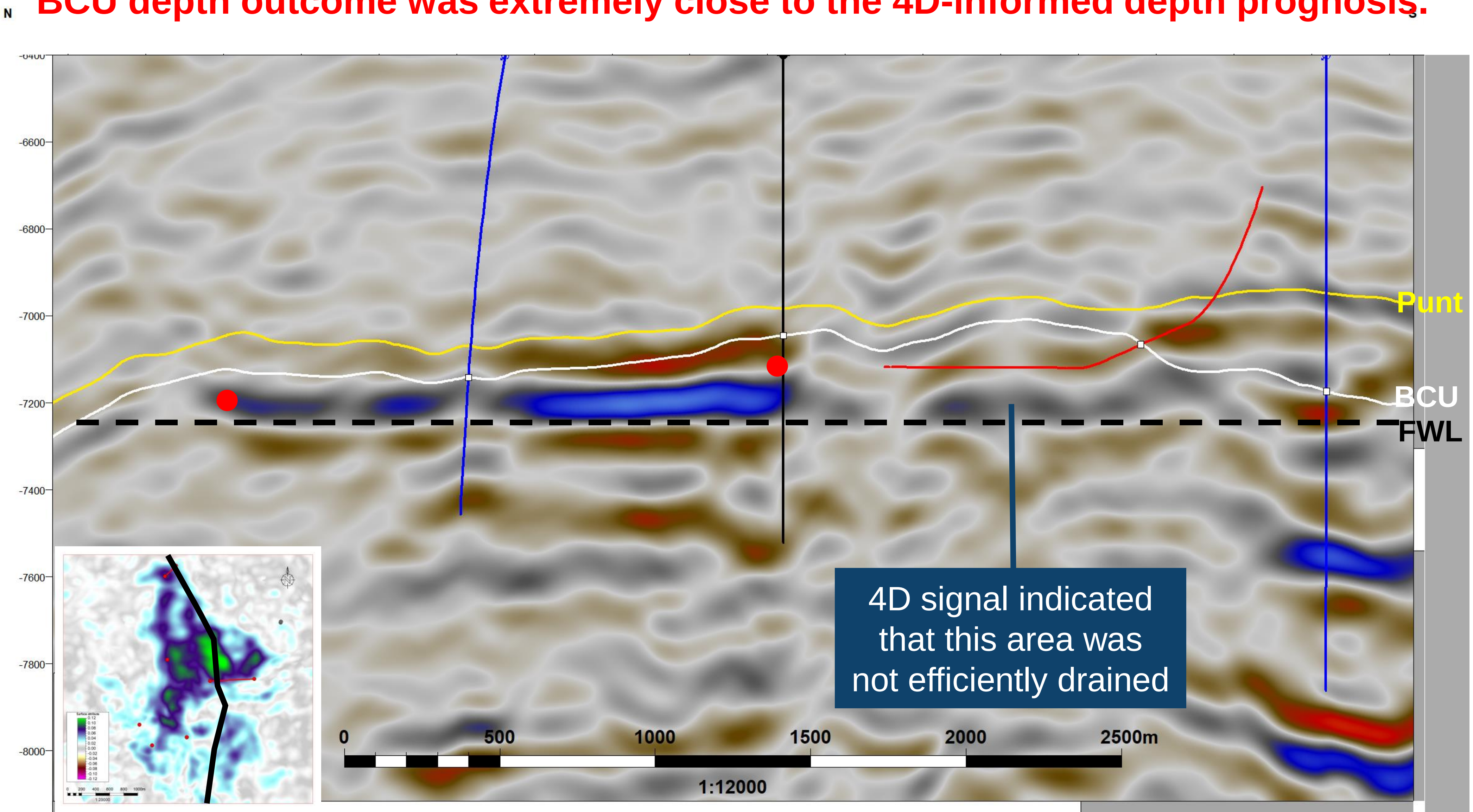


After 4D-informed depth correction

This infill well found dry oil and is now the best producer on the Golden Eagle field.

BCU depth outcome was extremely close to the 4D-informed depth prognosis.



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Summary and Conclusions

In Conclusion

Golden Eagle field

- Challenging overburden, subtle 3D and 4D seismic character
  - requires exceptional acquisition and processing
- Low relief: requires super-accurate depth conversion

Achieving exceptional 4D signal to noise in a difficult data area

- Acquisition fundamentals: high density OBN; repeat-repeat-repeat
- Marginal gains on 400 processes
- Top seven breakthroughs: 4D seismic wavefield harmony had the most impact

Impact on reservoir models and infill wells

- “Z4D” 4D-informed depth conversion

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

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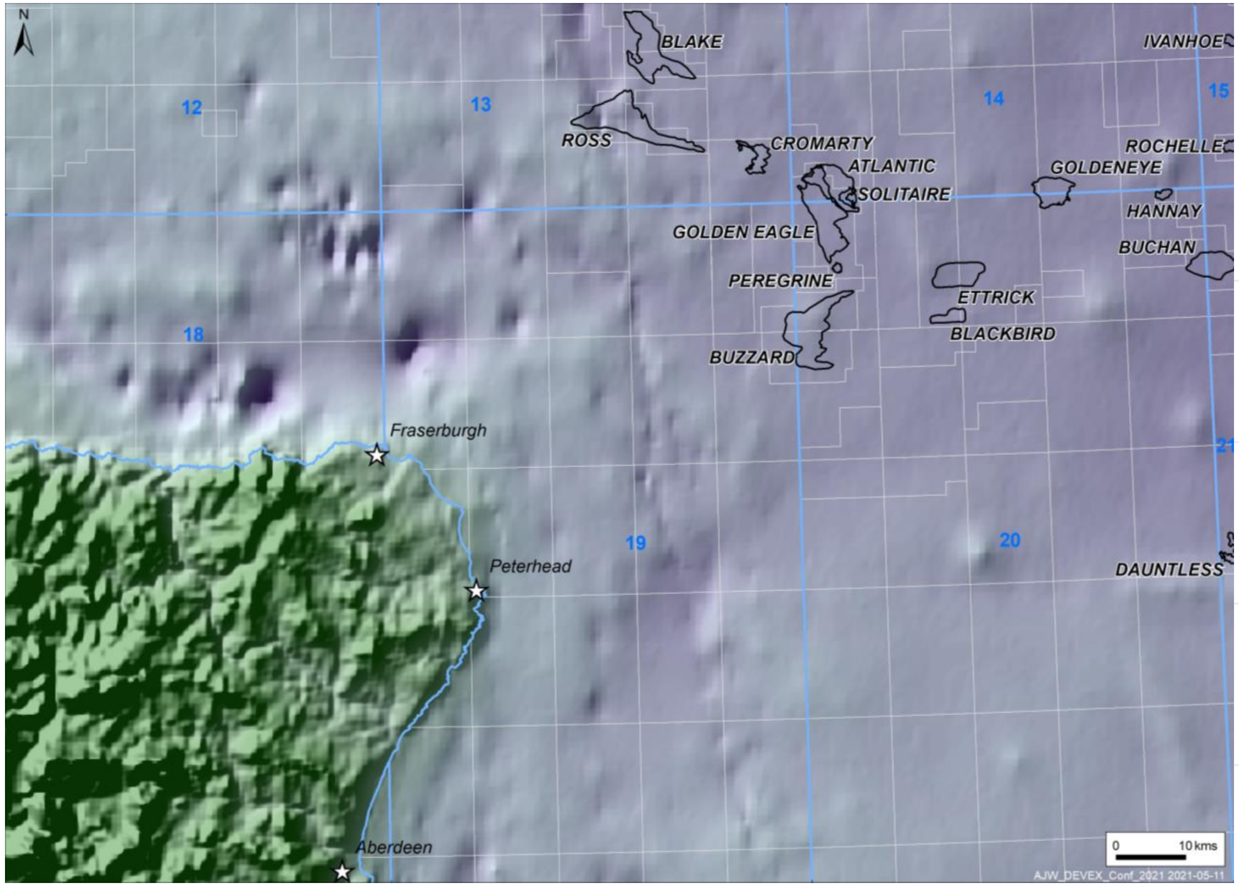
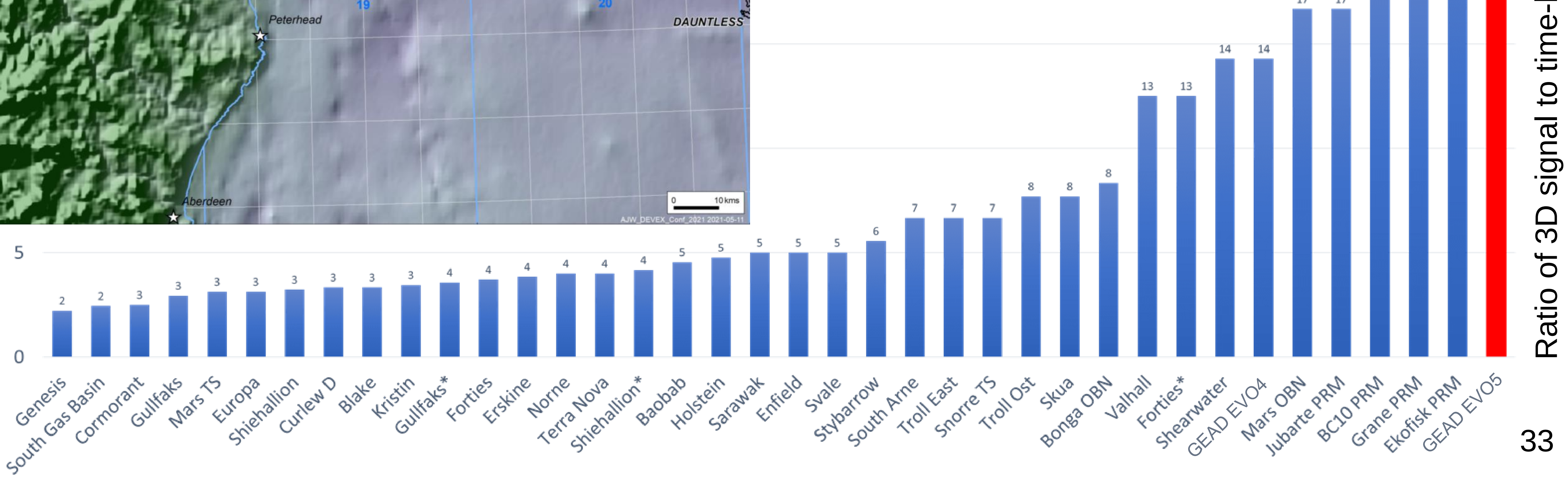
Additional Content for Anticipated Questions

Summary

The GEAD 4D project has achieved exceptional 4D noise levels through a combination of dense OBN seismic and a series of innovations in processing and interpretation. If this level of quality can be achieved on other fields then it signals a new era in our industry's ability to affordably use 4D seismic in difficult data areas such as the Moray Firth.





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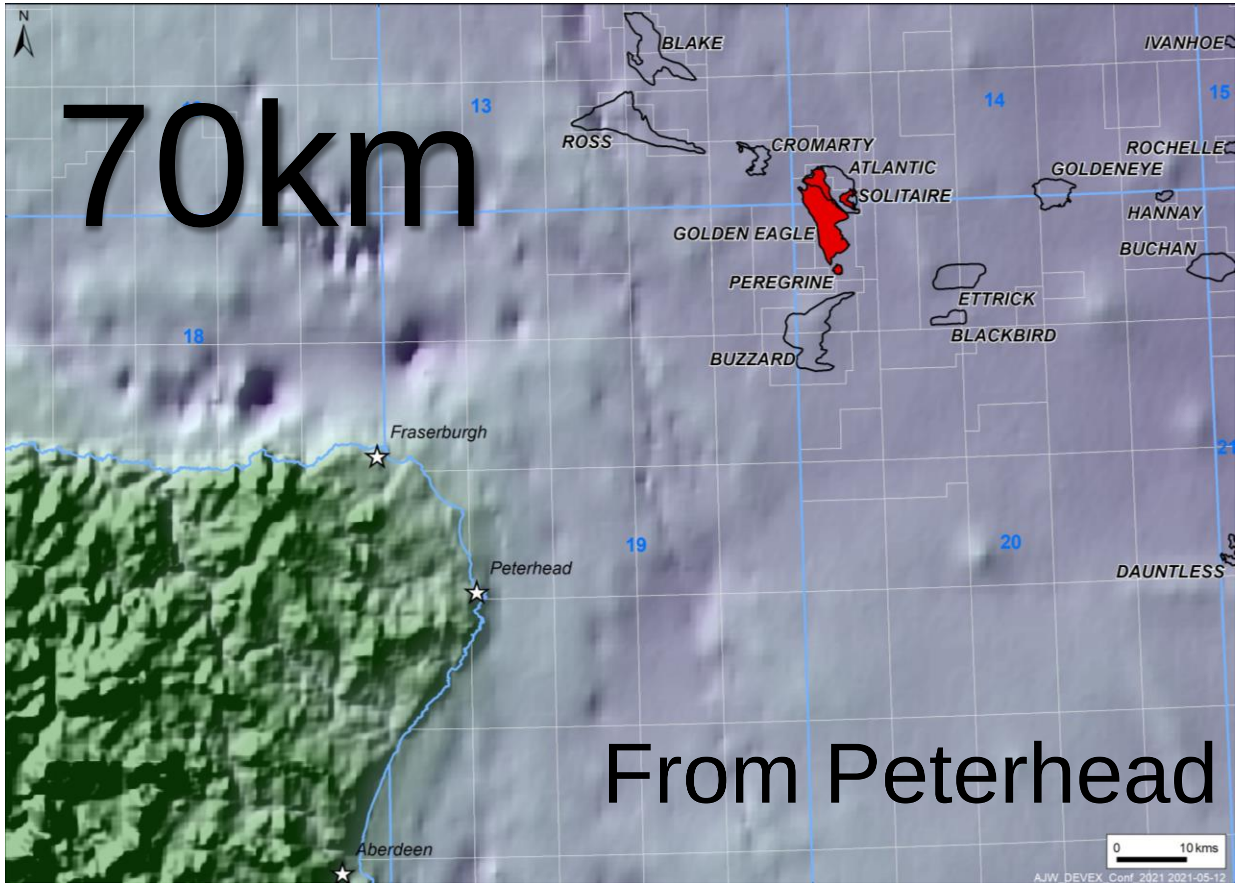
Golden Eagle: Key Facts



3 fields

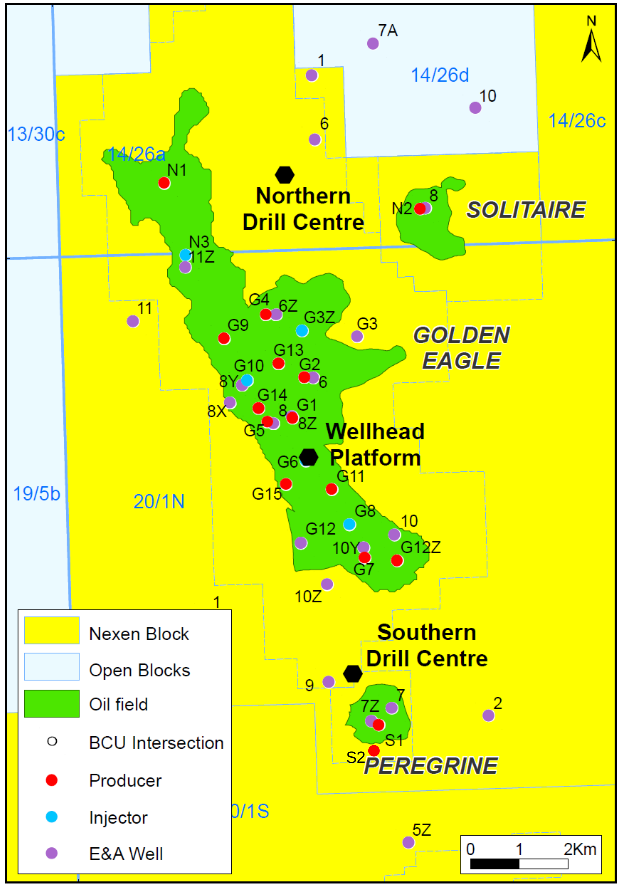
Golden Eagle

Solitaire

Peregrine

2

Reservoirs



100m

Water depth

18 Producers, 6 Injectors

Intelligent well technology

7000ft

Average reservoir depth

Golden Eagle: Timeline

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

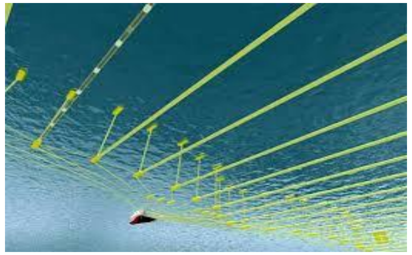
OBN acquisition

2016 — Development Drilling Finish

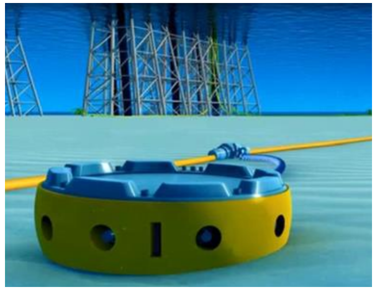
OBN PreSDM

4D OBN monitor

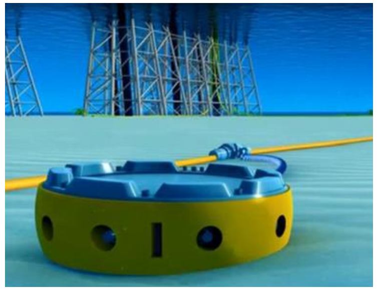
2020/21 — Platform Infill Drilling



Conventional Streamer



Ocean Bottom Nodes

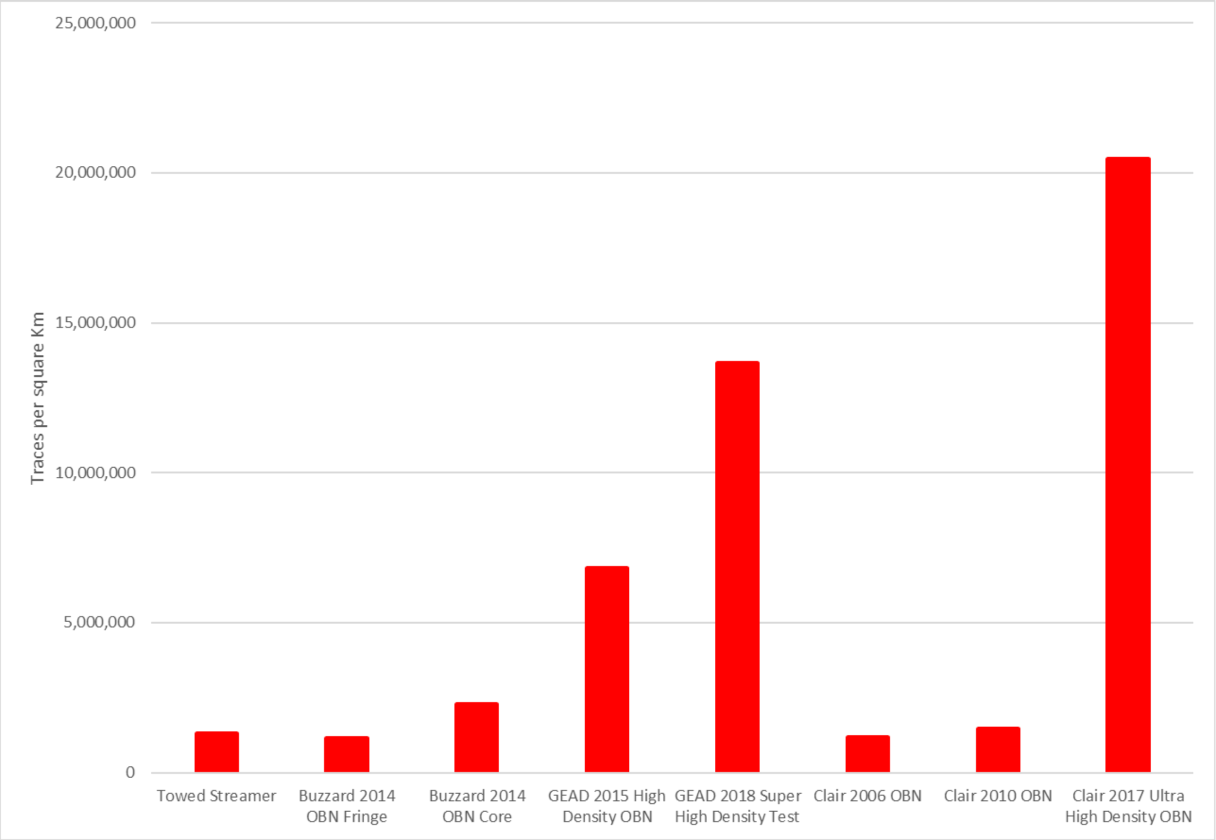


Ocean Bottom Nodes

Geowave Commander on close approach to Golden Eagle platform complex

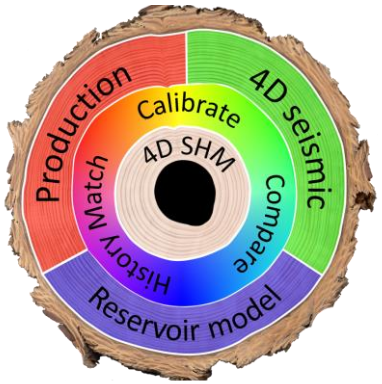
Golden Eagle: Summary

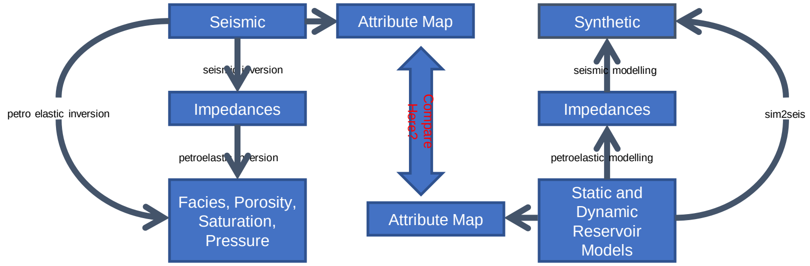
- The Golden Eagle area has a combination of an unusually challenging overburden and subtle reservoir seismic character.
- 3D and 4D seismic reservoir characterisation at GEAD requires an exceptionally high quality of seismic acquisition and processing.
- Golden Eagle is a low relief field and infill 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.

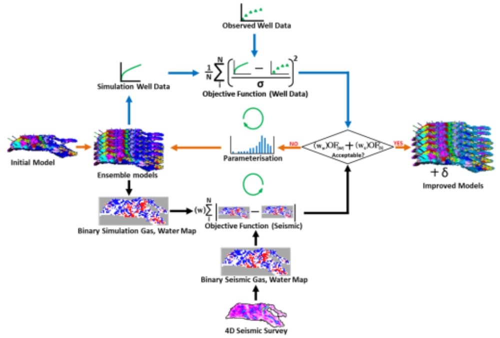


GEAD 4D Seismic Interpretation Strategy

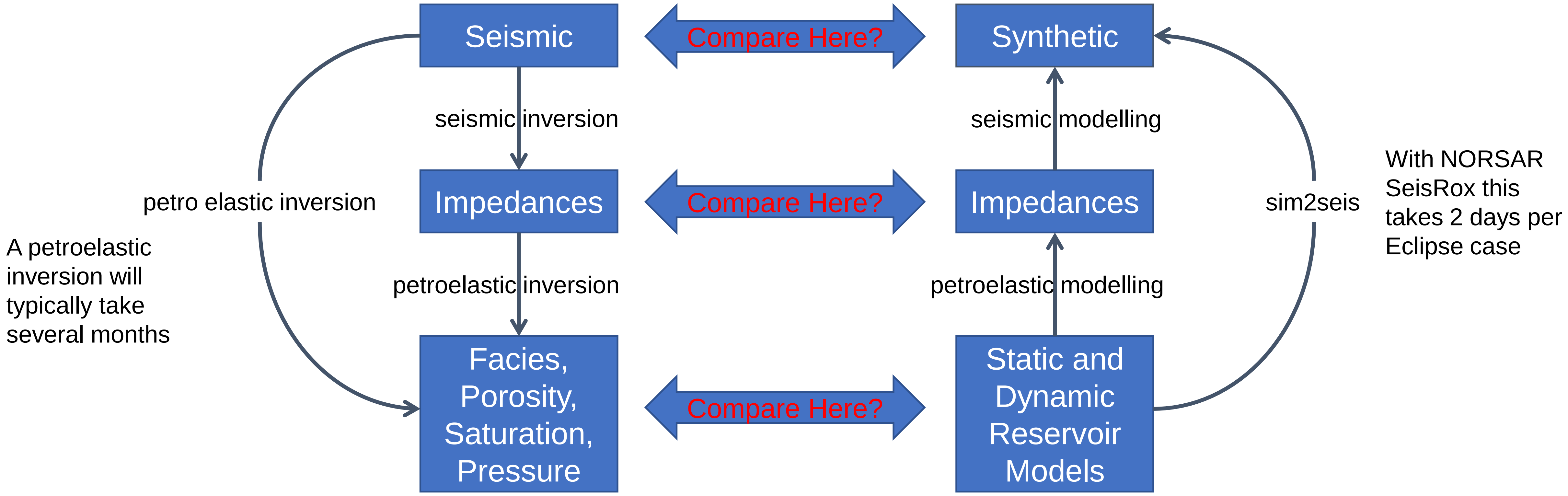
- Follow the “tree trunk” tiered, structured approach to 4D seismic interpretation
- Explicit aim to make 4D interpretation consistent with geological and engineering observations
- Avoid premature “black box” optimisation of a single objective function
- Develop simple, robust meaningful 4D seismic 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



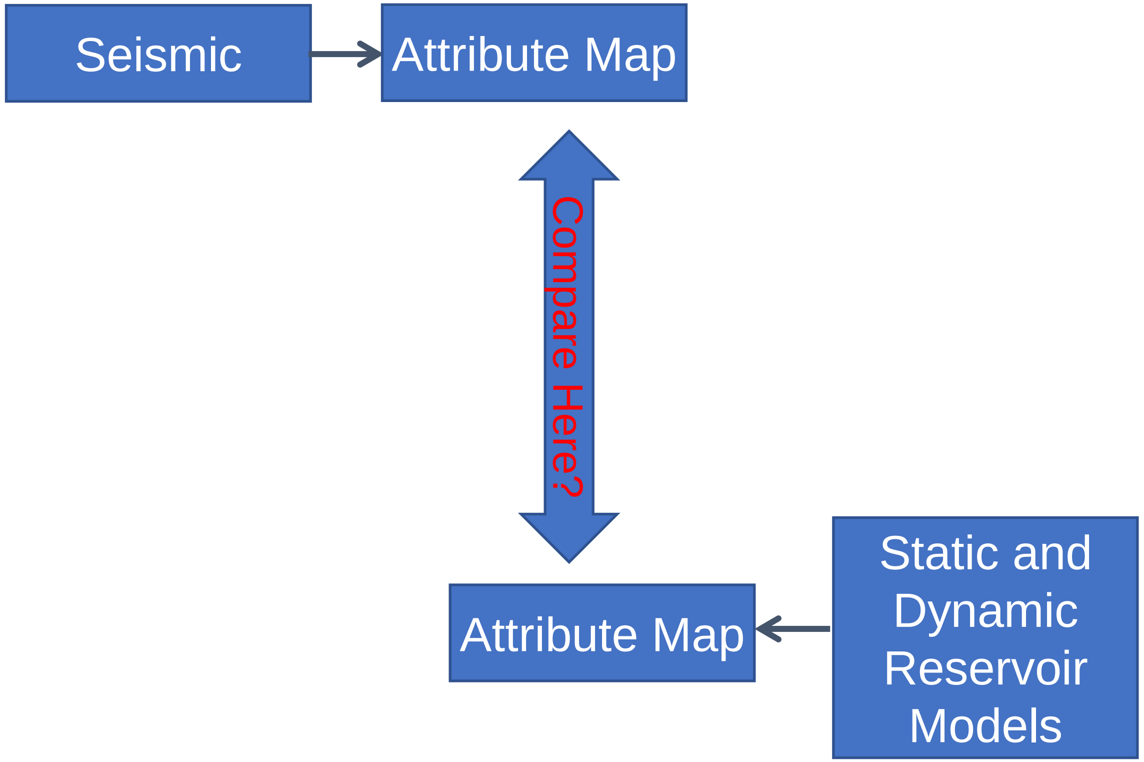




Relating Seismic and Reservoir Models

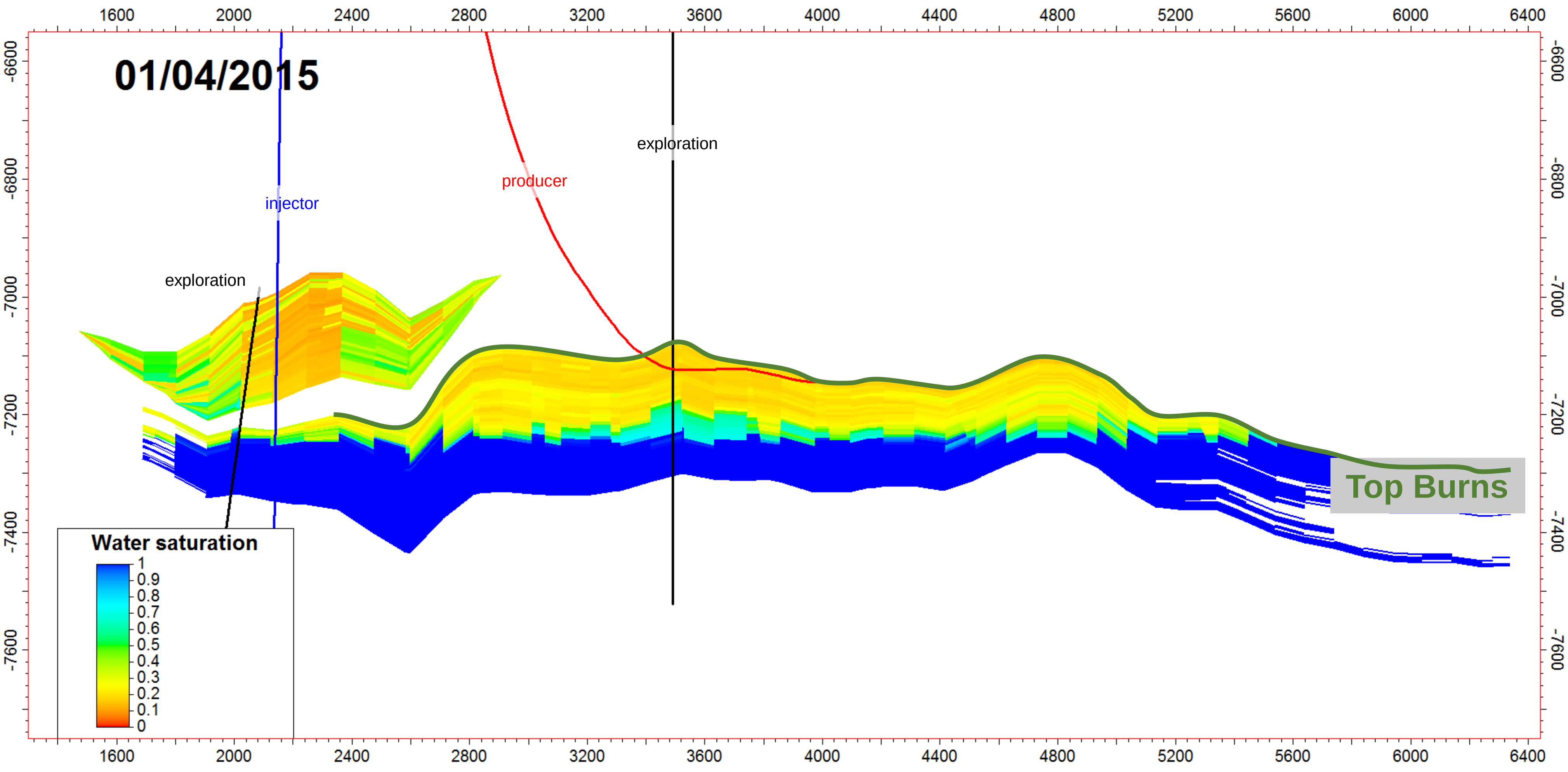


Relating Seismic and Reservoir Models

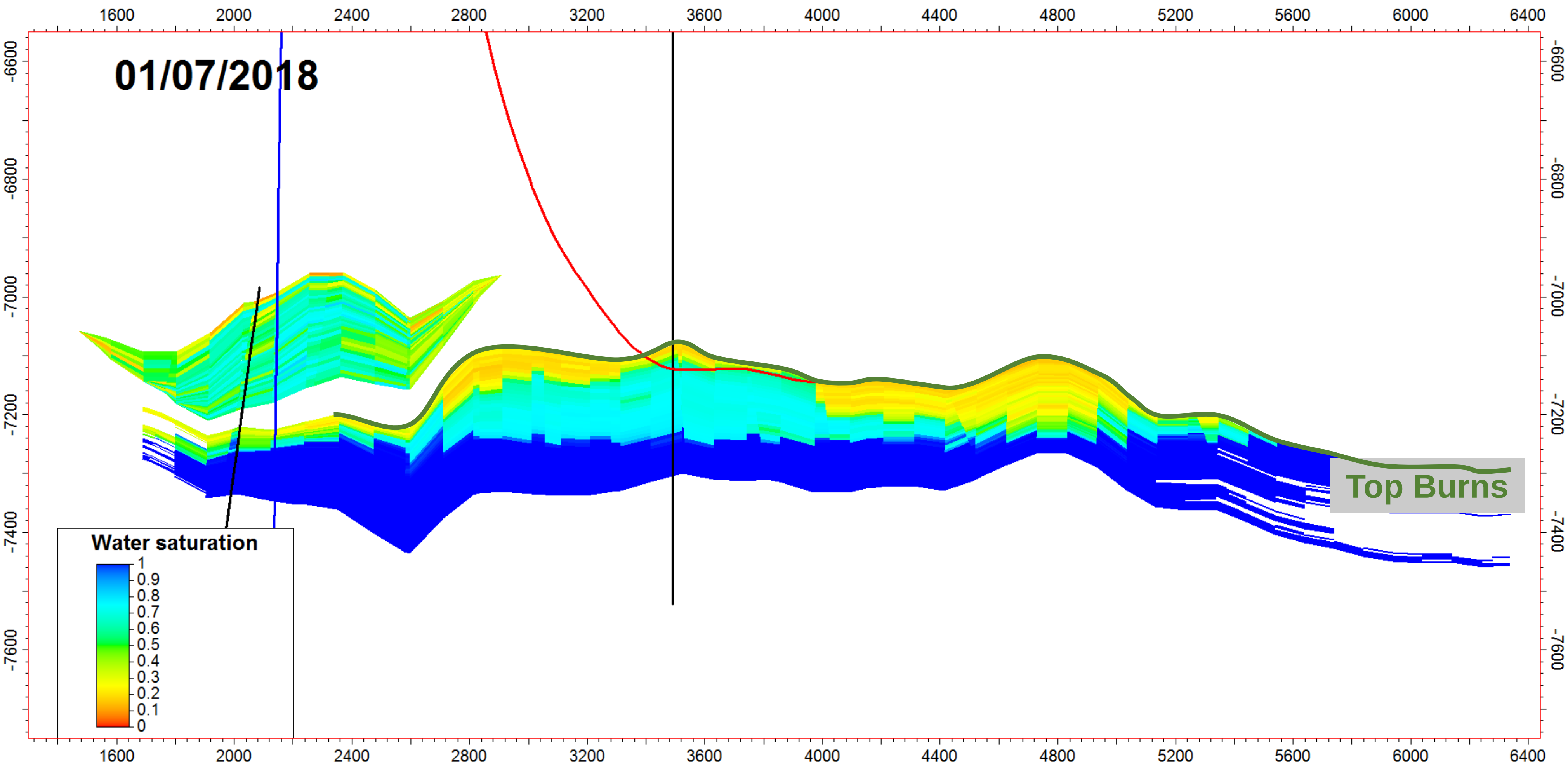


In the Burns the 4D response is dominated by water sweep and we have an effective 4D seismic attribute (max hardening on 4D quadrature) and an effective reservoir proxy attribute (swept oil volume).

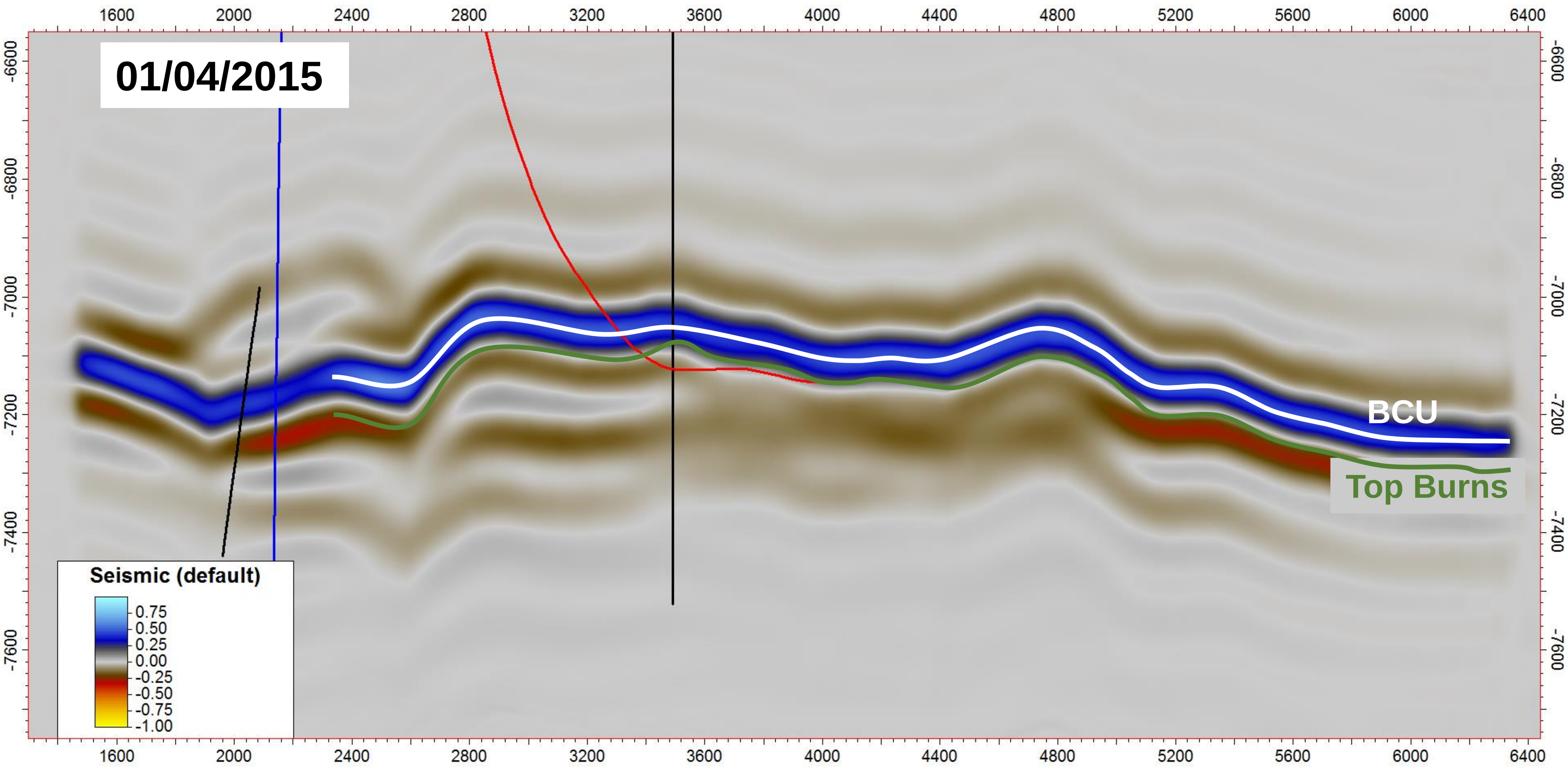
Saturation at time of baseline survey



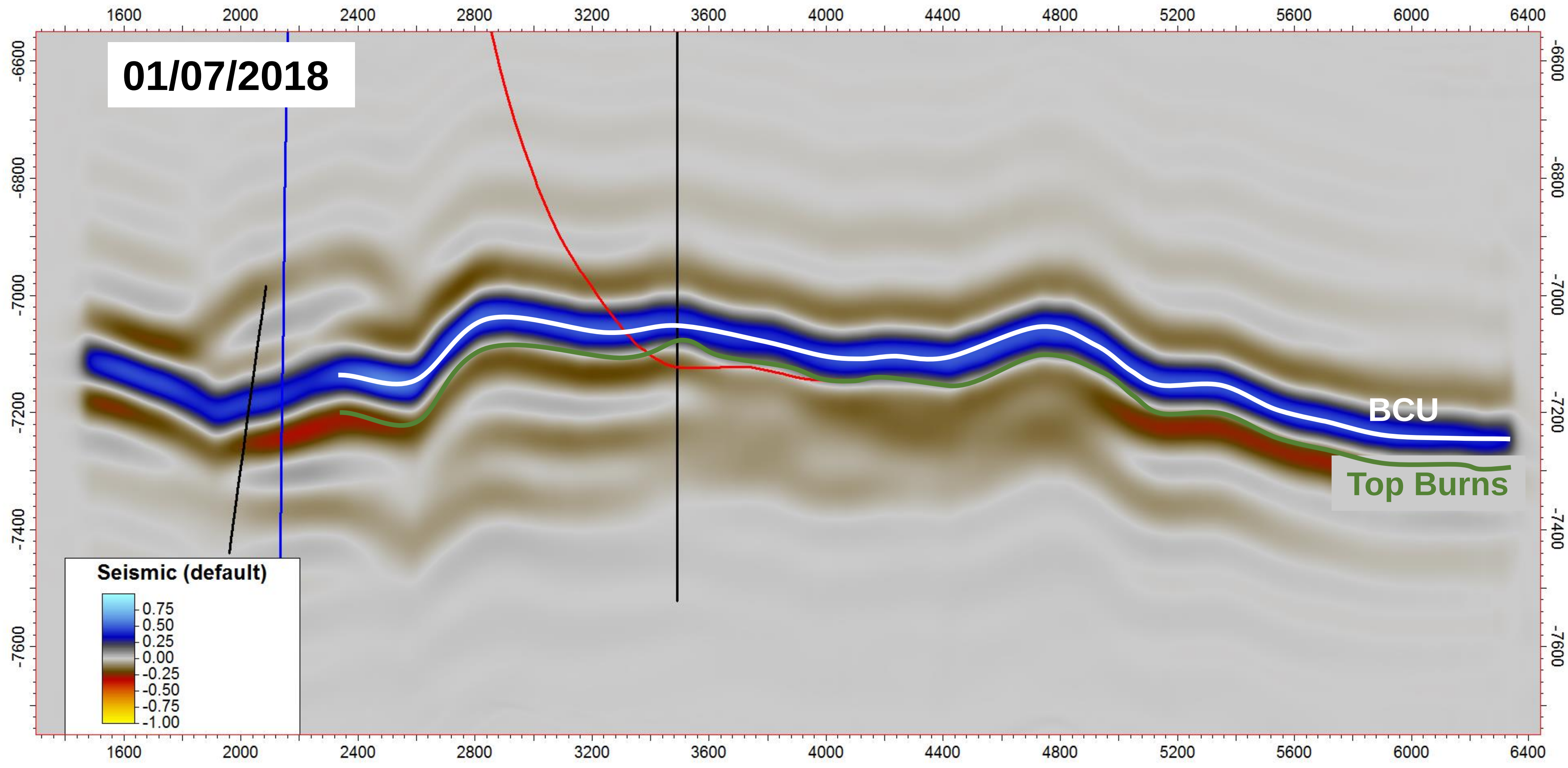
Saturation at time of monitor survey



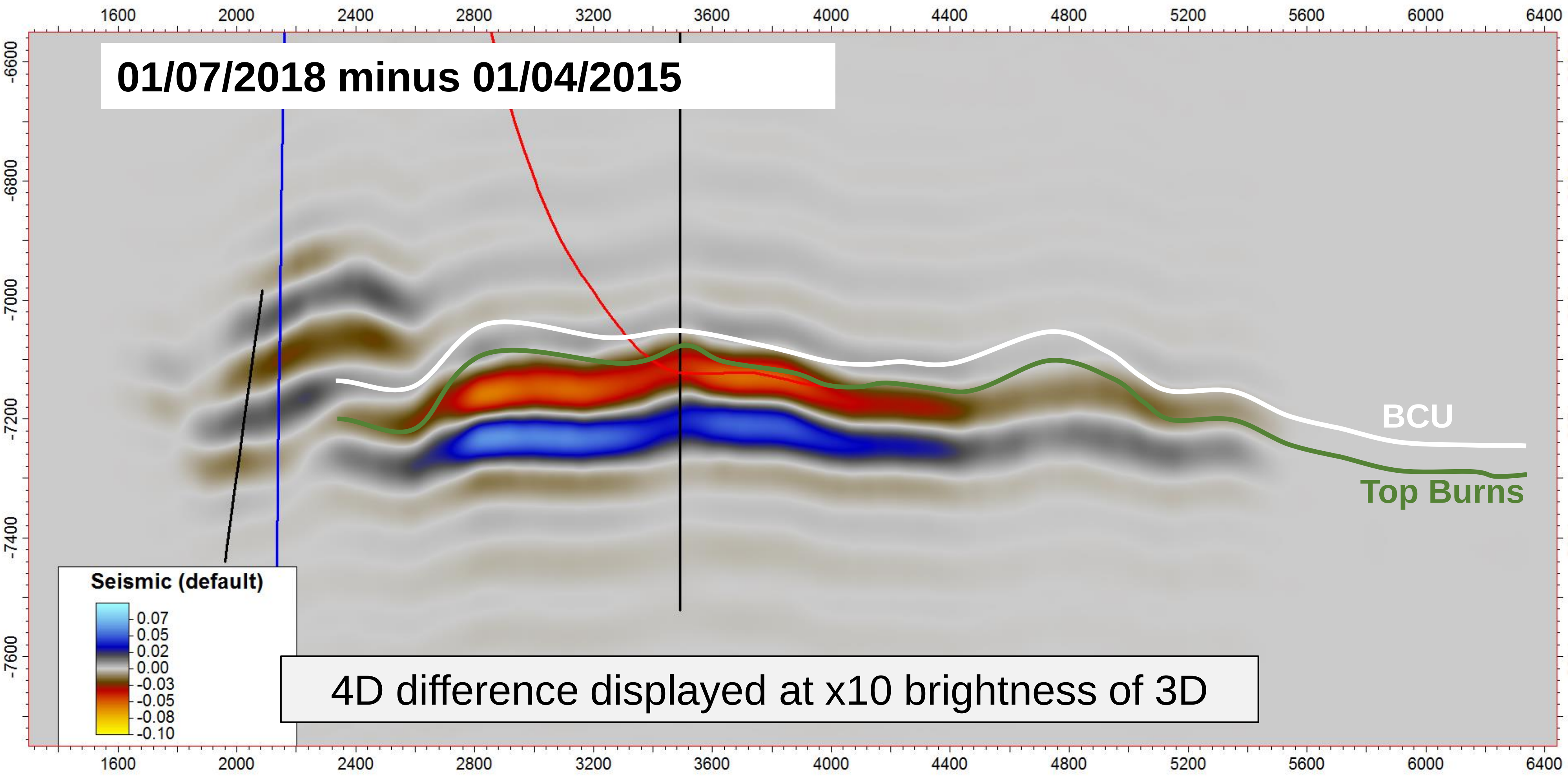
Synthetic seismic – baseline survey



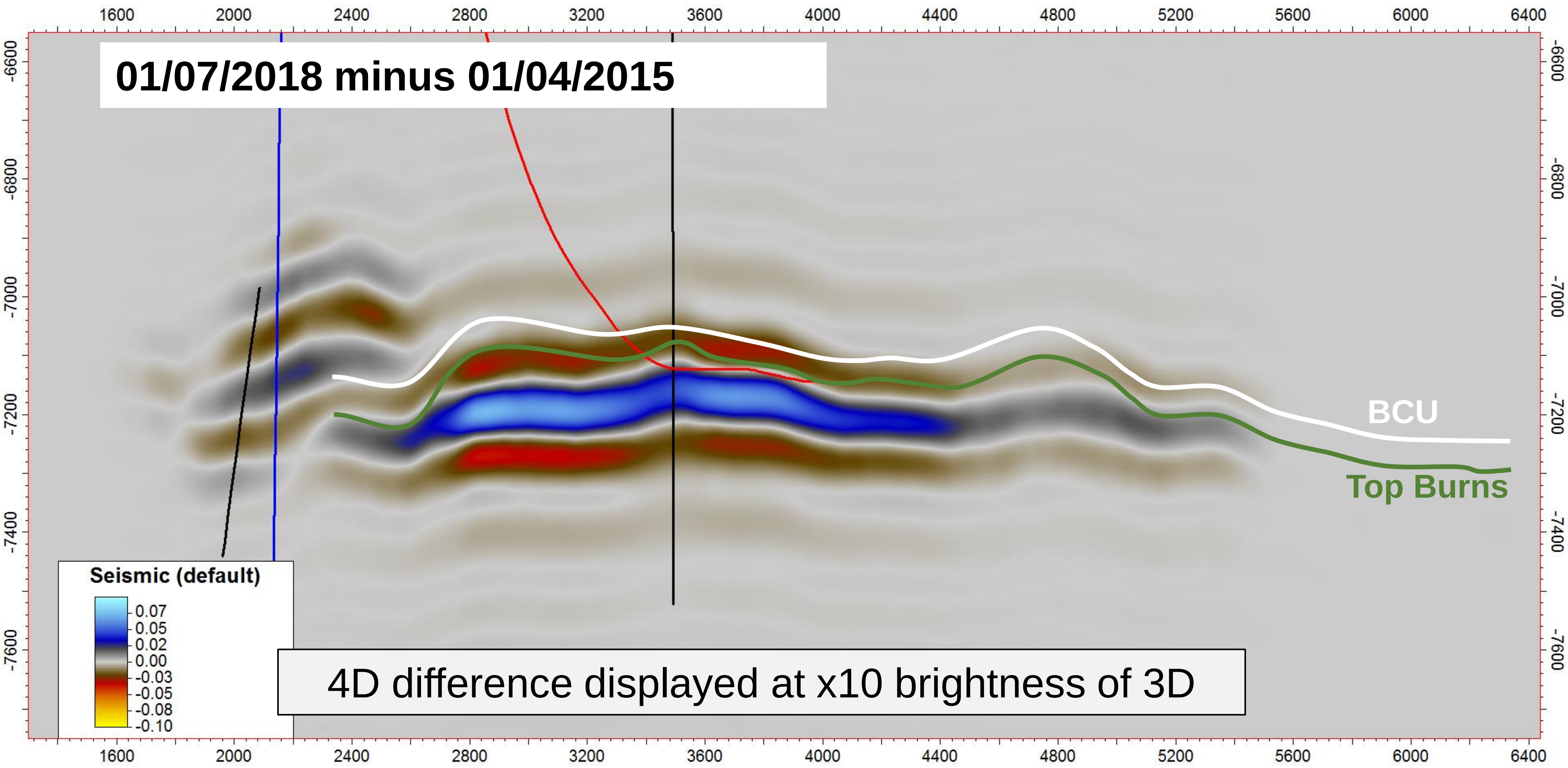
Synthetic seismic – monitor survey



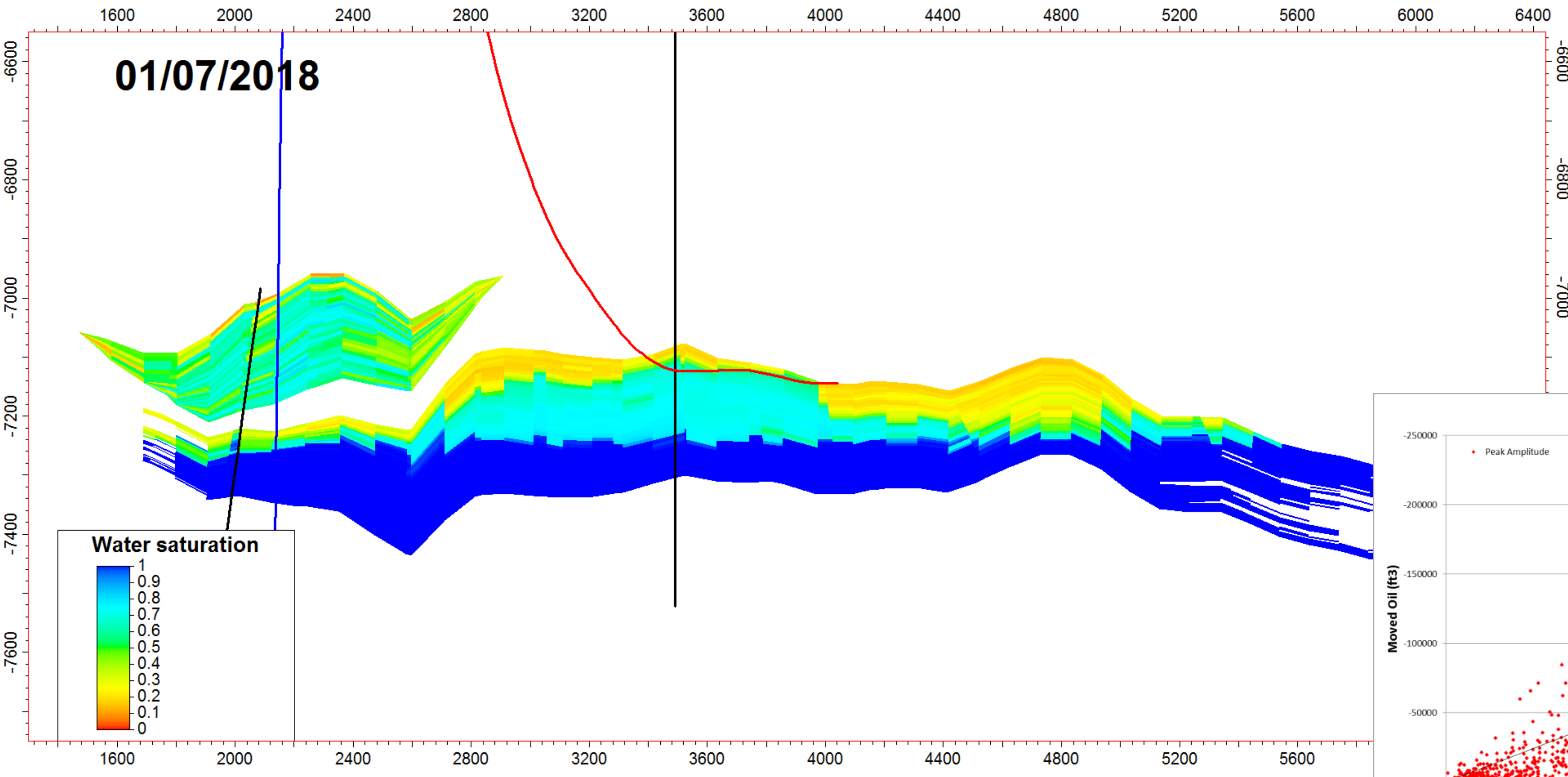
Synthetic seismic difference – monitor minus baseline

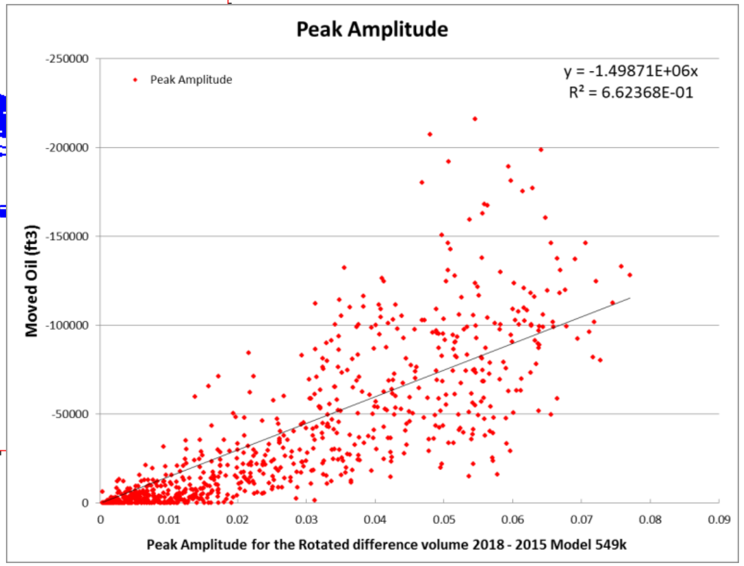


Synthetic seismic – quadrature of 4D difference

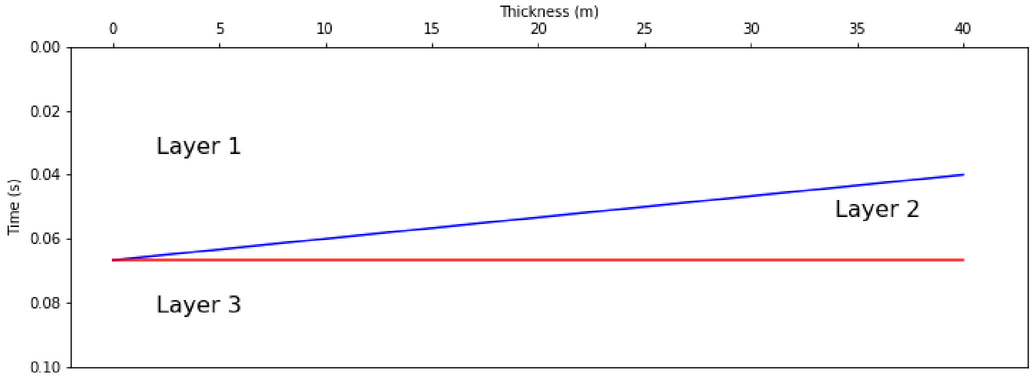


Robust correlation between amount of moved oil and maximum amplitude of the 4D quadrature in a window below BCU

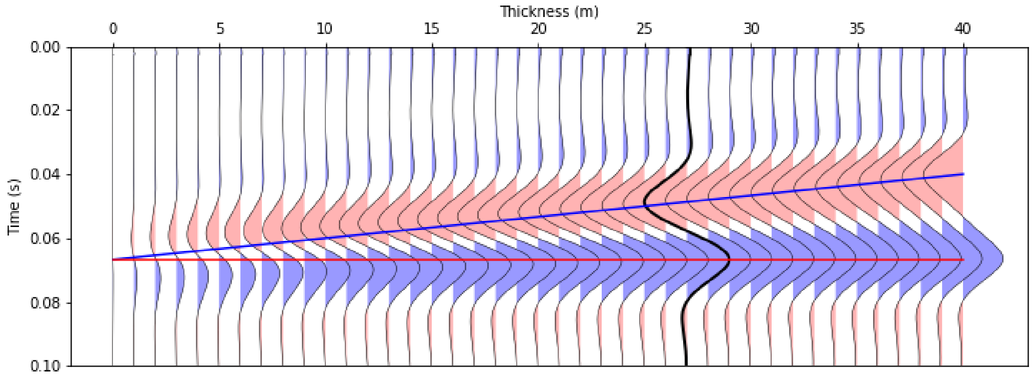




4D-informed depth correction: some implementation details

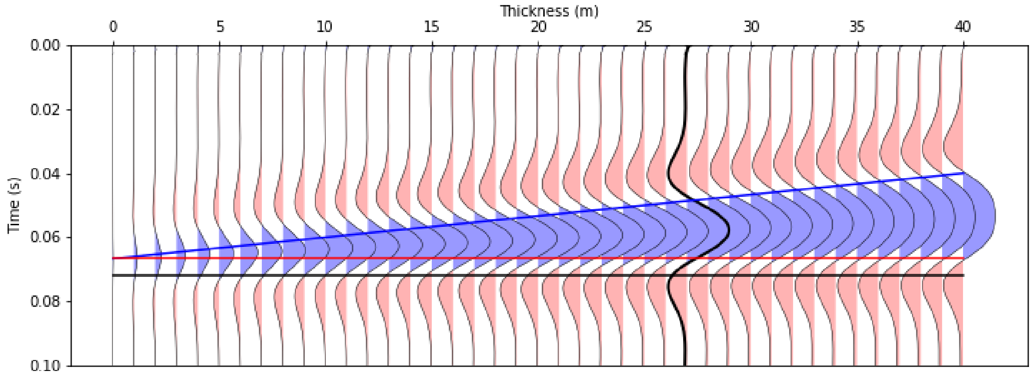


Thickness of swept layer



4D difference

Tuning thickness = 27m ~ 90ft



4D quadrature difference

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

20ms TWT ~ 100ft @ 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.

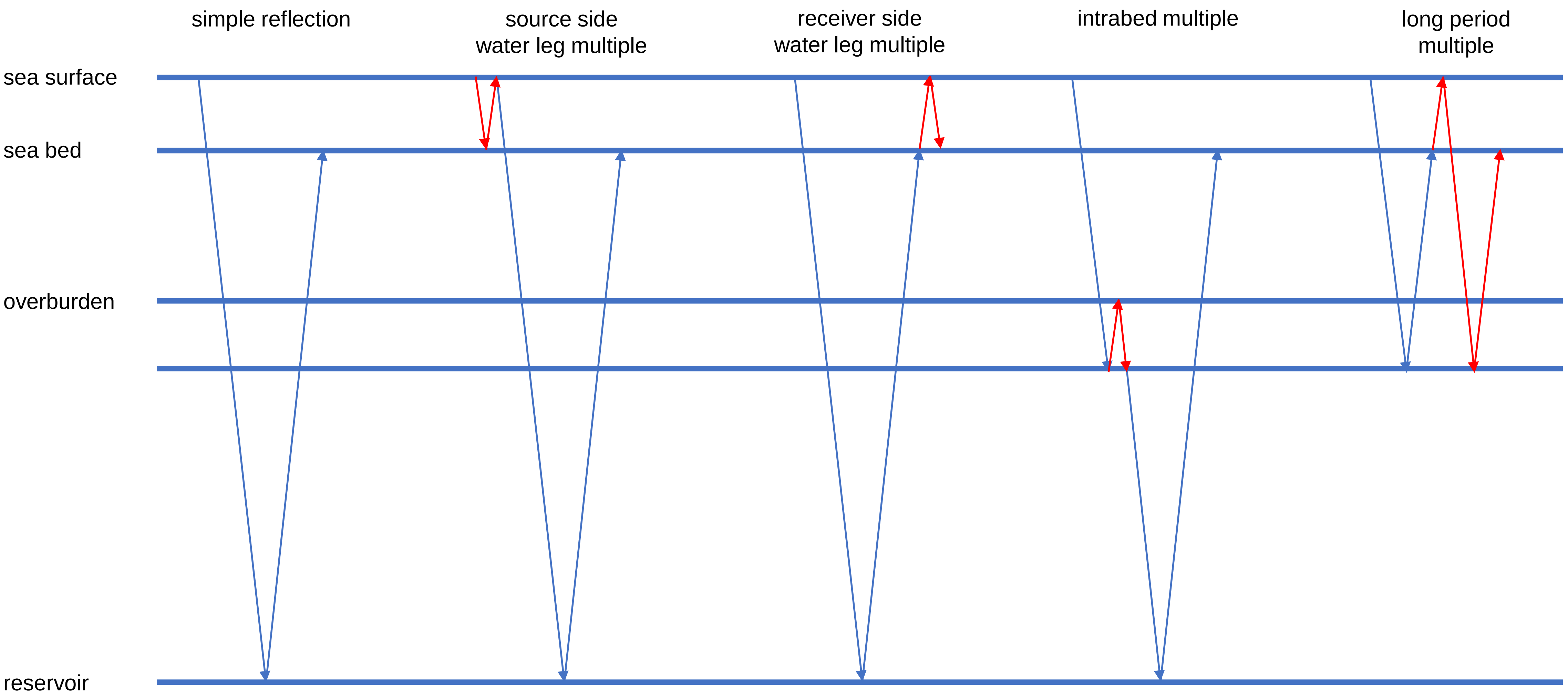
$$4D\ NRMS = \frac{RMS(monitor - base)}{0.5 * [RMS(monitor) + RMS(base)]}$$

- 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

4D Wavefield Harmony

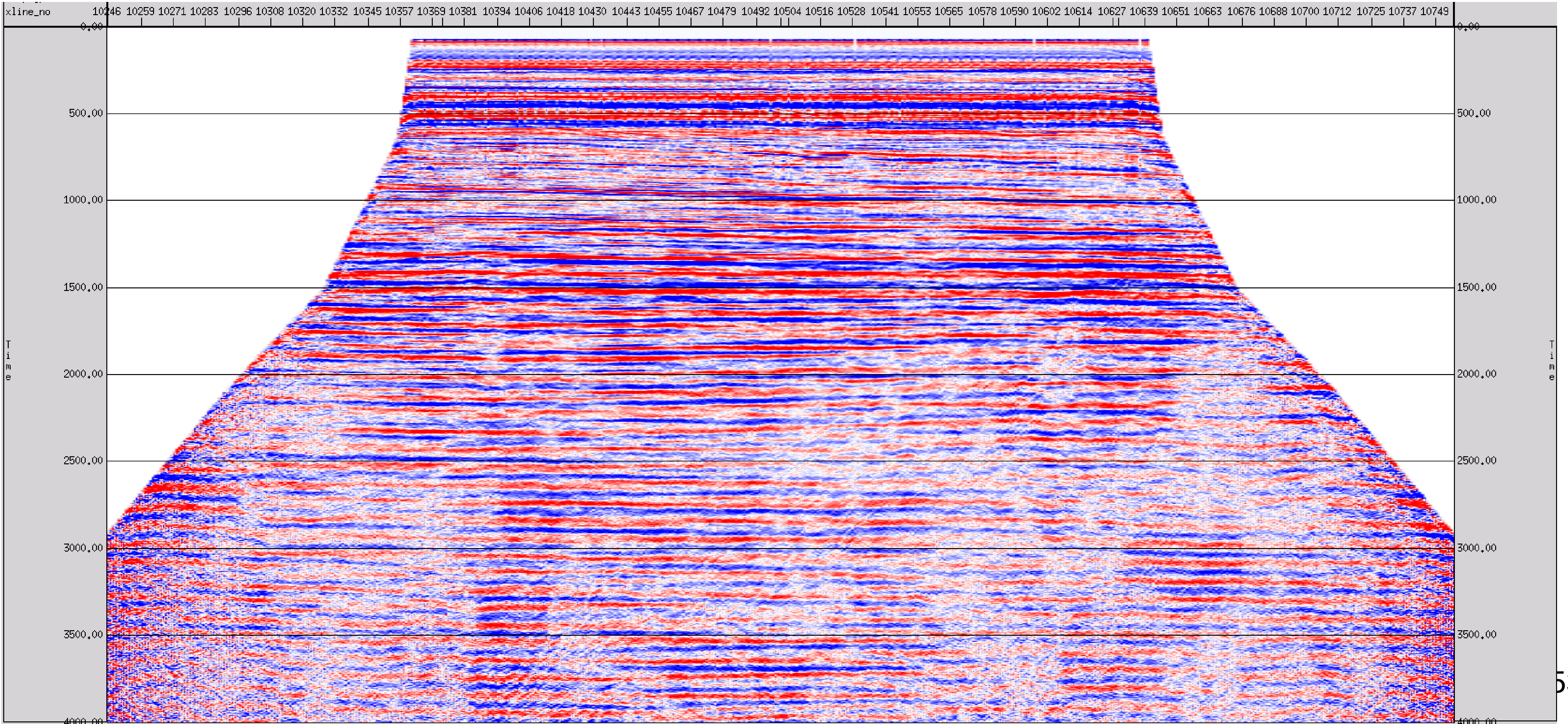
- What are seismic “multiples” and why do they matter to GEAD?
- What is special about OBN seismic that helps us tackle multiples?
- What is PZ summation (essential concept only)?
- What are these wavefields and what are the implications for GEAD 4D?
  - upgoing
  - downgoing
  - reflectivity
- What 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**.

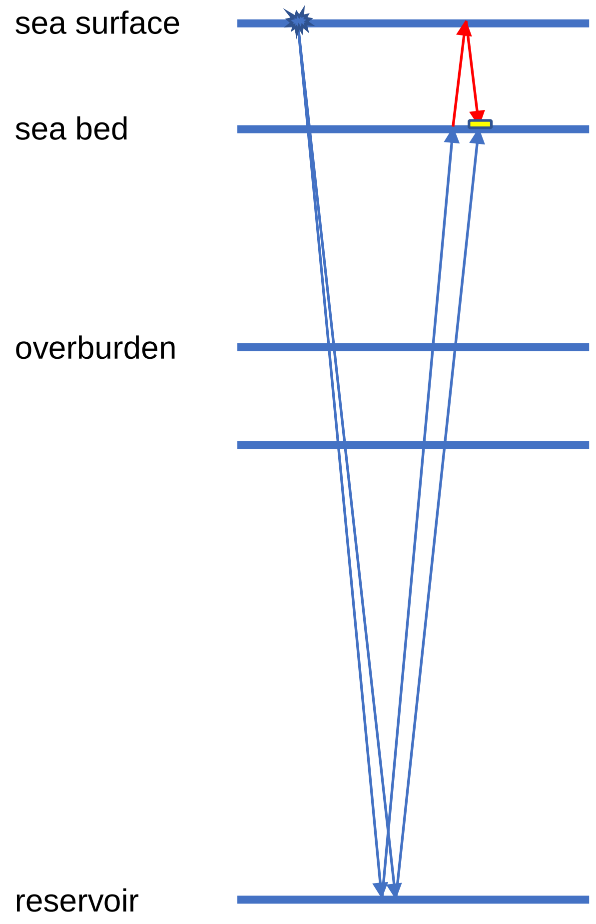
Geophones

- 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.

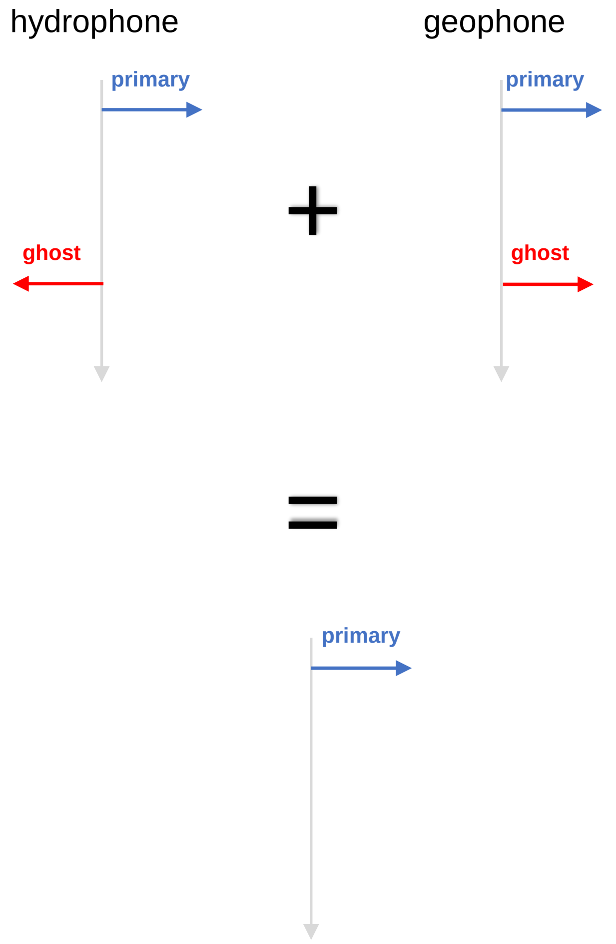
The receiver side water leg multiple (also known as the receiver ghost) is reflected off the sea-surface (which has a reflection coefficient of -1) so has opposite polarity to the primary reflection.

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.

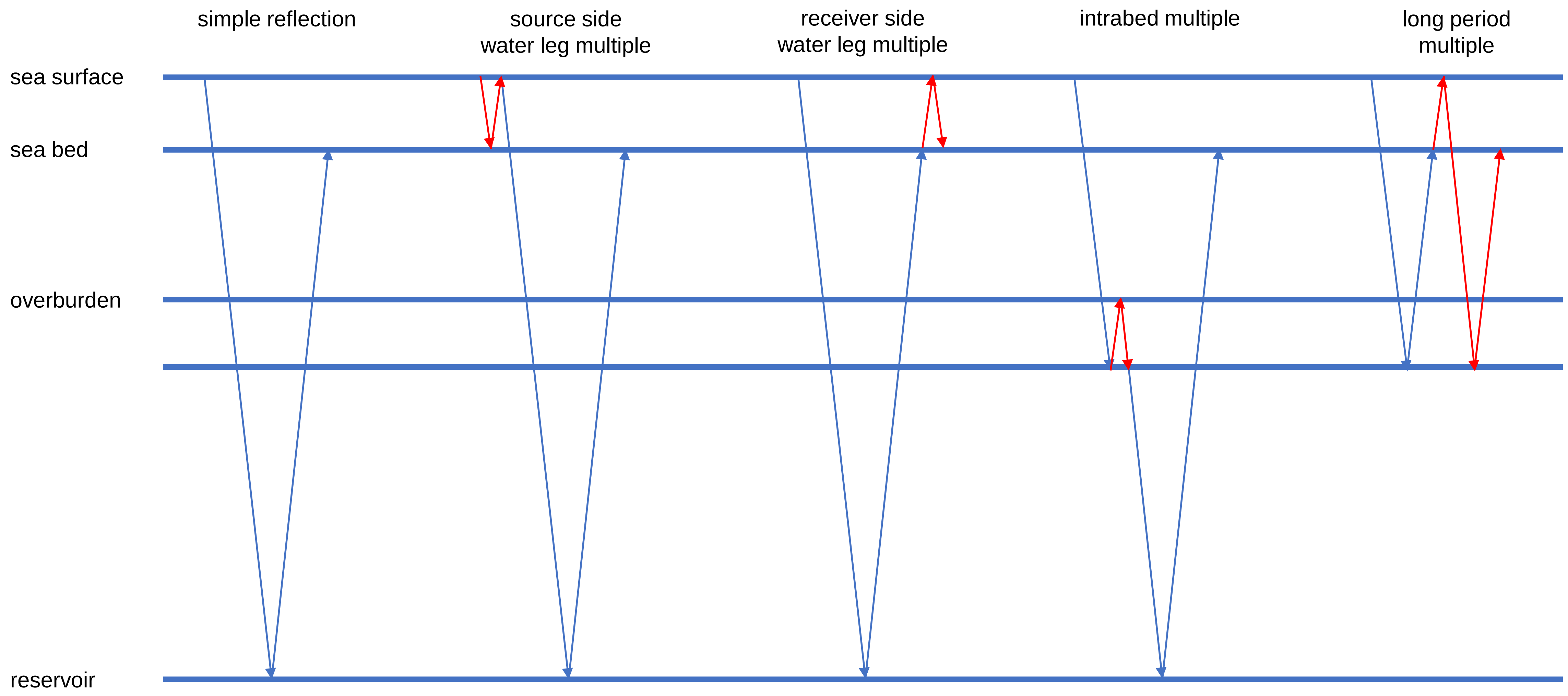


One step beyond the conceptual essence

- 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.

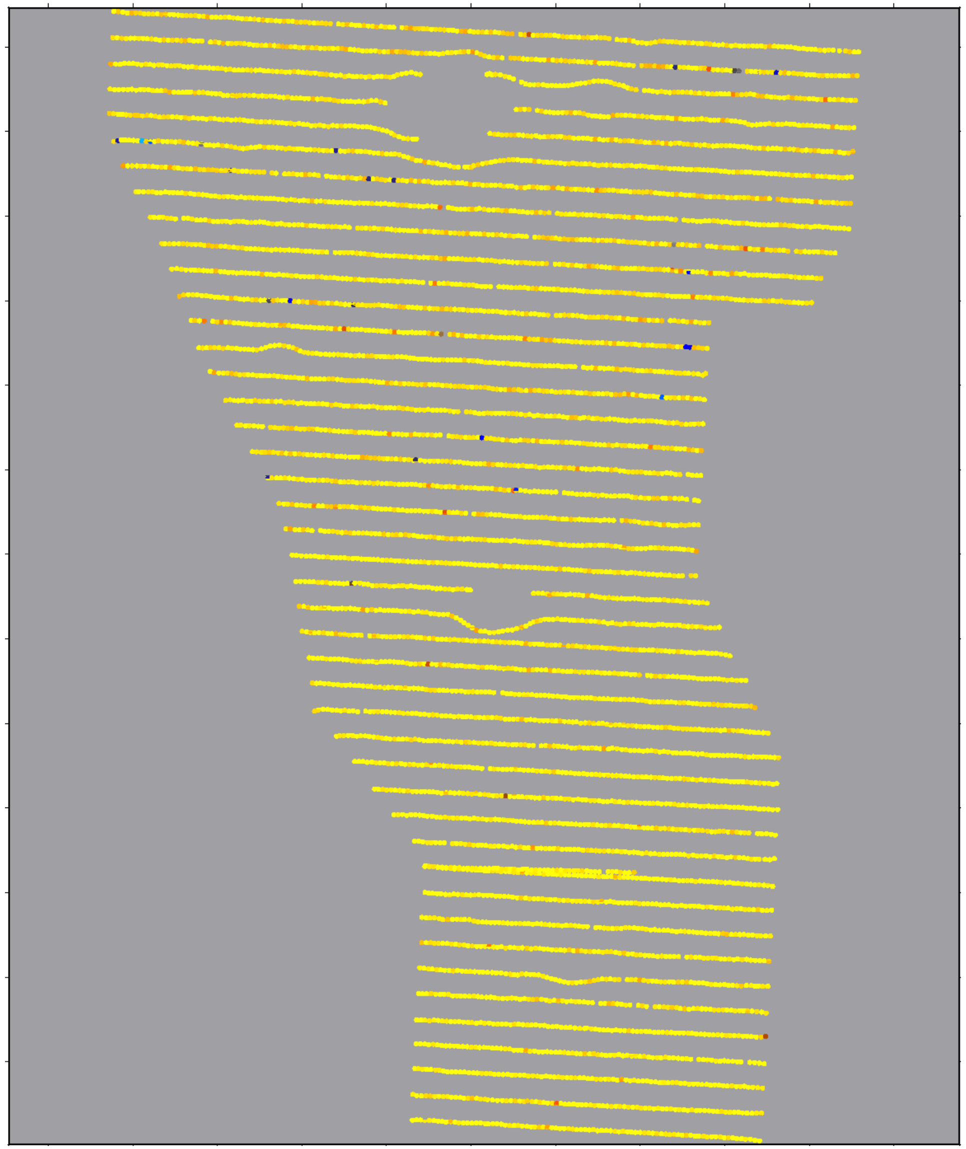
When is 99.995% Not Good Enough?

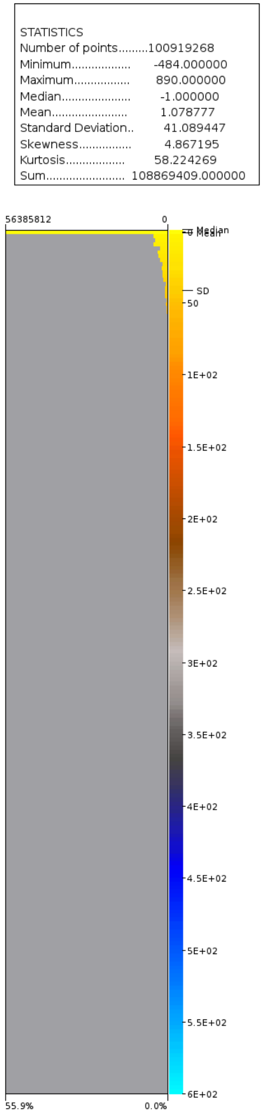
- Q: When is 99.995% Not Good Enough?
- A: When you're aiming for world class 4D noise levels
- The following 3 slides show one example of the holistic approach applied to data QC and denoise during the 2018/19 4D processing project
- This identified an unexpected 3D noise source impacting 0.005% of the raw seismic traces
- This noise source was not detected by previous 3D processing and probably would not be detected in any routine seismic processing job where data QC is typically done on a limited number of test lines rather than on the whole seismic volume

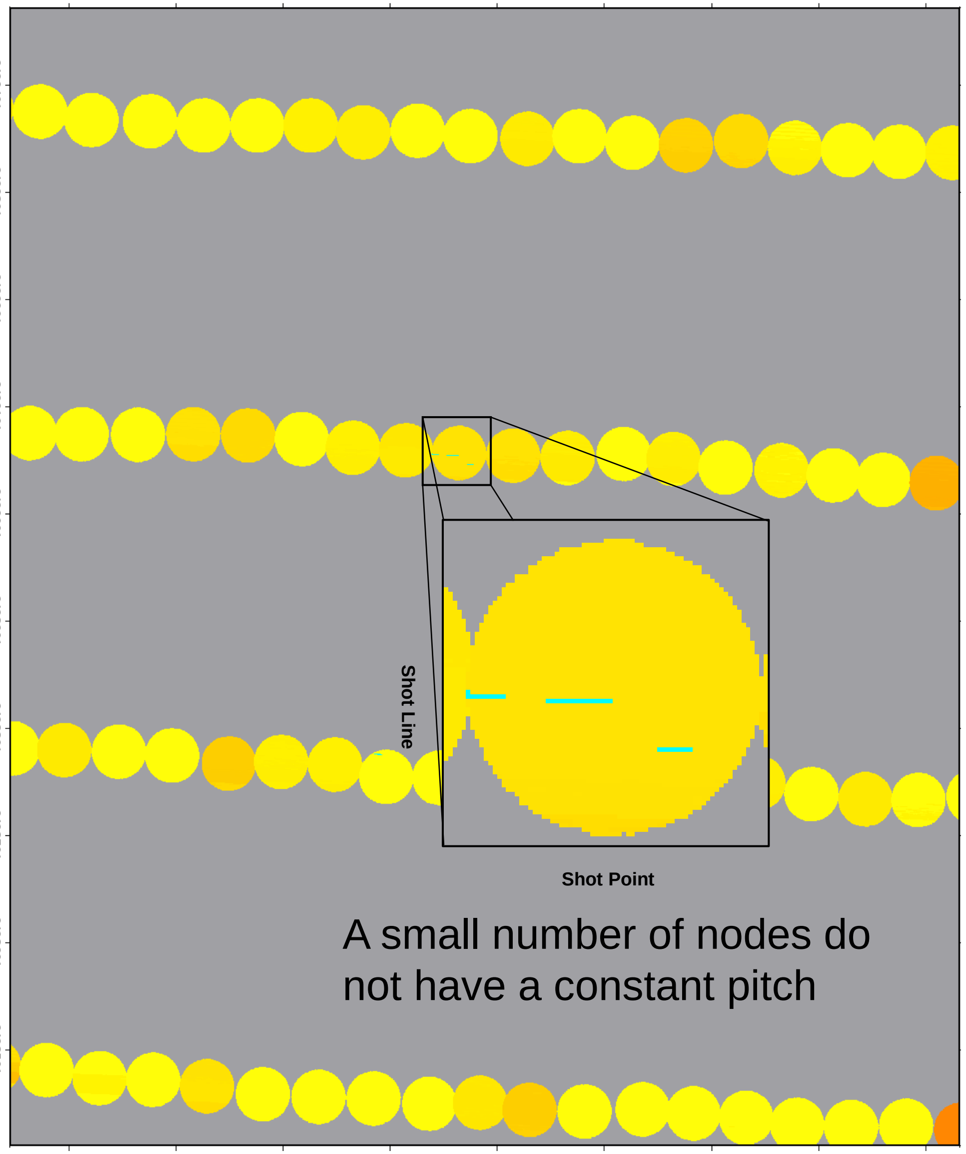
- Before we begin…..
- The sea bed is not perfectly flat and the OBN receivers contain a tilt meter that allows the vertical Z component of the seismic signal to be calculated from the three orthogonal geophones
- Sometimes nodes move during a survey and so the tilt is recorded per shot
- The tilt is expressed as "pitch" which is the rotation from horizontal in the along-the-receiver-line direction and "roll" which is the rotation in the orthogonal-to-the-receiver-line direction

60

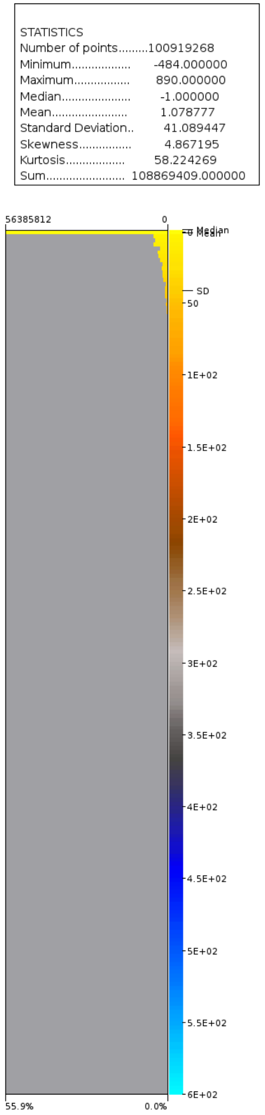
OBN Receiver Node Pitch
plotted with shotlines and shotpoints up to 3000m offset



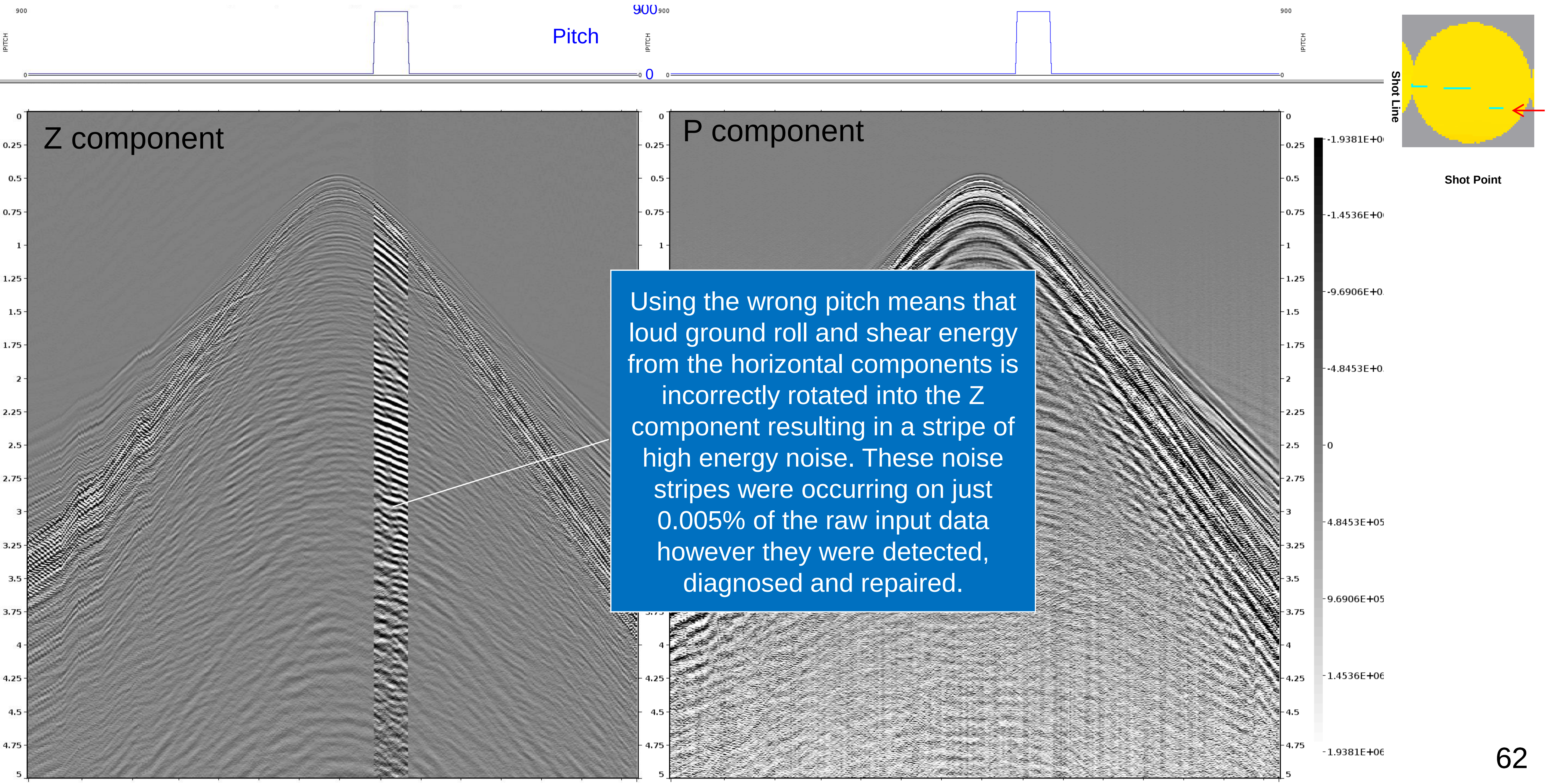




A small number of nodes do not have a constant pitch

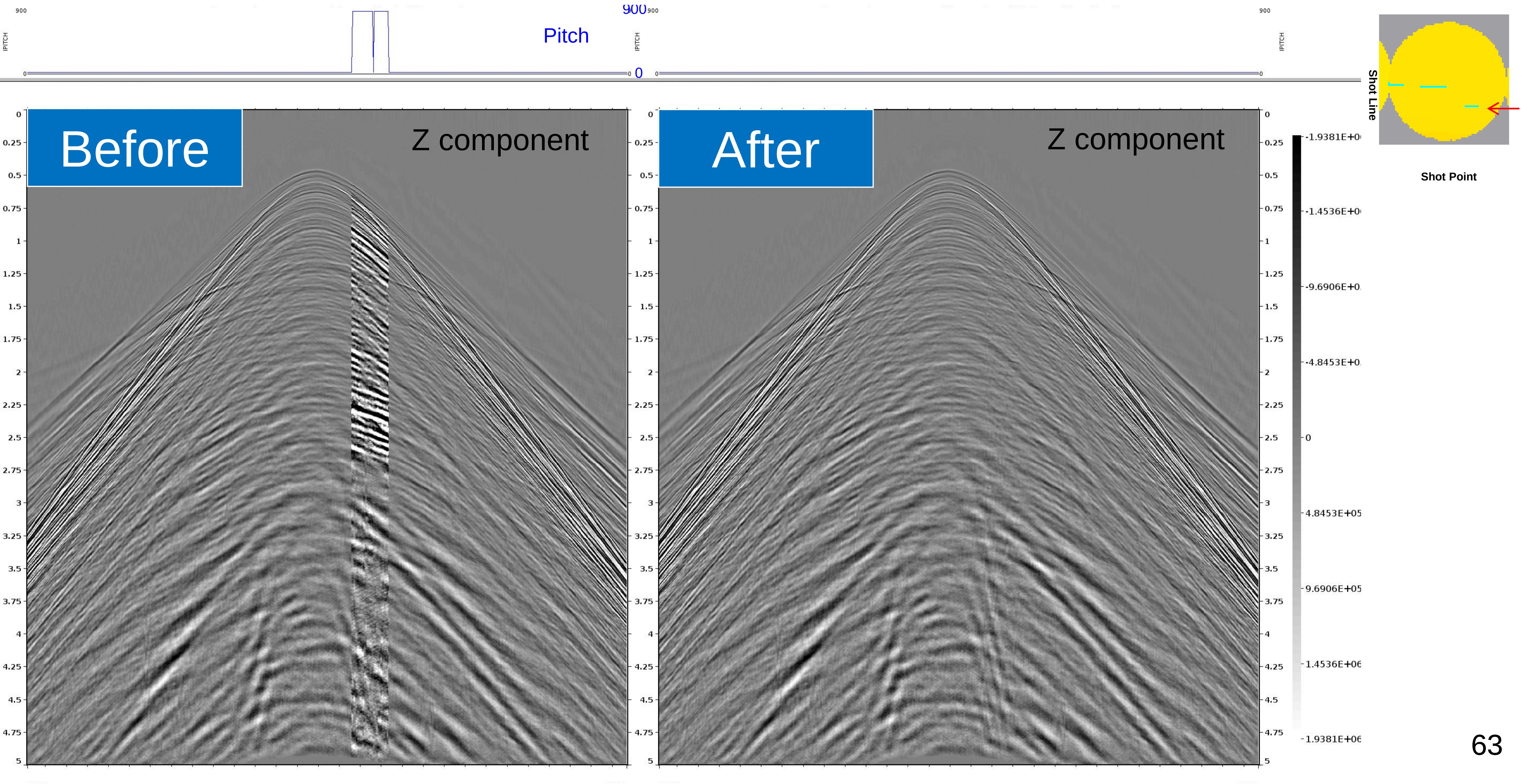


Detection and Diagnosis



Using the wrong pitch means that loud ground roll and shear energy from the horizontal components is incorrectly rotated into the Z component resulting in a stripe of high energy noise. These noise stripes were occurring on just 0.005% of the raw input data however they were detected, diagnosed and repaired.

Repair



Pitch
900
0
Before
Z component
After
Z component
Shot Line
Shot Point
-1.9381E+0
-1.4536E+0
-9.6906E+0
-4.8453E+0
0
4.8453E+05
9.6906E+05
1.4536E+06
1.9381E+06