Why are we recording multi-component data? and what about the shear waves?

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GSH talk September 2014

Introduction

- I gave the 2012 North America SEG Honorary Lectures
  - It was 80% PP and 20% PS. Why?
- Rob Stewart is now the GSH organizer, so I thought to rise to the challenge and try to answer the above question
  - Rob's shear waves course is enjoyable and motivating
  - I took it 20 years ago, I was exited and expecting a lot
- The business has not been as good as predicted
- Shear waves did not turn out to be a business driver. On the other hand, pleasant surprize: better P waves turned out to be a driver
- Why? What happened? What is going to happen?
- This talk will be 95% shear and 5% P.

Here is the 5% : Streamer to Node comparison: Maersk Dan

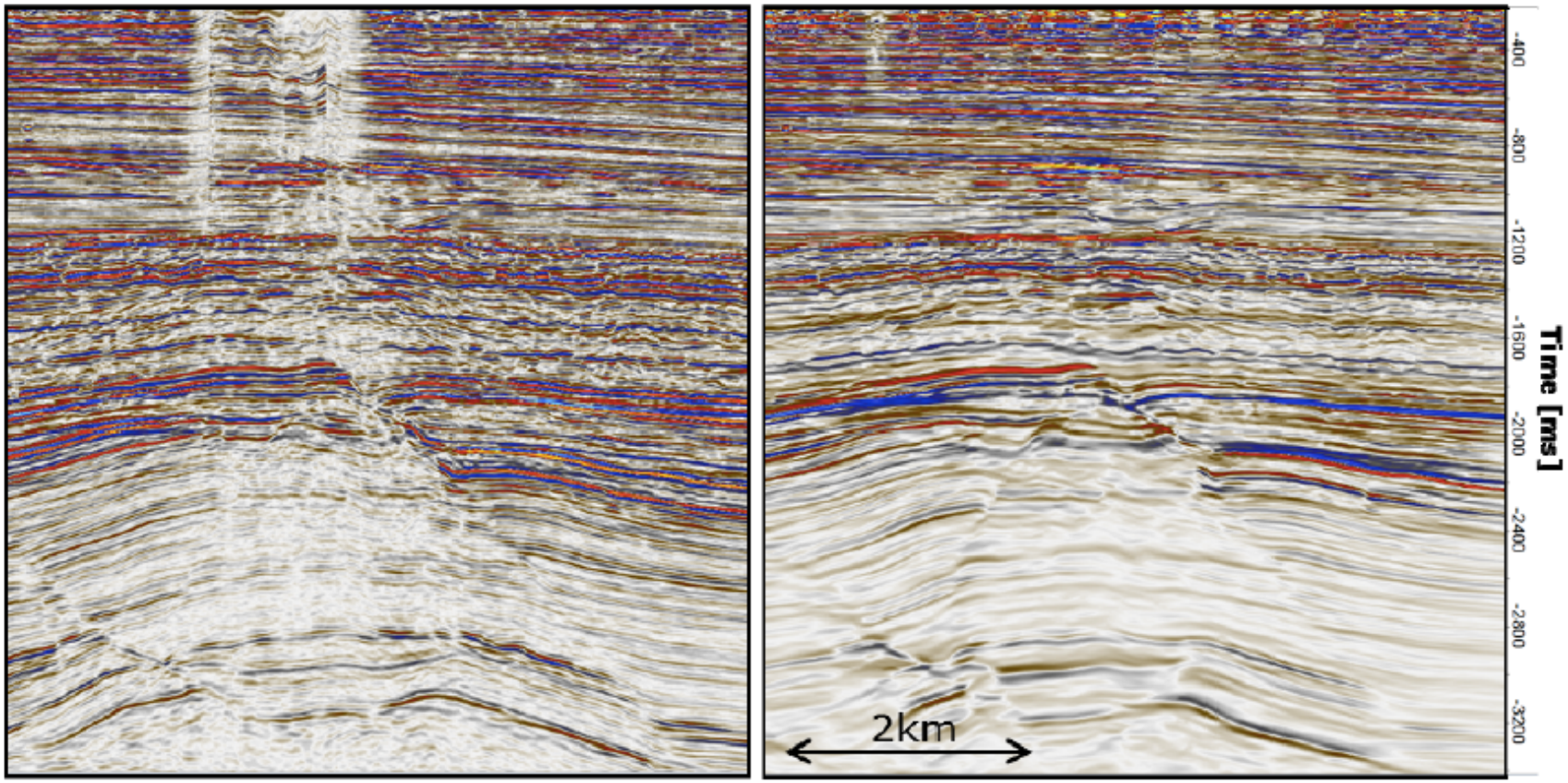


Figure 3 *Comparison between 2012 Streamer acquisition with undershoots and OBN RTM results along Line L2 shown in Figure 1. Left: Streamer, Right: OBN full frequency bandwidth. Faults and structure are better defined through the whole section. The OBN results show a wider frequency bandwidth.*

Streamer to Node comparison

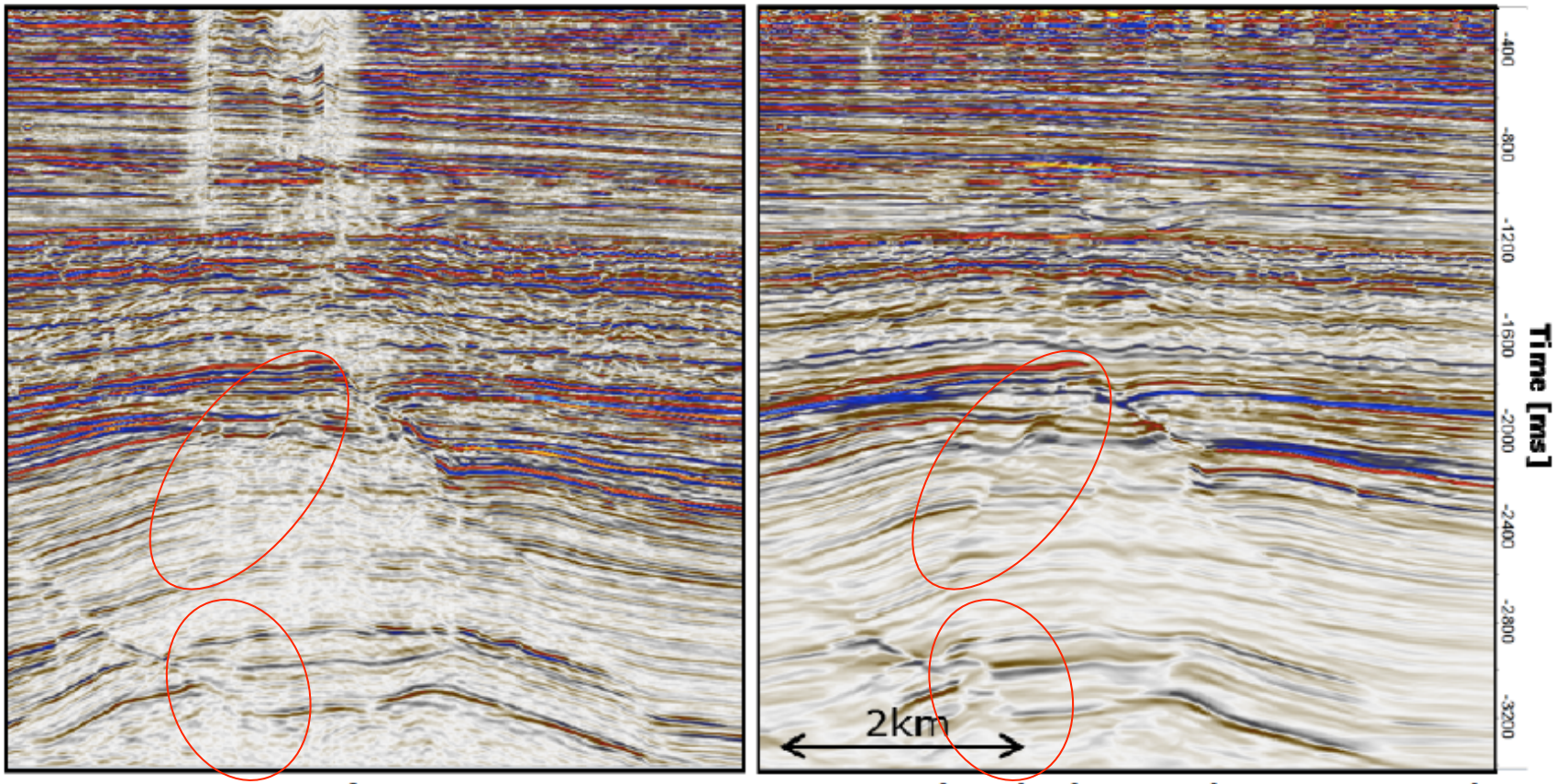


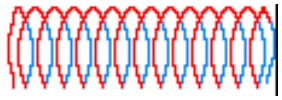
Figure 3 *Comparison between 2012 Streamer acquisition with undershoots and OBN RTM results along Line L2 shown in Figure 1. Left: Streamer, Right: OBN full frequency bandwidth. Faults and structure are better defined through the whole section. The OBN results show a wider frequency bandwidth.*

The multi-component business

- The business is drivern by P waves
  - We are getting better P-wave images and velocity models when we put receivers on the seabed. We understand why: full-azimuth well-sampled common receiver gathers, imaging with multiples, obstructions, wider band, low ambient noise
  - It is also multi-component: we separate Up/Down
- We are recording also shear wave
  - OBNs have 4 components
  - The surveys are not always designed to illuminate with shear waves, but we always record them
  - We rarely do much with the horizontal components

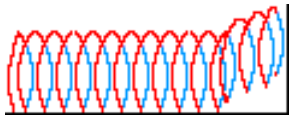
P waves and Shear waves

Primary (P) waves



$$V_p = \sqrt{\frac{K+4/3\mu}{\rho}}$$

Secondary (S) waves



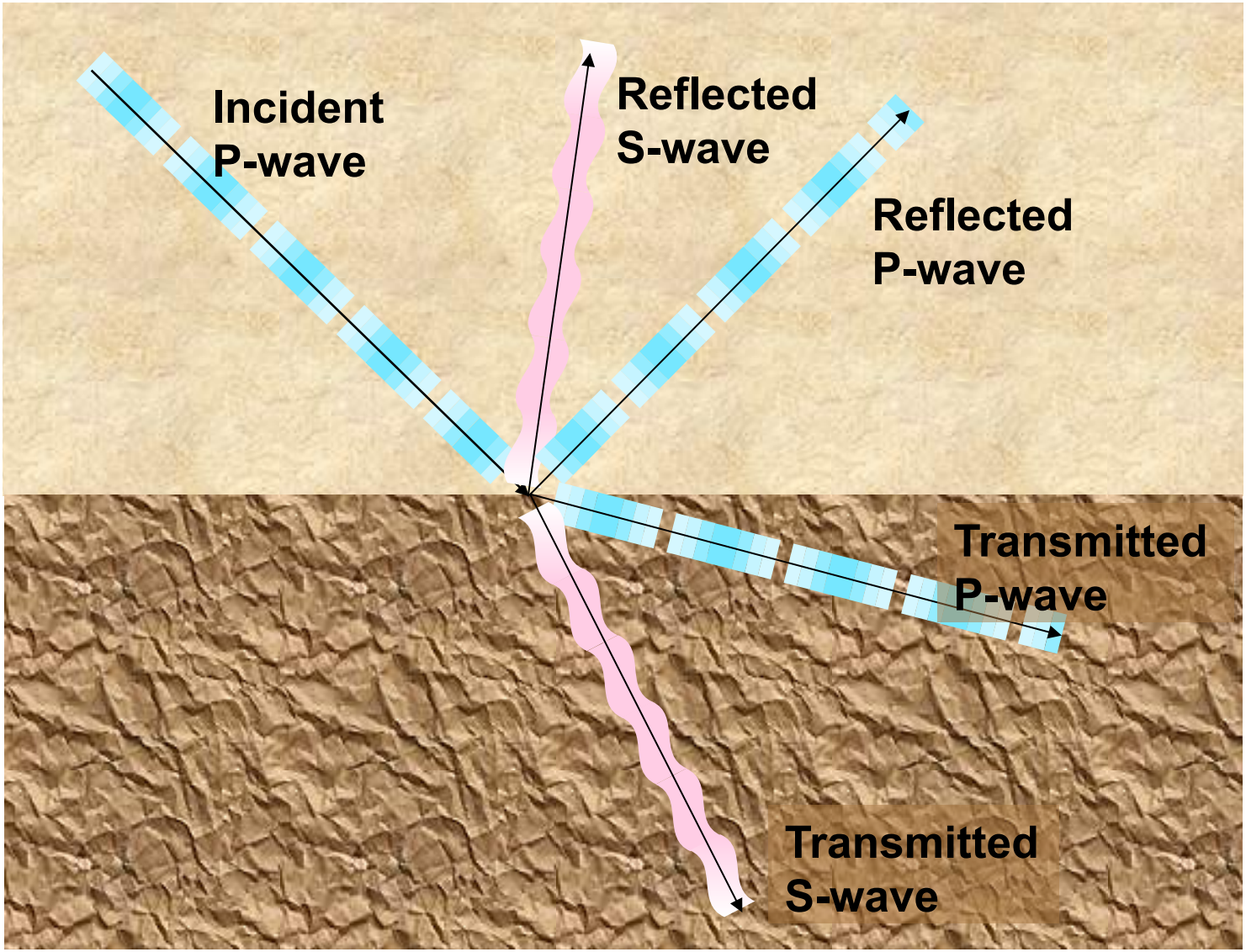
$$V_s = \sqrt{\frac{\mu}{\rho}}$$

K = *Bulk modulus: depends on fluids (low in gas)*
μ = *shear modulus: no contribution from fluid/gas*
ρ = *density*

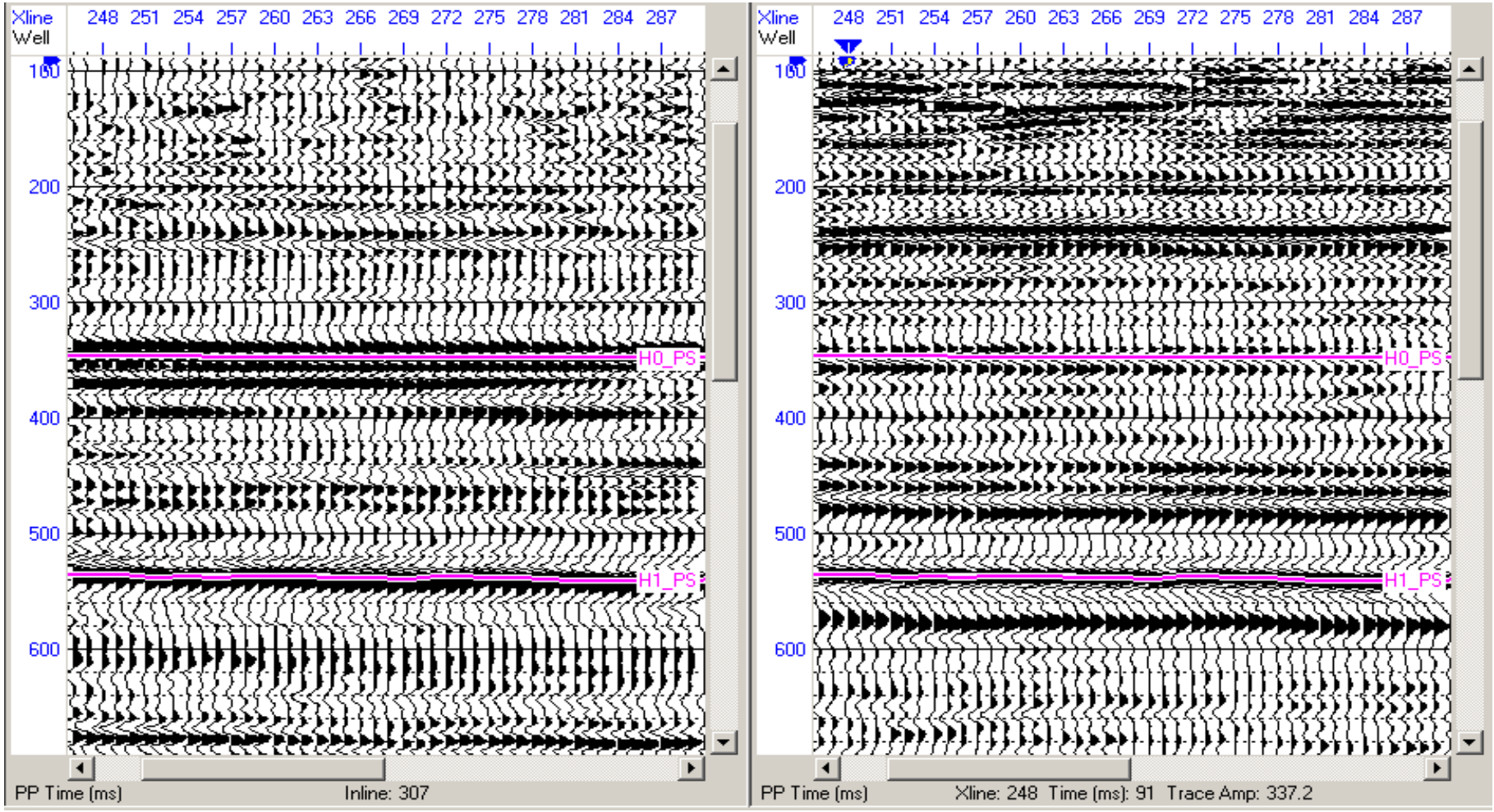
P and S waves "see" different things:

- P-waves sensitive to compressibility, rigidity and density
- S-waves sensitive to rigidity and density
  … and they can be polarized

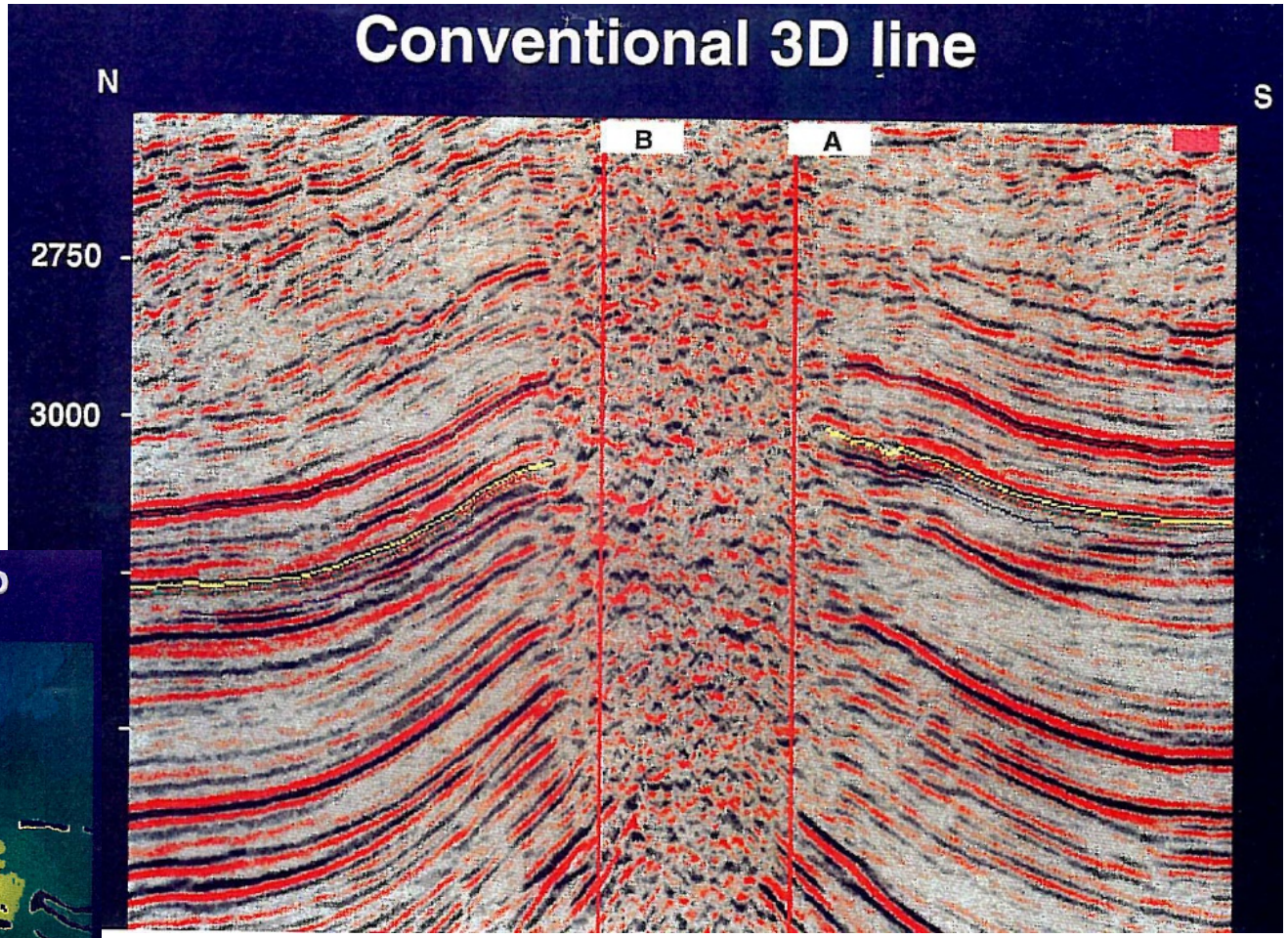
We are using converted waves

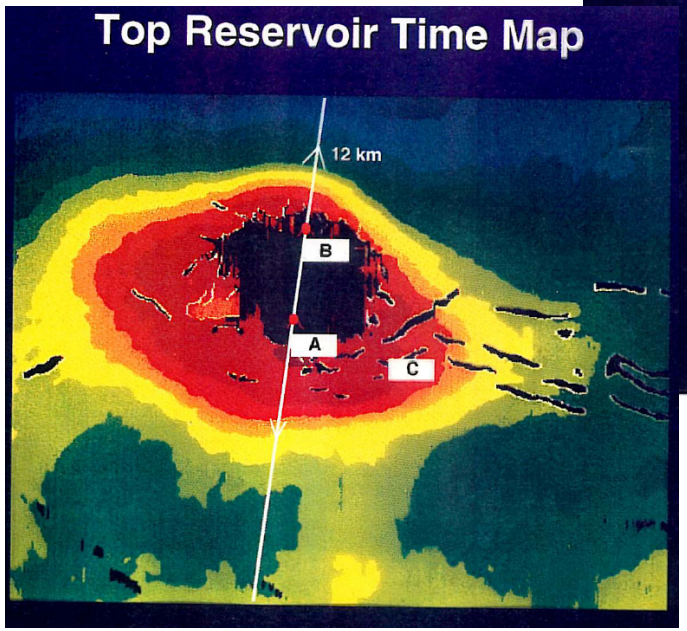


Well tie driven PP-PS event registration (Canada)



Gas cloud: Tomoliten (1992 acquisition, 1994 EAGE)





Courtesy of Statoil

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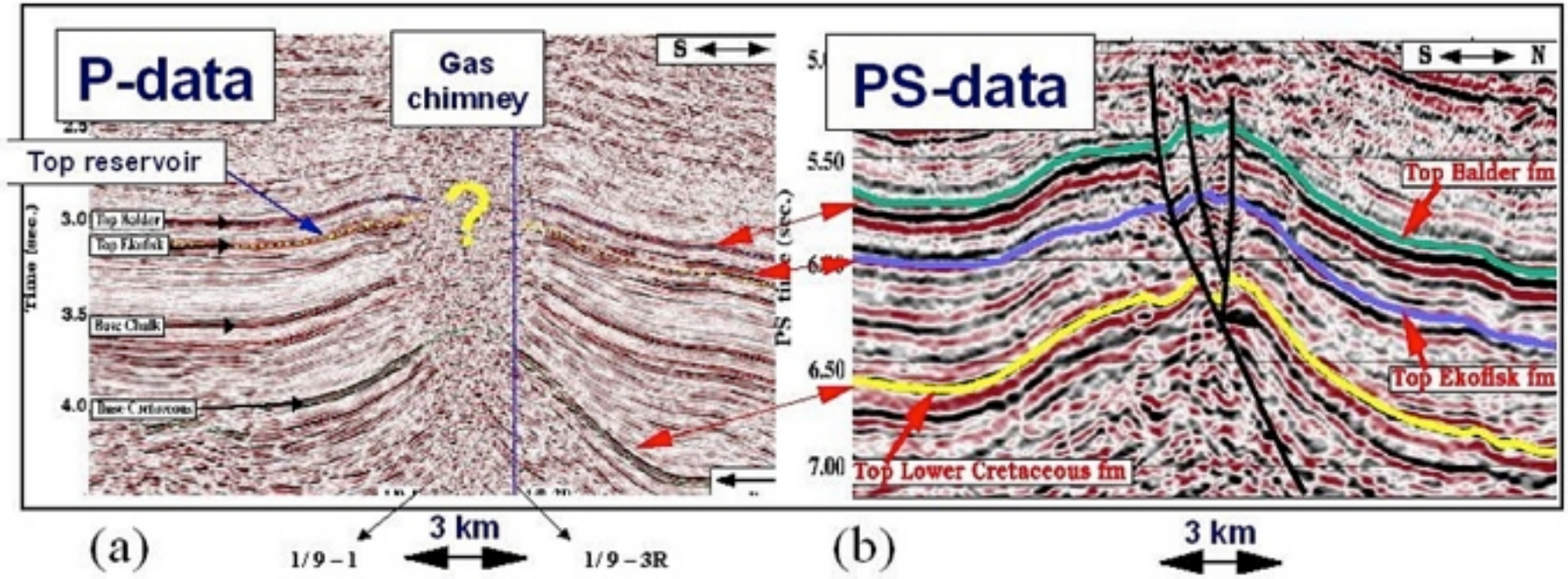


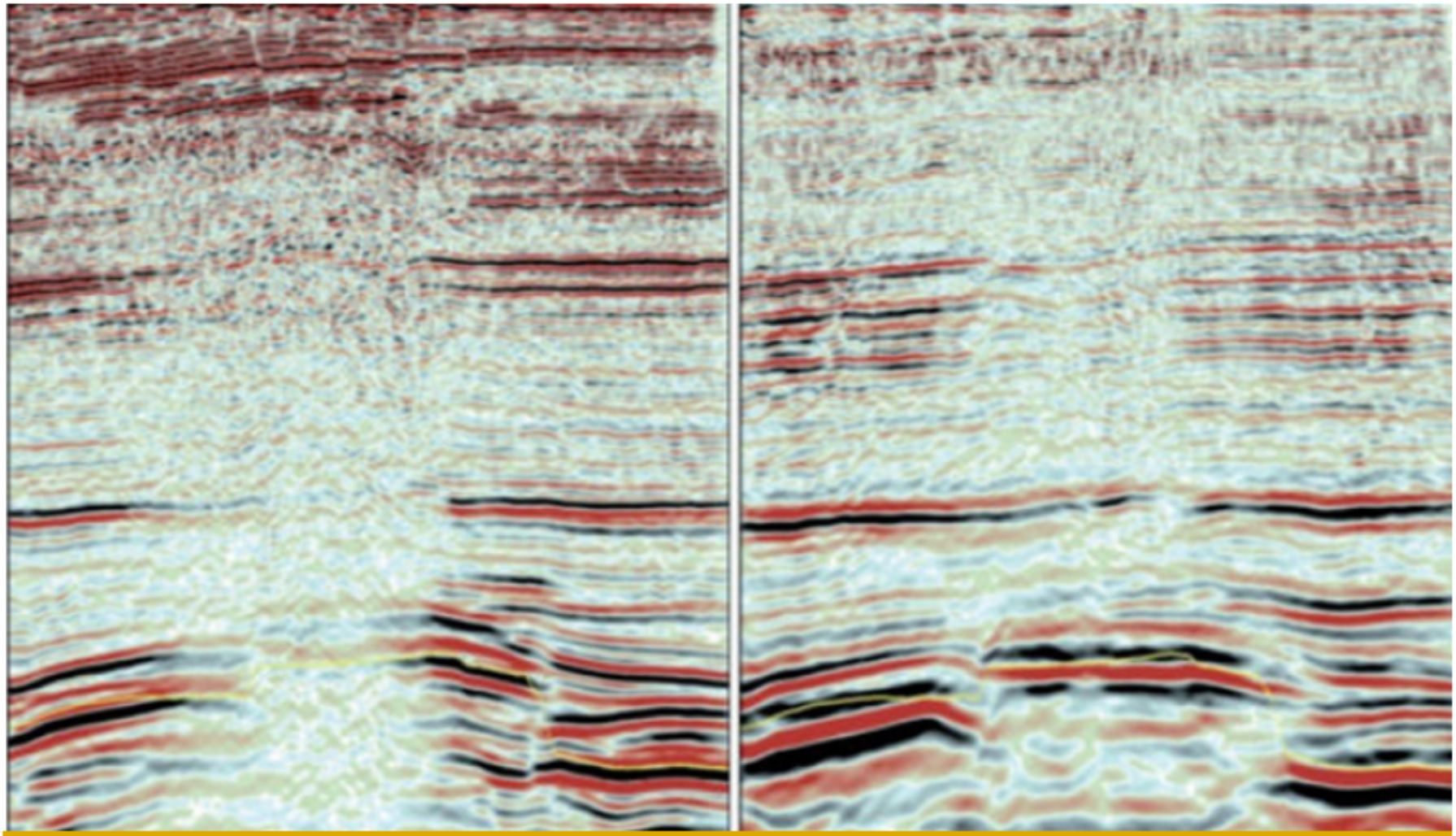
(a) PP image
(b) PS image

ROV deployed OBN data (SUMIC)

(It is a pity that (b) is rendered with interpretation.)

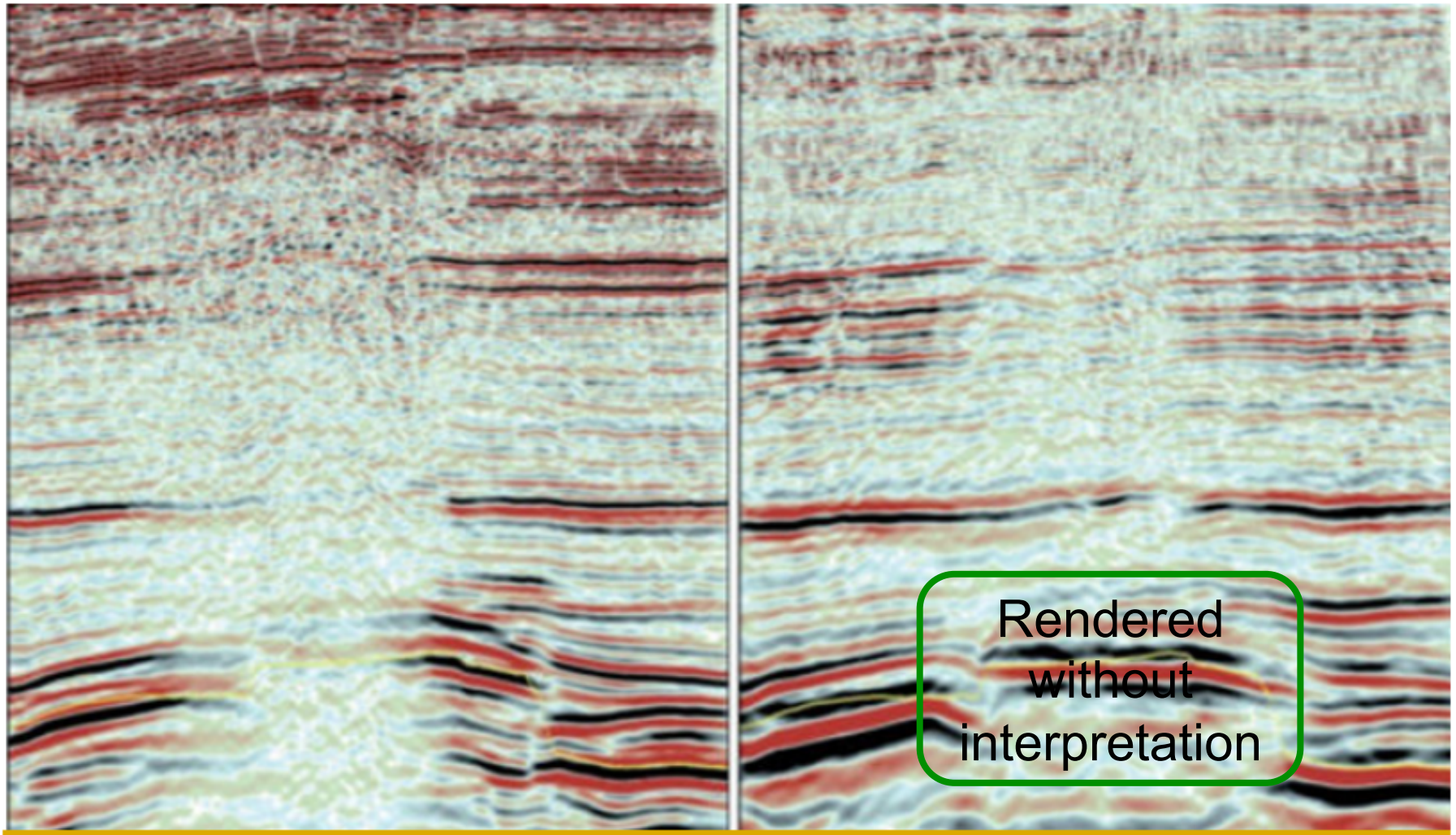
Courtesy of Statoil

Gas clouds going strong: Snøhvit



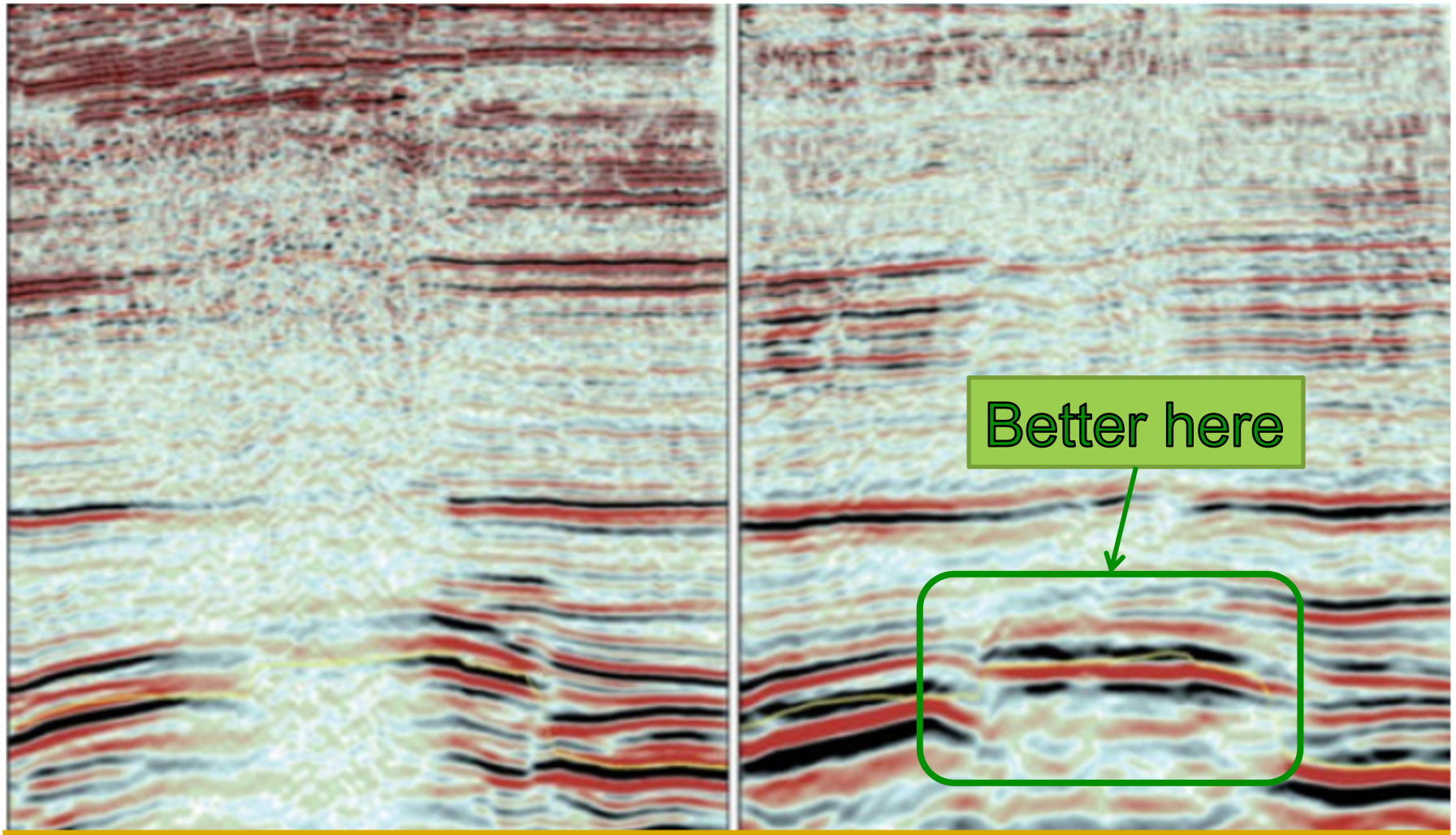
The PS image (right) reveals details of the reservoir which are hidden on the PP image (left) by effects from the shallow gas. Data courtesy of StatoilHydro.

Snøhvit



The PS image (right) reveals details of the reservoir which are hidden on the PP image (left) by effects from the shallow gas. Data courtesy of StatoilHydro.

Snøhvit



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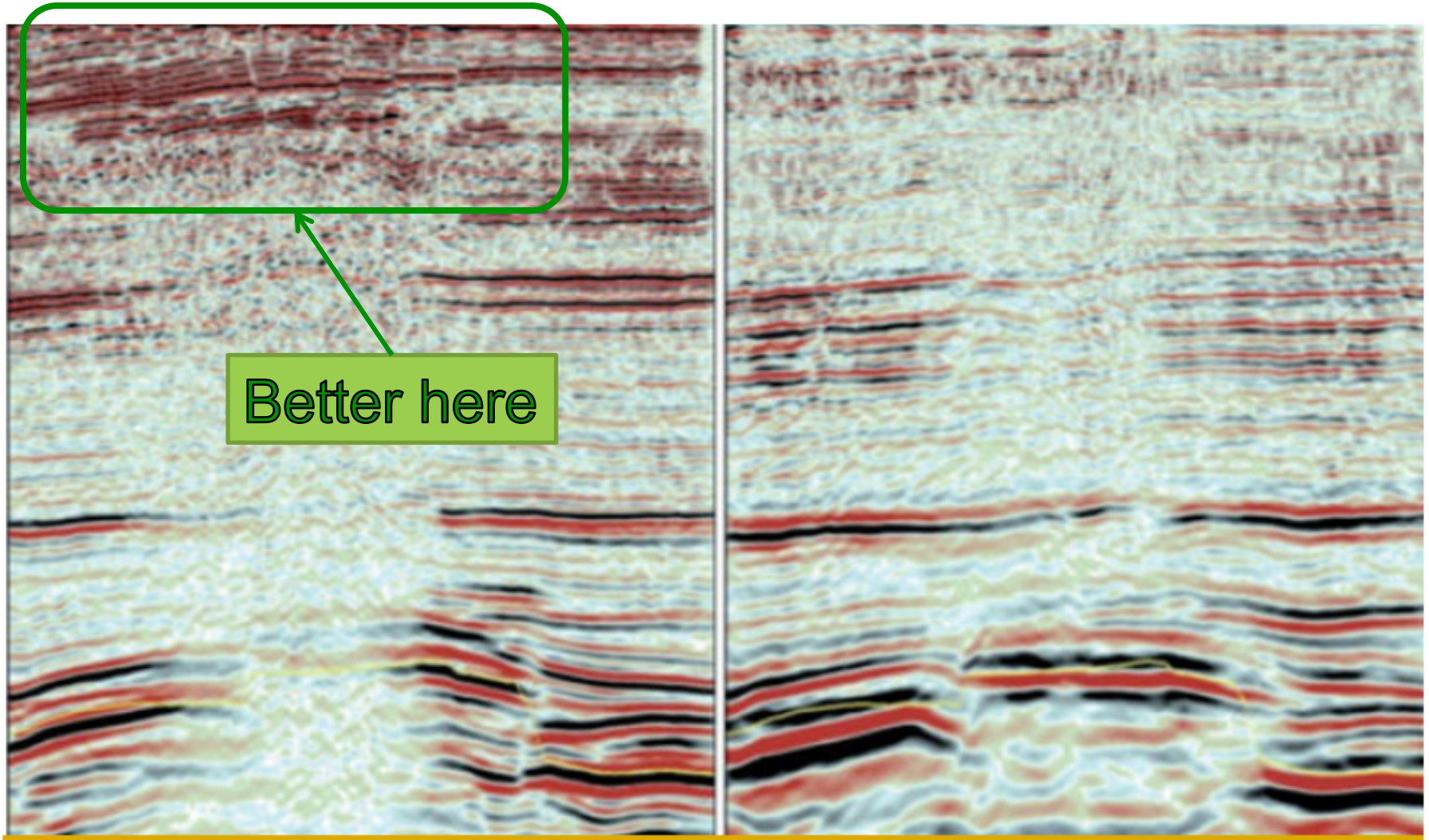
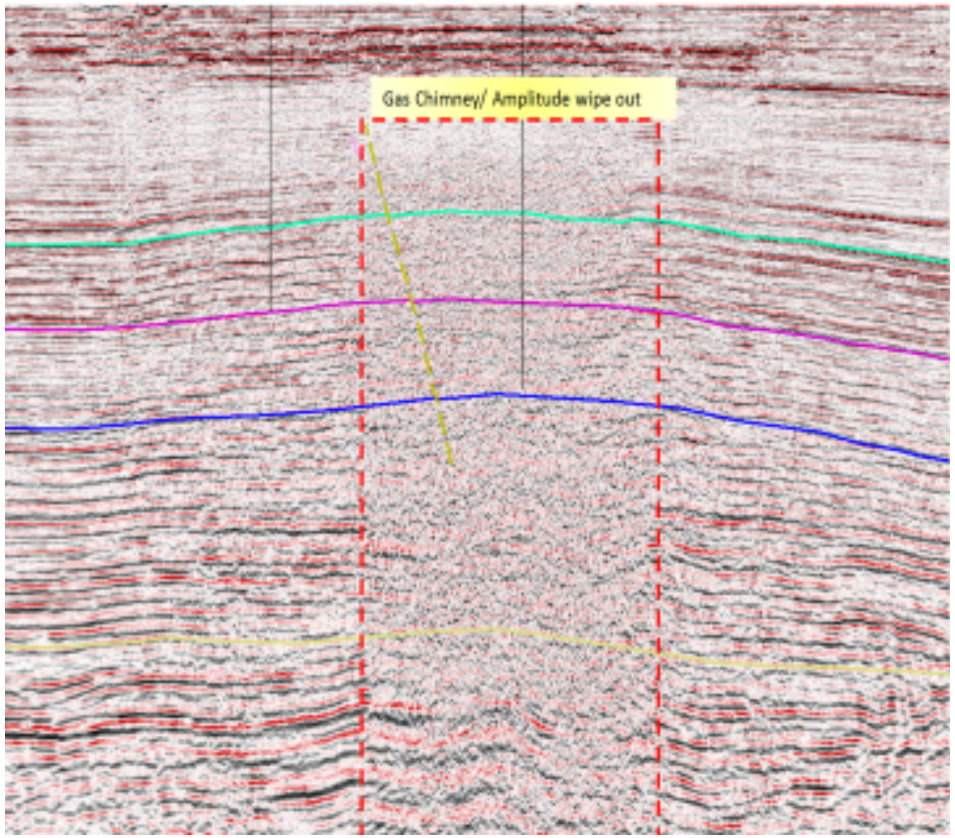


The PS image (right) reveals details of the reservoir which are hidden on the PP image (left) by effects from the shallow gas. Data courtesy of StatoilHydro.

More imaging under gas—offshore malaysia

Narrow Azimuth Streamer data (P)

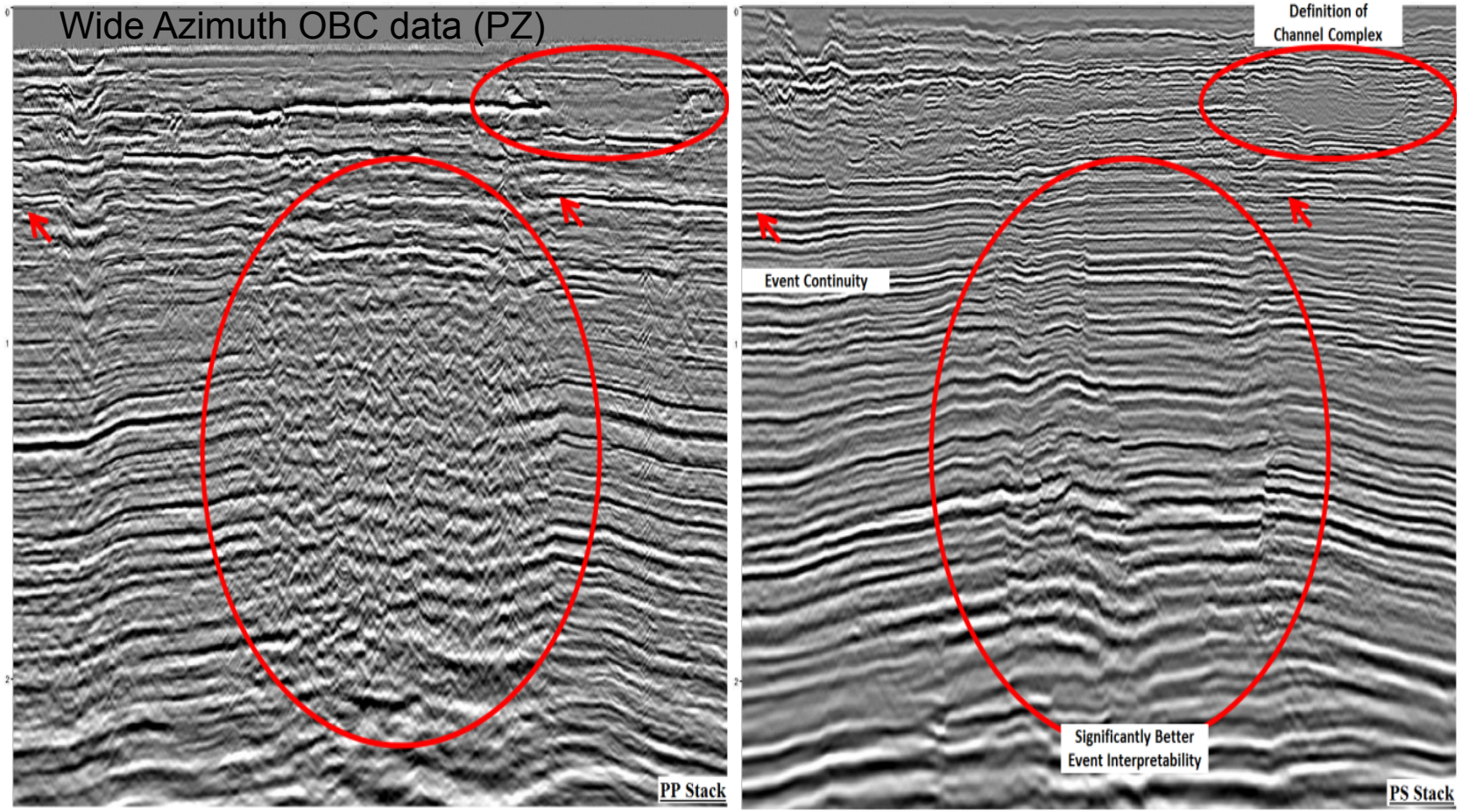


- Streamer data
  - Gas Chimney
  - Amplitude Wipe out

Multicomponent processing for imaging under gas cloud – offshore Malaysia, *Shivaji Maitra*[*2], Riaz Alai[1], M Shah B Sulaiman[1], Rohaila Bt Roslan[1], Agus Wardoyo[2], and Libo Zi[2] ([1]PETRONAS Carigali, [2]CGG)*

Courtesy of Statoil

Imaging under gas—offshore malaysia (Maitra, 2014)



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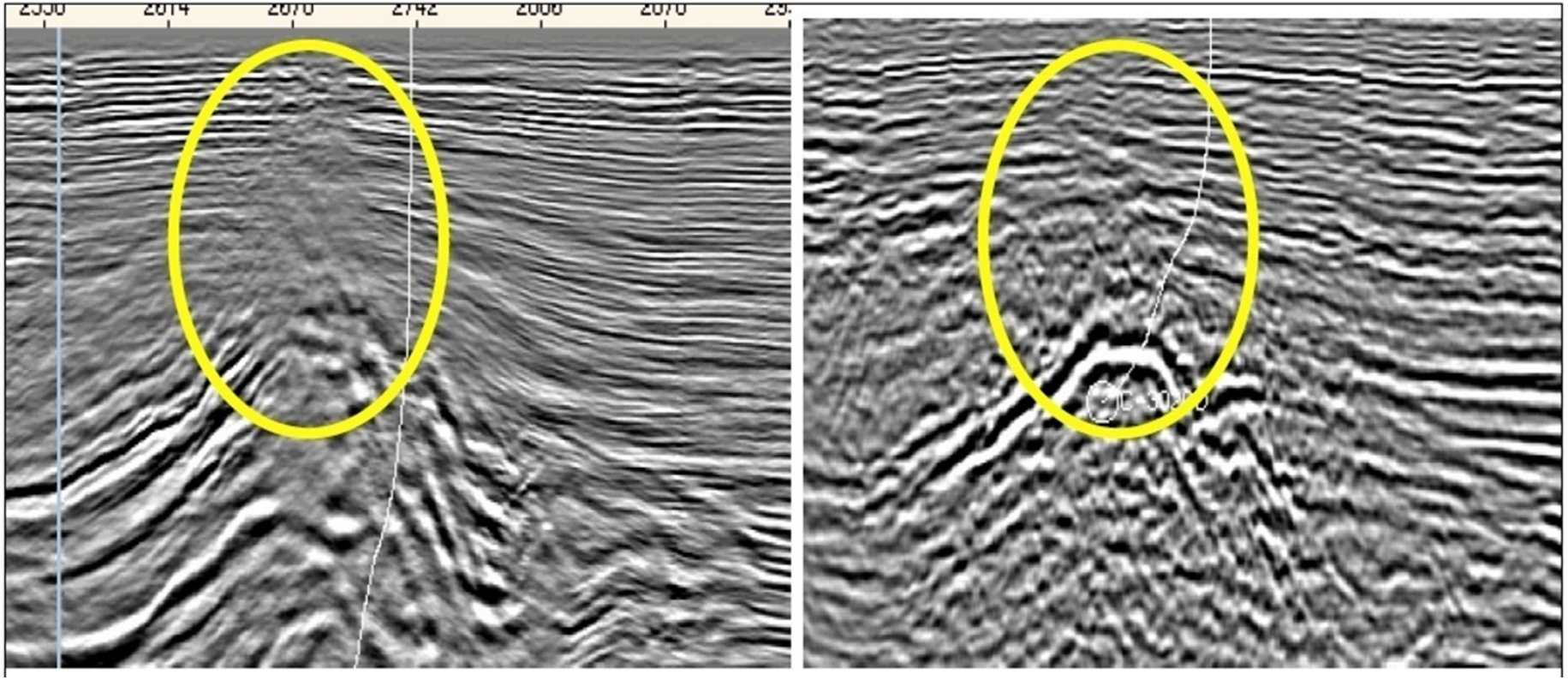
Courtesy of Petronas

Gas cloud with sparse nodes



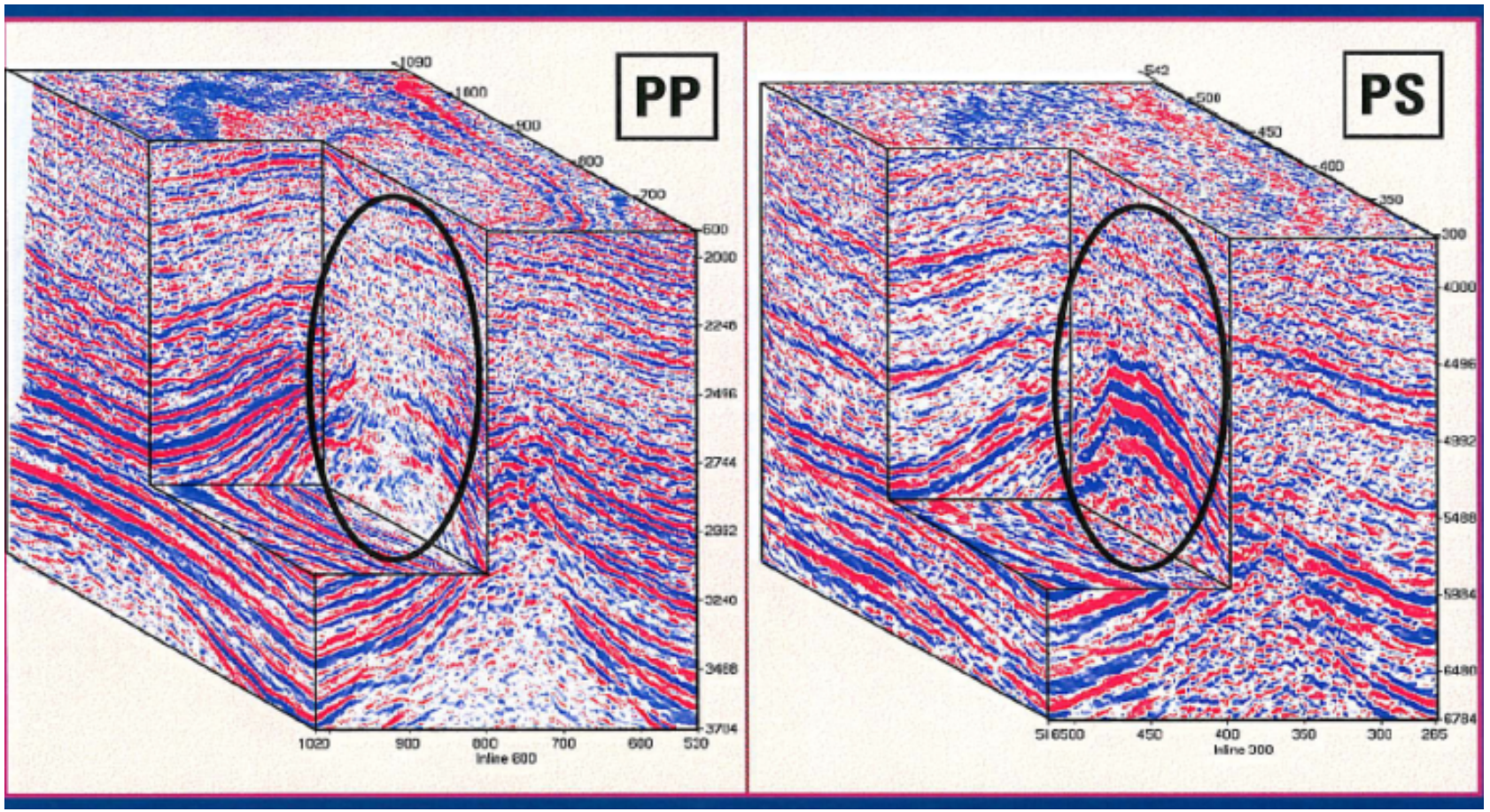
Wide Azimuth OBN data (PZ)

Wide Azimuth OBN data (PS)

ROV deployed OBN data (CASE)

Courtesy of Pemex

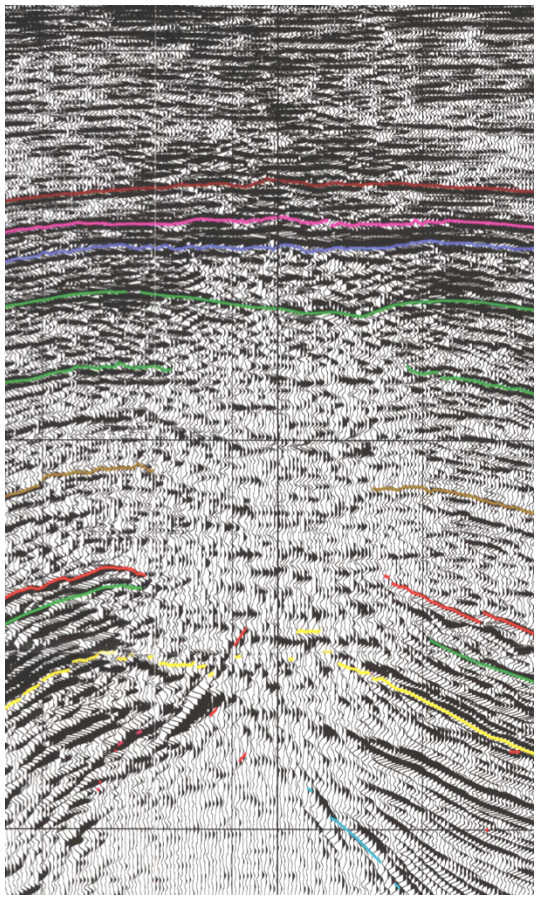
Gas cloud: Lomond (1999 acquisition, 2000 EAGE)



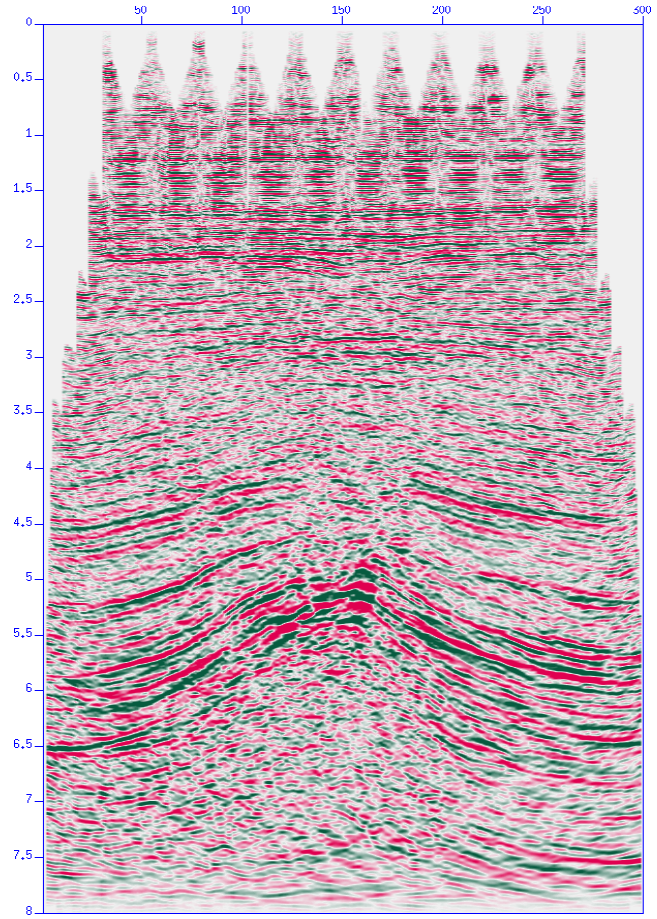
Courtesy of BP

Gas cloud: Lomond (1999 acquisition, 2000 EAGE)

P: 2D streamer



PS: 3D OBC



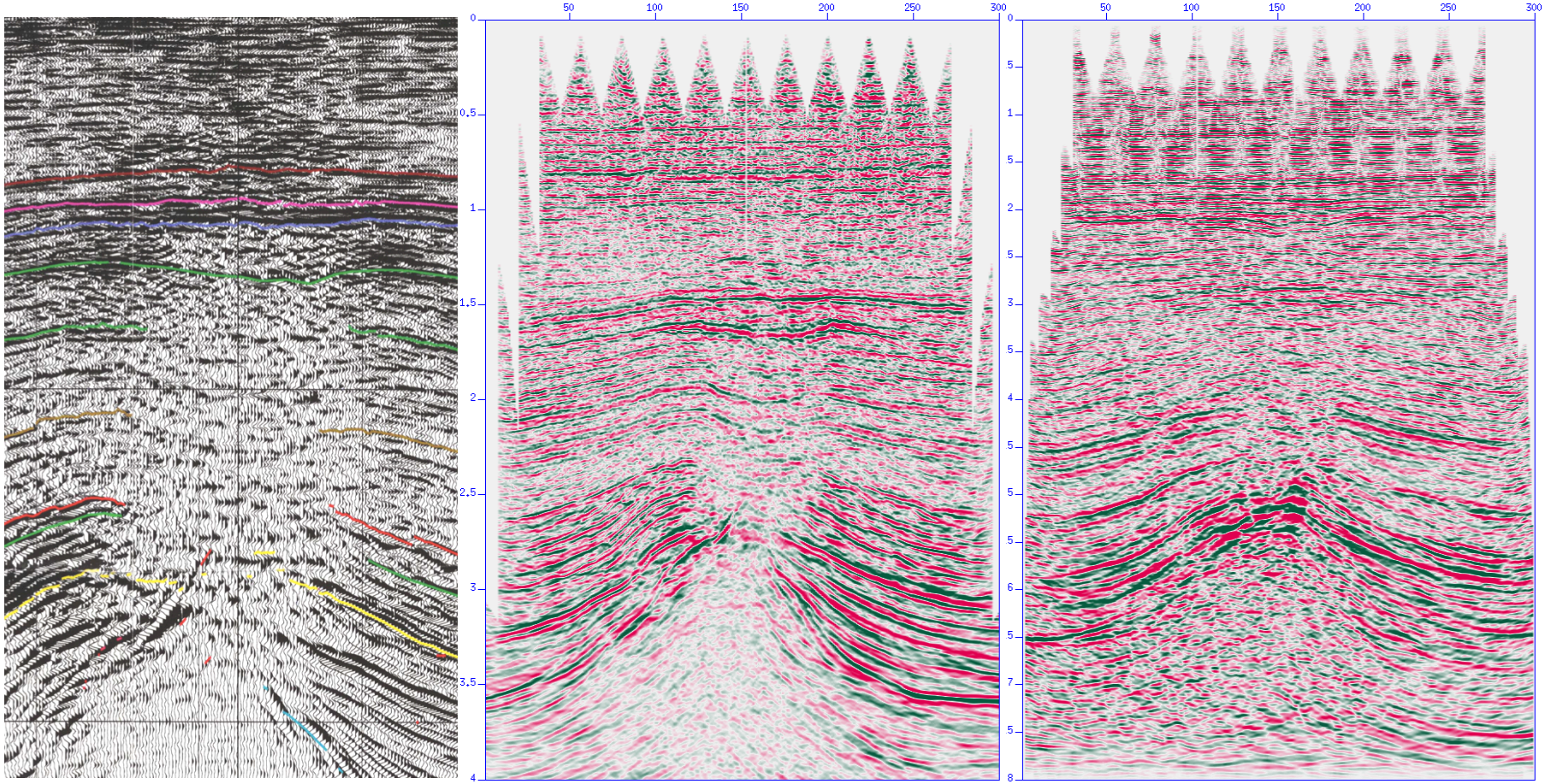
Courtesy of BP

Gas cloud: Lomond (1999 acquisition, 2000 EAGE)

Narrow az P

Wide azimuth PZ

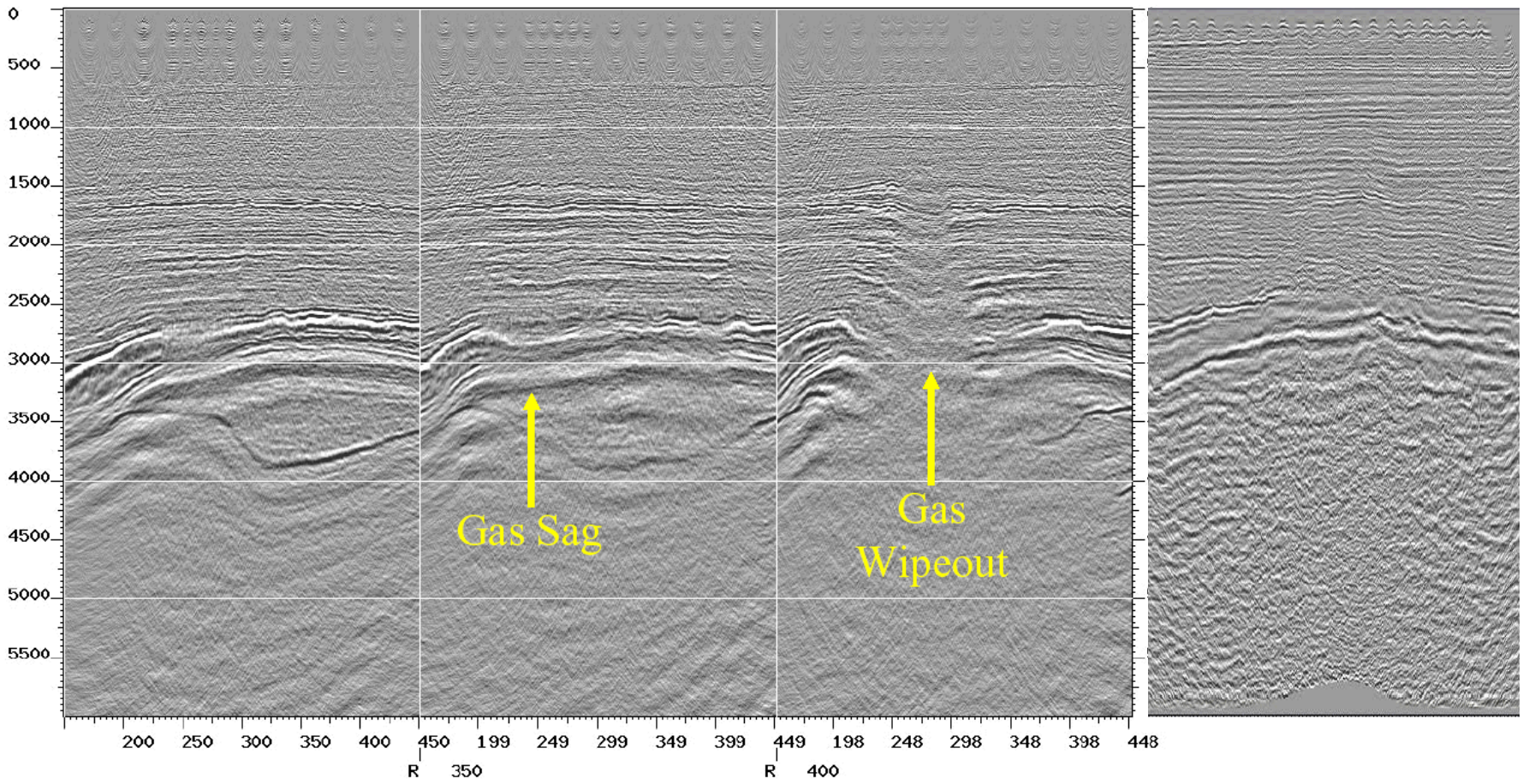
Wide azimuth PS



AMOCO

Courtesy of BP

Valhal PP Vs PS

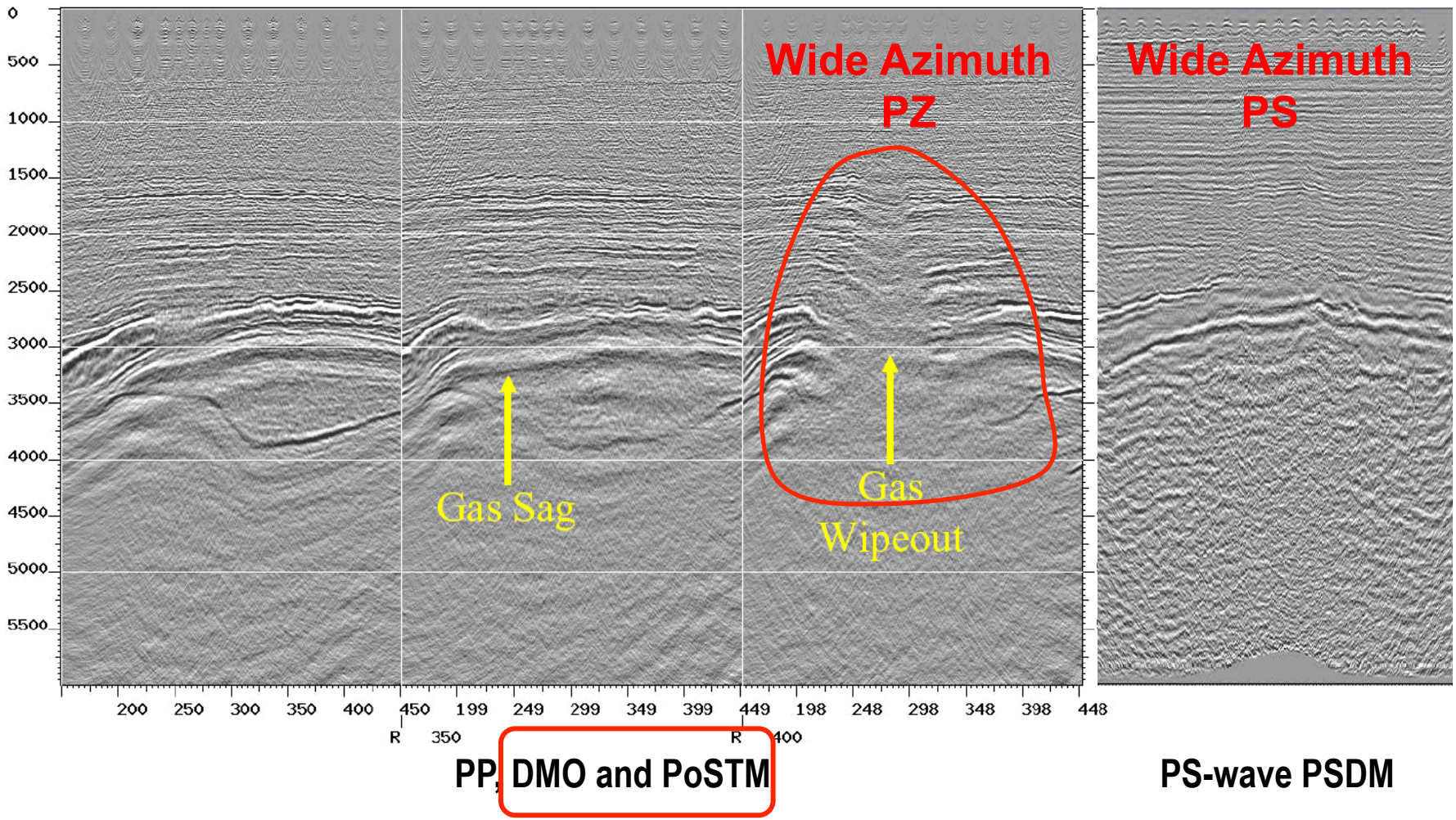


PP, DMO and PoSTM

PS-wave PSDM

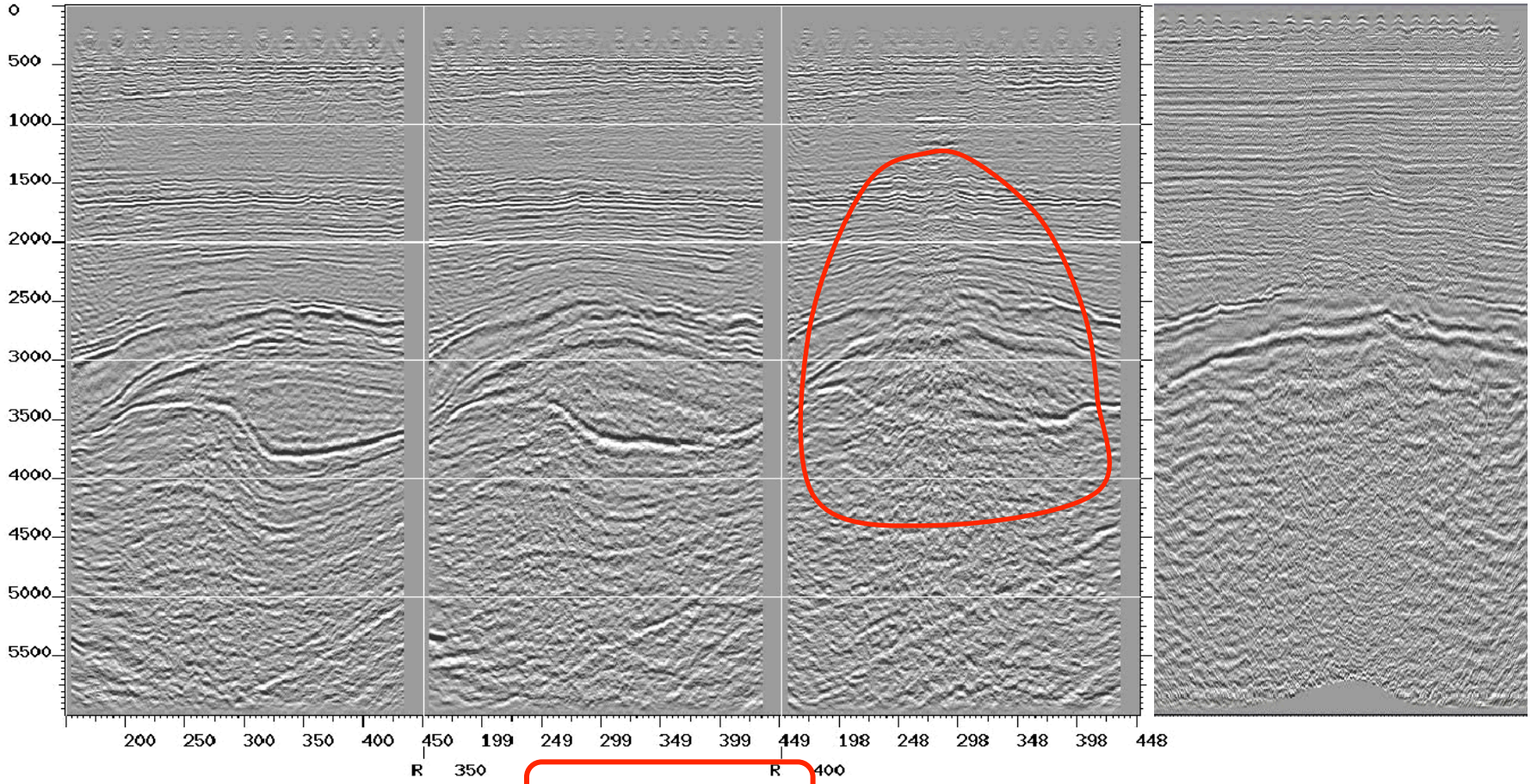
Dellinger et al., 2001

Valhal PP Vs PS



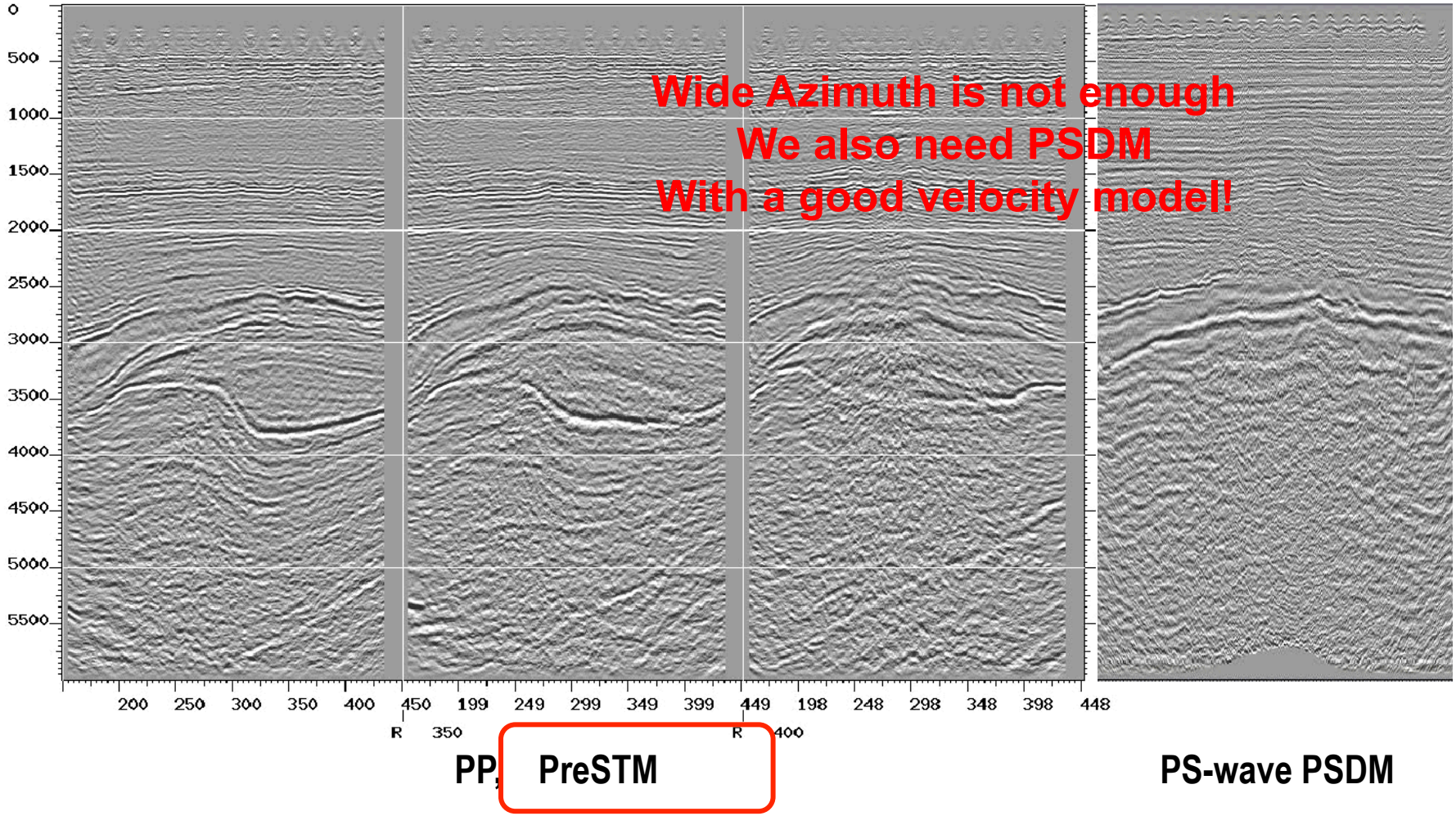
Dellinger et al., 2001

Valhal PP Vs PS



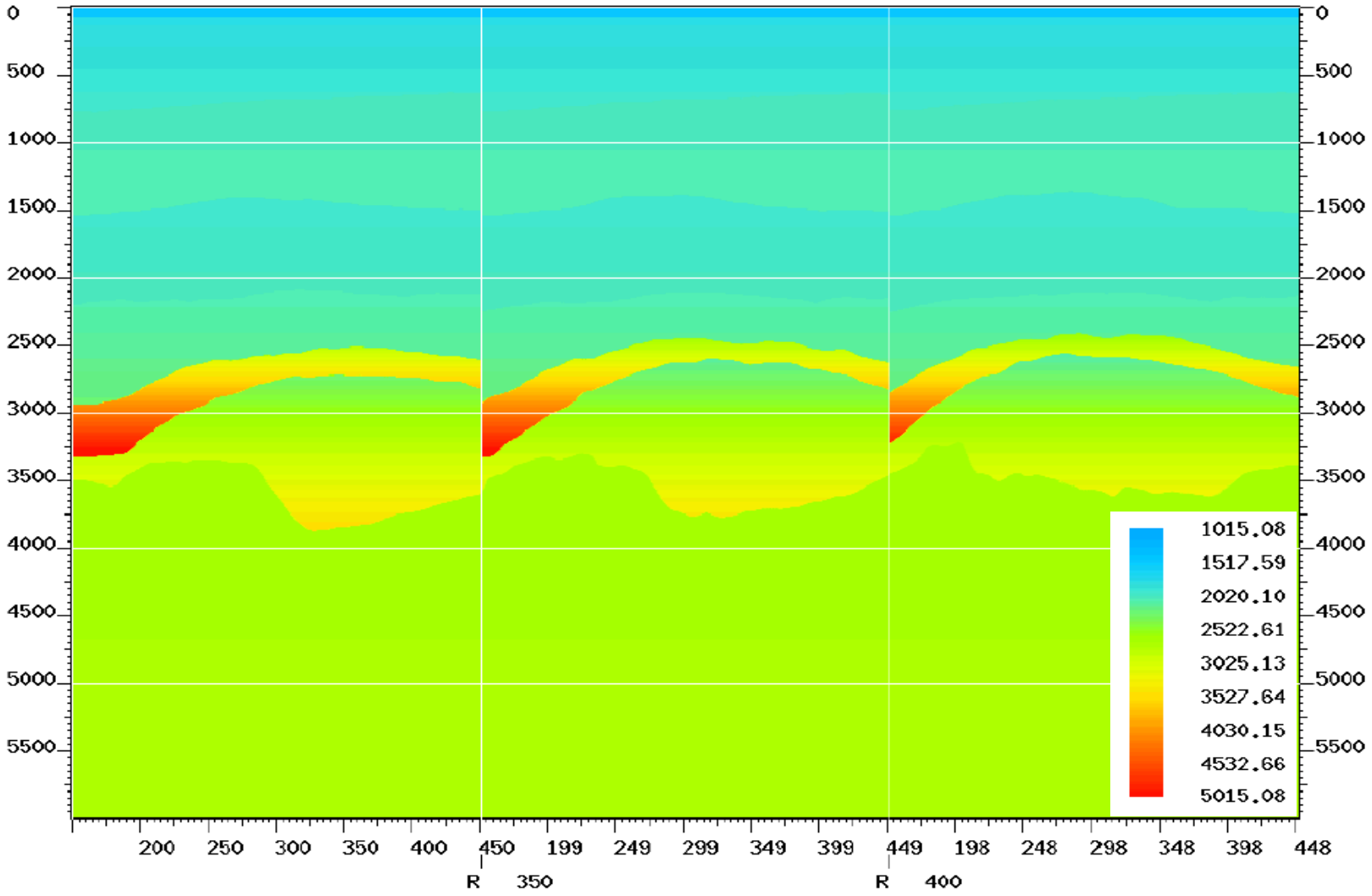
Dellinger et al., 2001

Valhal PP Vs PS



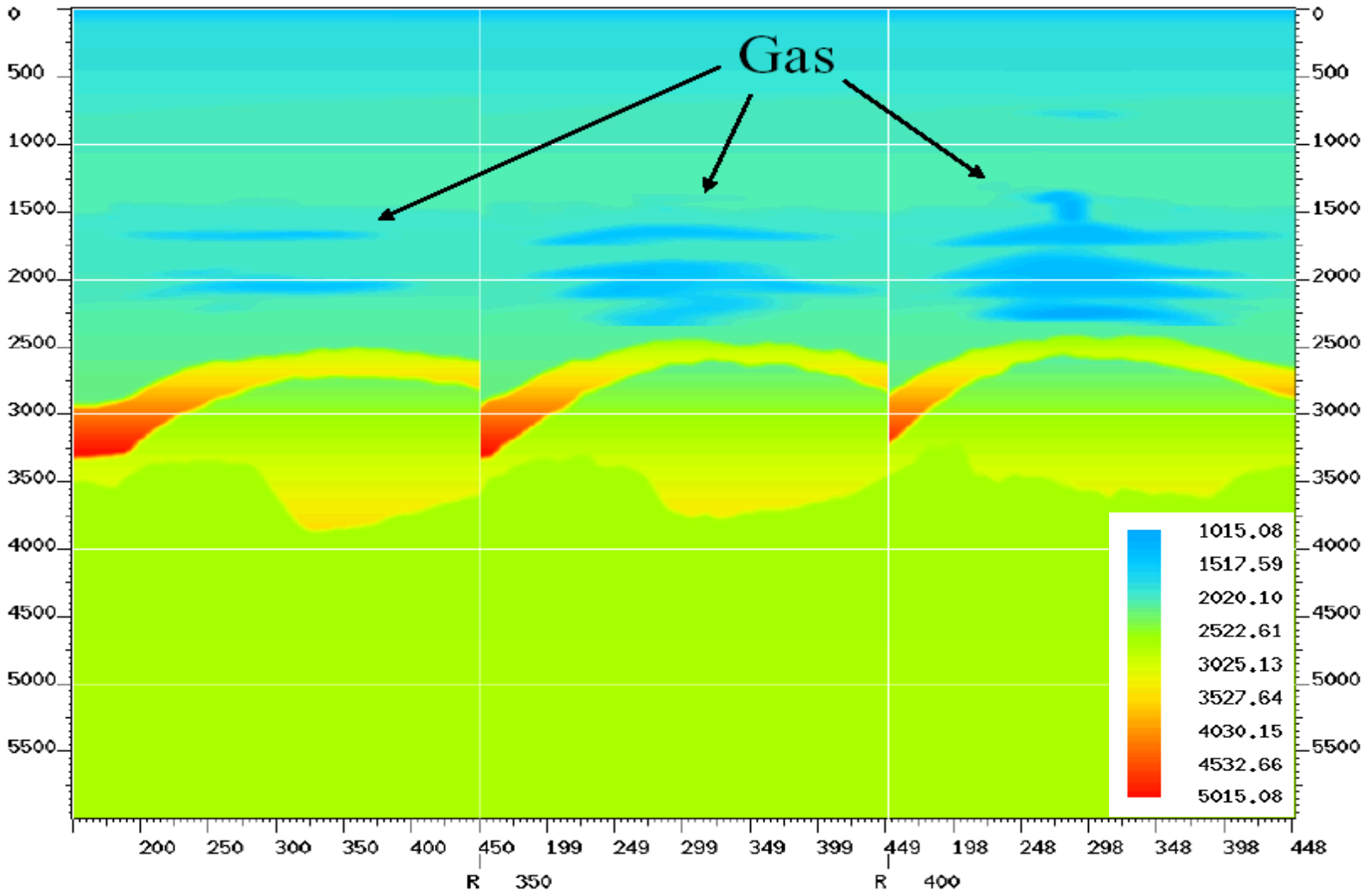
Dellinger et al., 2001

Valhal PoSTM velocity model



Dellinger et al., 2001

Valhal PreSTM velocity model



Dellinger et al., 2001

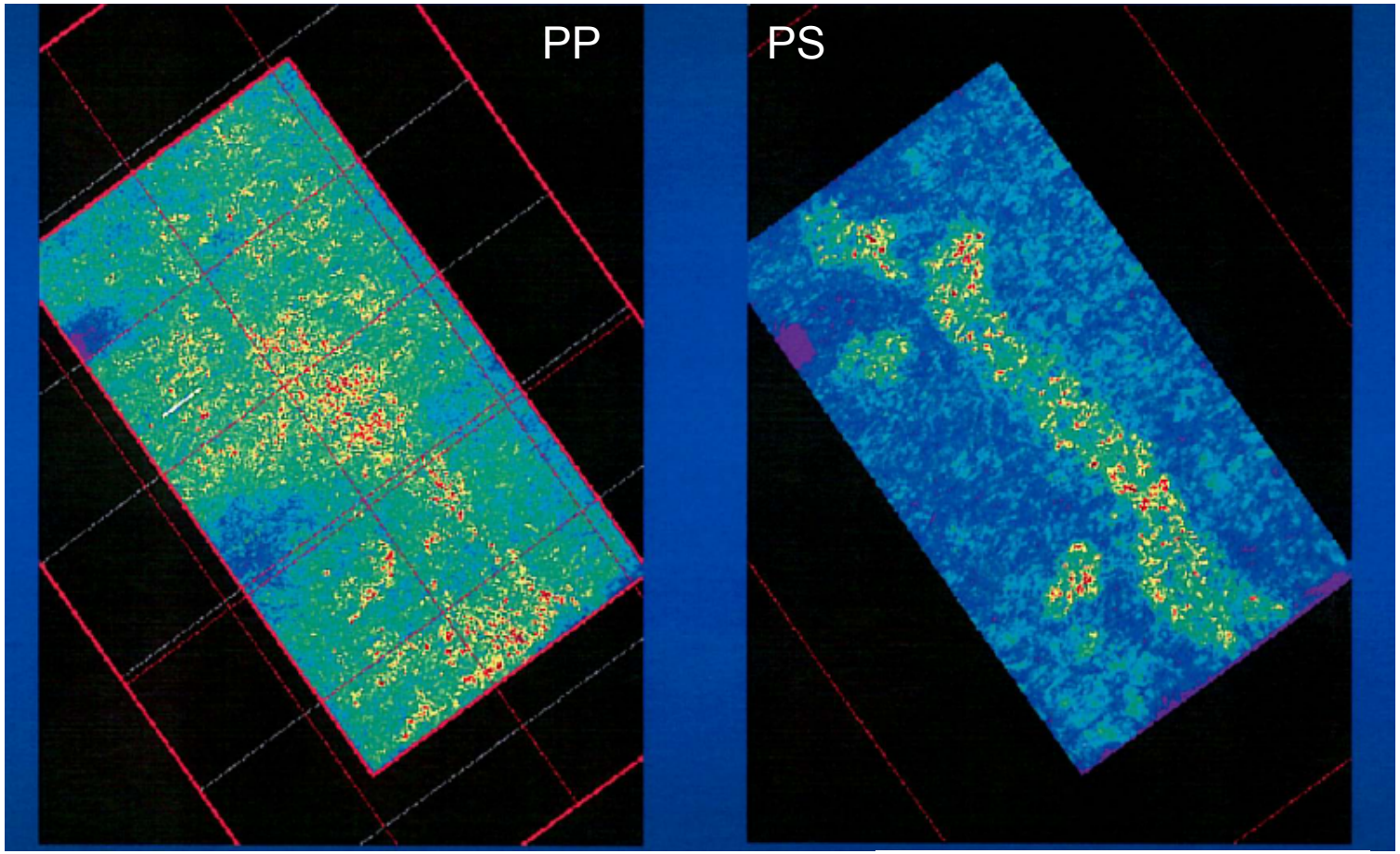
Gas clouds summary

- For a few years, gas clouds were the “killer application” of shear waves
- Lomond and Valhal showed that Wide Azimuth and PSDM with careful velocity model building make P waves image stand up to the converted PS waves image
- Gas clouds are still a good application of OBC / OBN
- But the “killer application” status is somewhat tarnished

Alba (the Leading Edge, 1999)

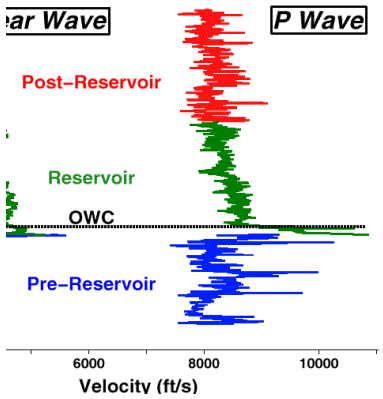
Low P impedance contrast at top sand.

Channel invisible on PP image, but visible on PS data

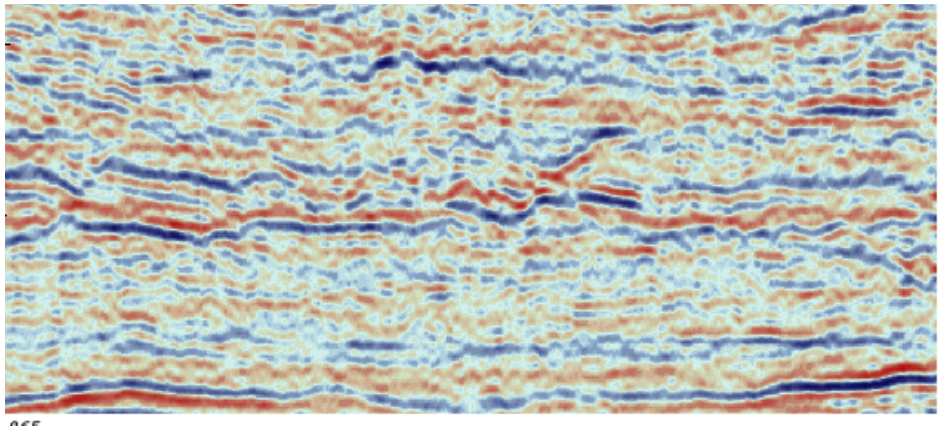


Courtesy of Chevron

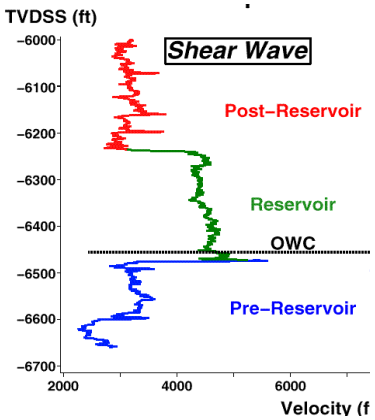
Alba (1998 acquisition, 1999 the Leading Edge)



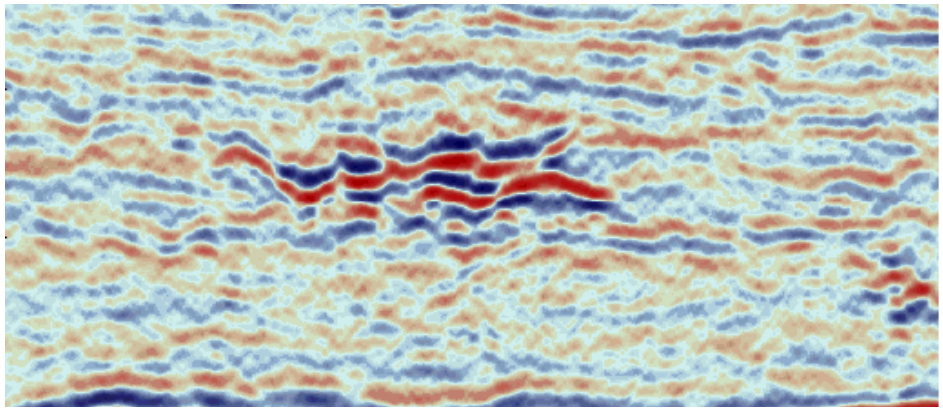
P Sonic log



PP Towed streamer data



S Sonic log

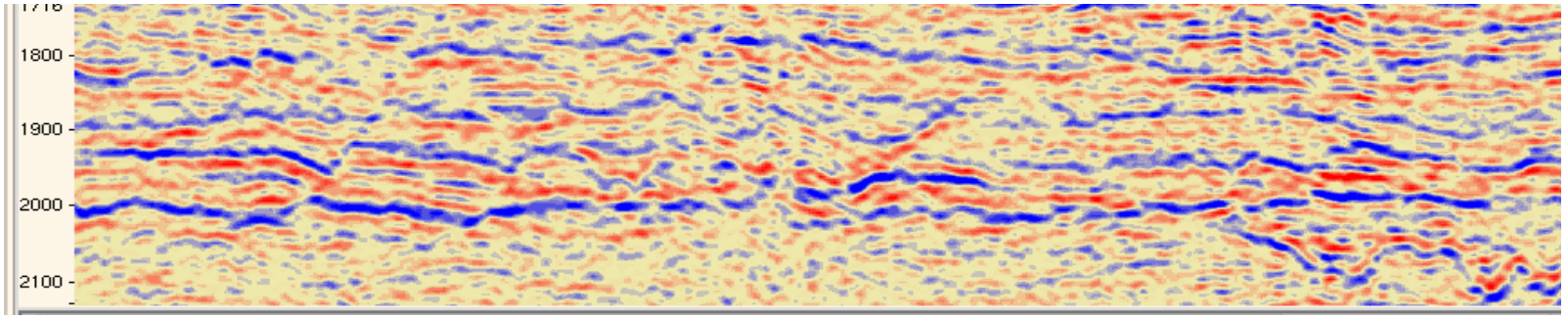


PS Converted wave data

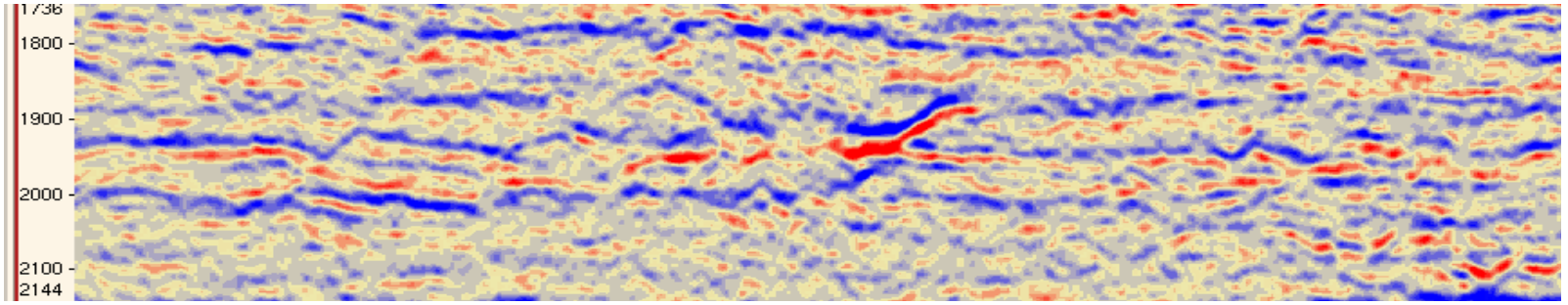
Courtesy of Chevron

Alba (1998 acquisition, Wilkinson, 2003 SEG)

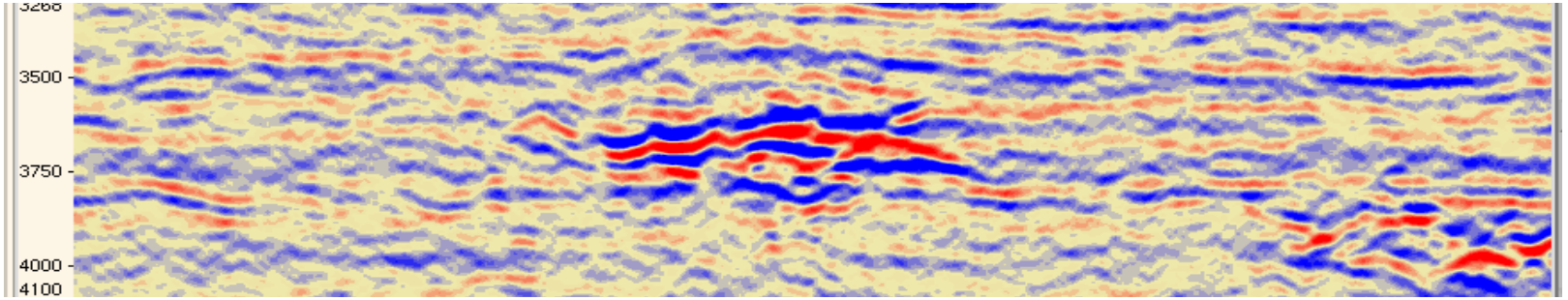
PP



PP
Far
offset



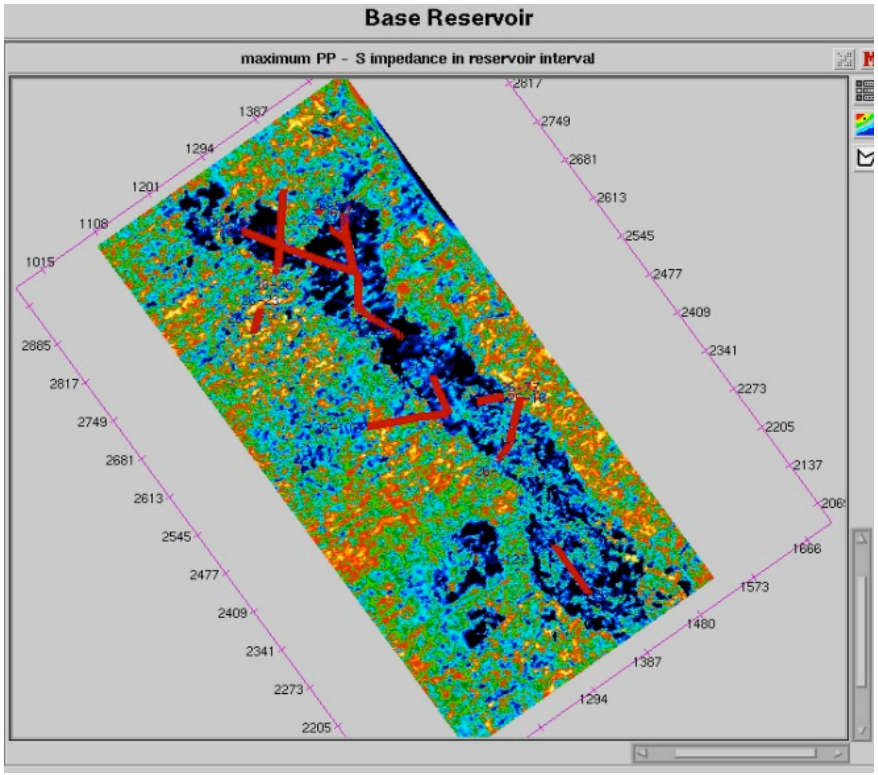
PS



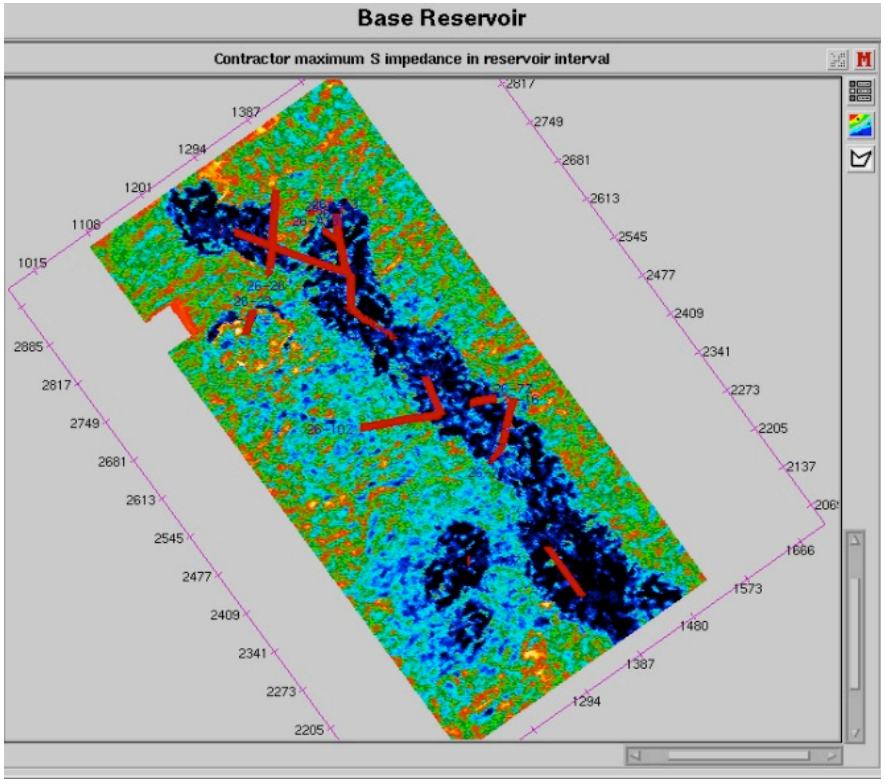
Courtesy of Chevron

Alba (1998 acquisition, Wilkinson, 2003 SEG)

From PP data (AVO)



From PS data (OBC)



Courtesy of Chevron

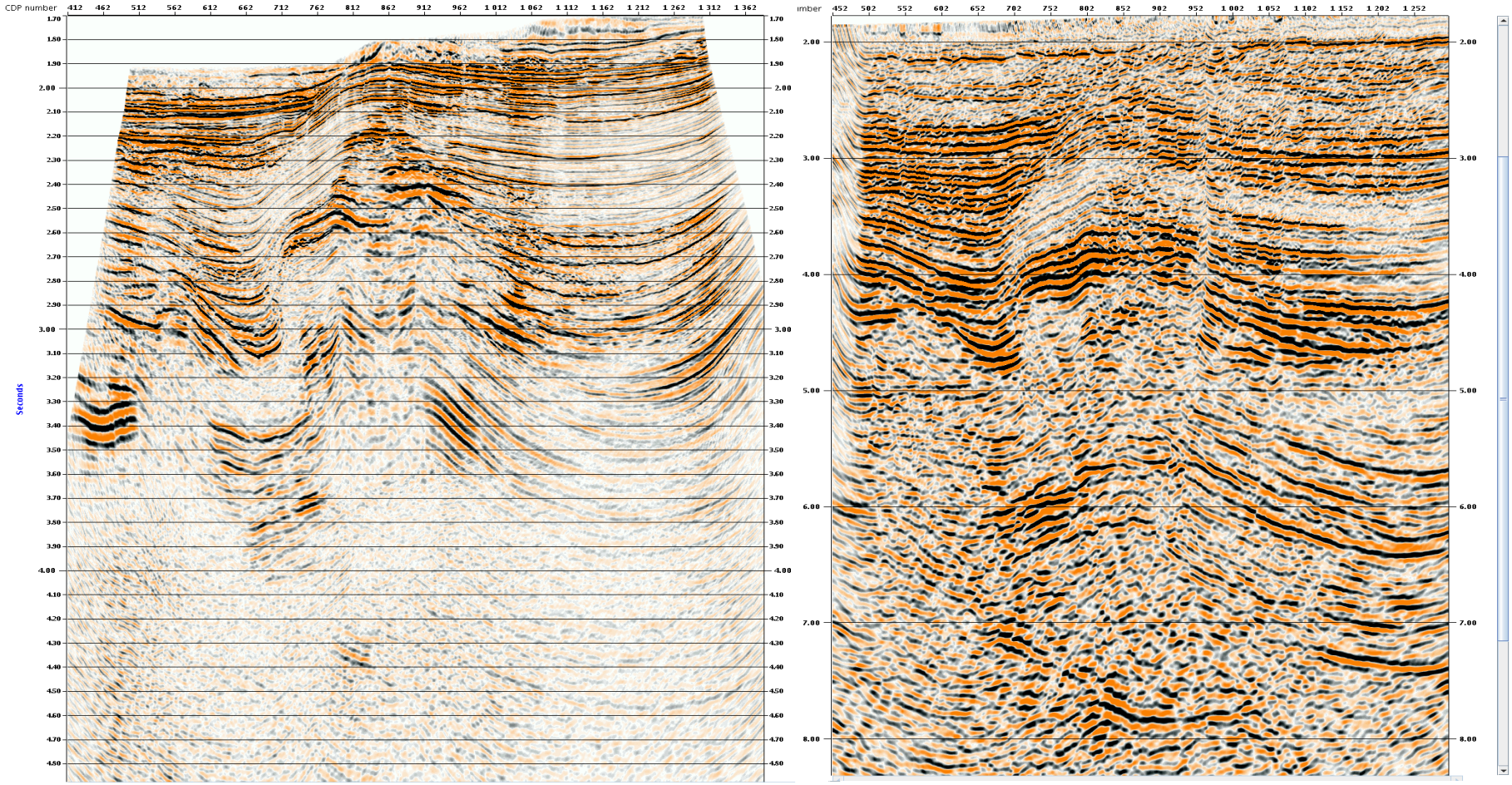
Alba story summary

- For a few years, 1998-2003, low P impedance (Alba-like) seemed to be another “killer application” of shear waves
- In 2003 it was shown that AVO provided, arguably better image
- The Alba story made a lot of damage to shear waves
  – Tarnished credibility of “you’ve got to record the shear”

Another counter productive PS Vz PP Example

PZ

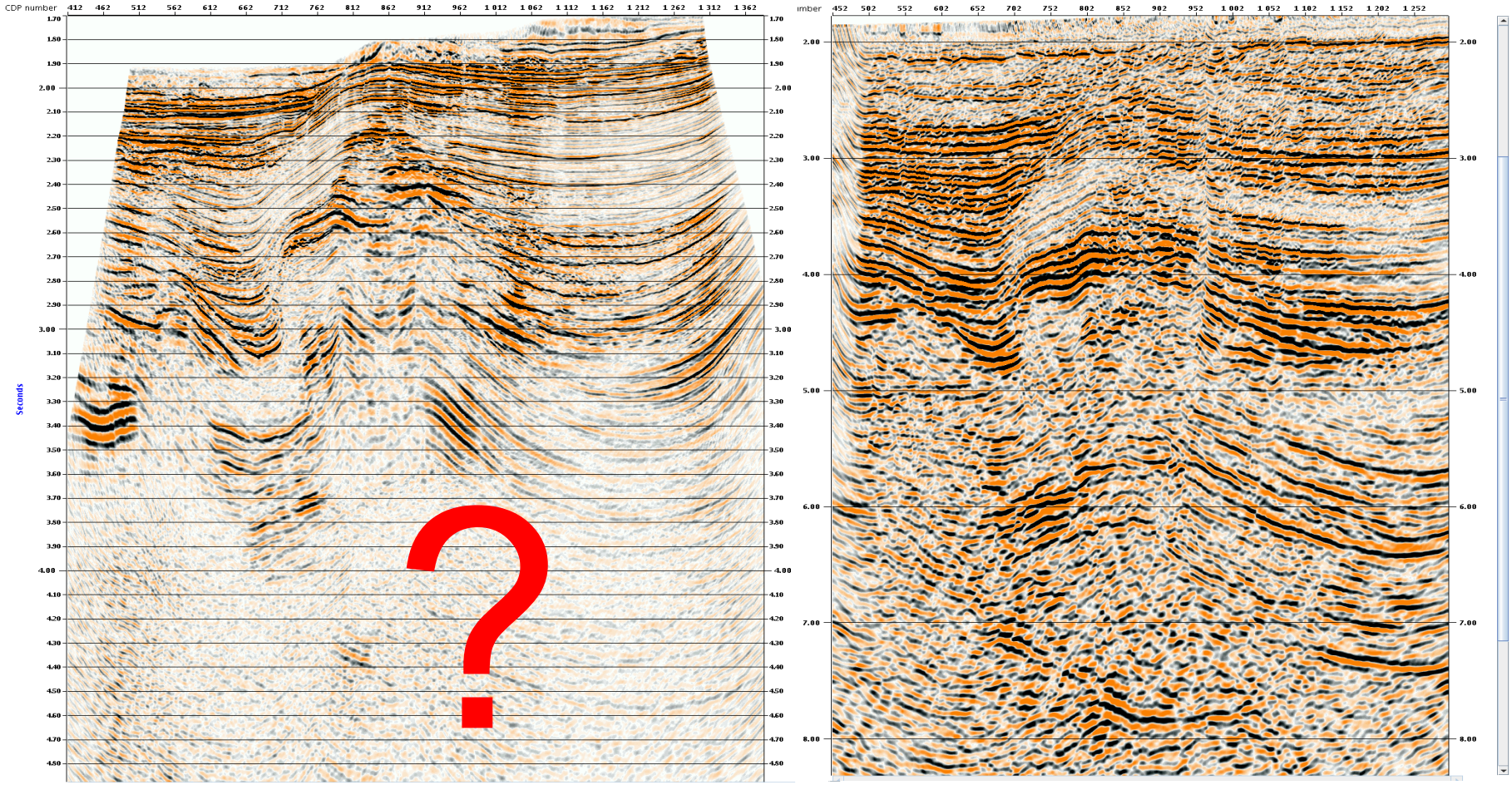
PS



Another counter productive PS Vz PP Example

PZ

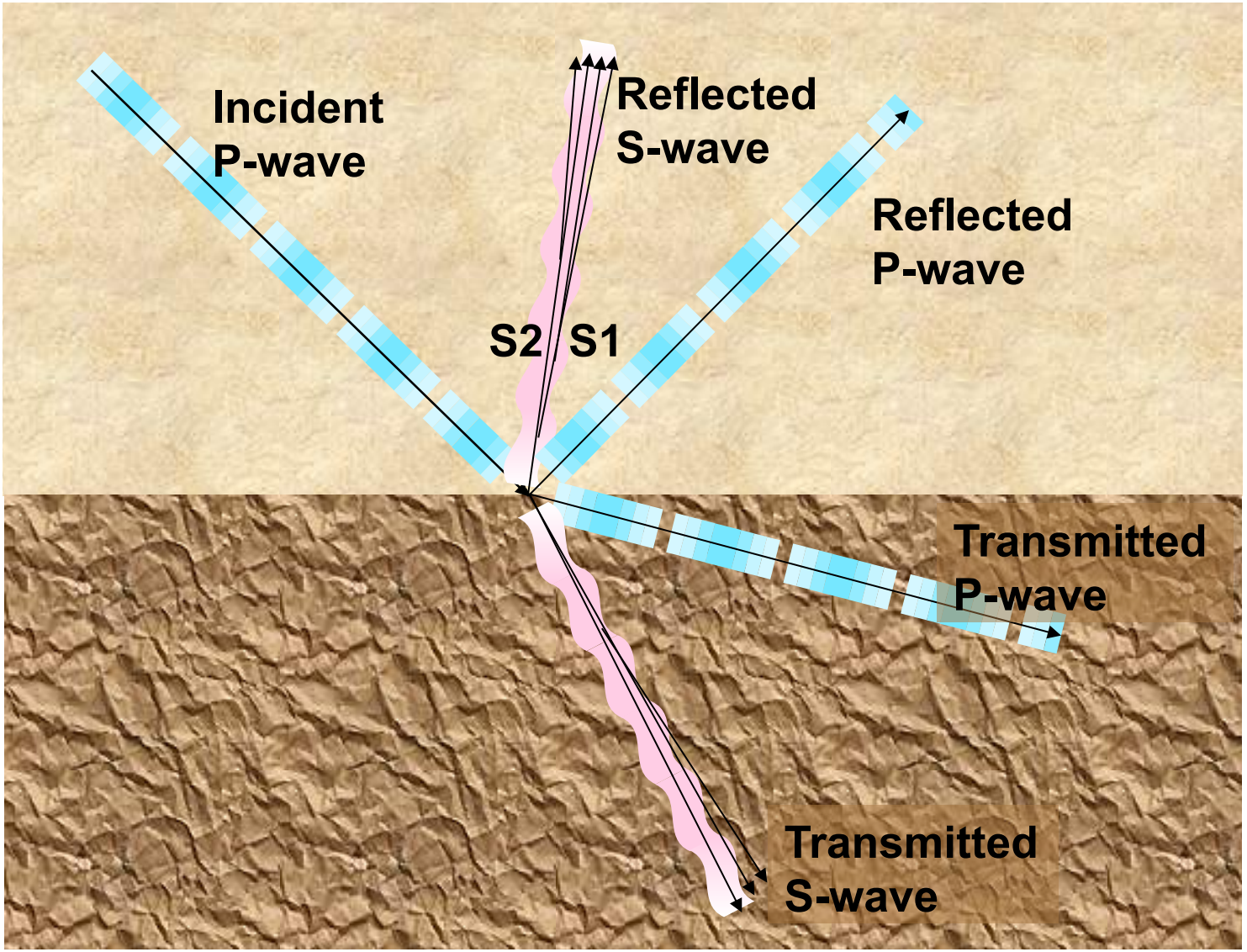
PS



Tarnished case histories were not the only problem

- More or less consistently, with rare exception of gas clouds, P waves provided better images than PS waves
- Why?
  - Acquisition issues: low data quality?
  - Processing issues:
    - Shear wave statics?
    - Shear wave splitting?
    - Long turn around time?
  - Interpretation issues?
- Probably all of the above

We are using converted waves



Shear wave splitting: Khafji (Holden, 2014)

Radial PS1+PS2

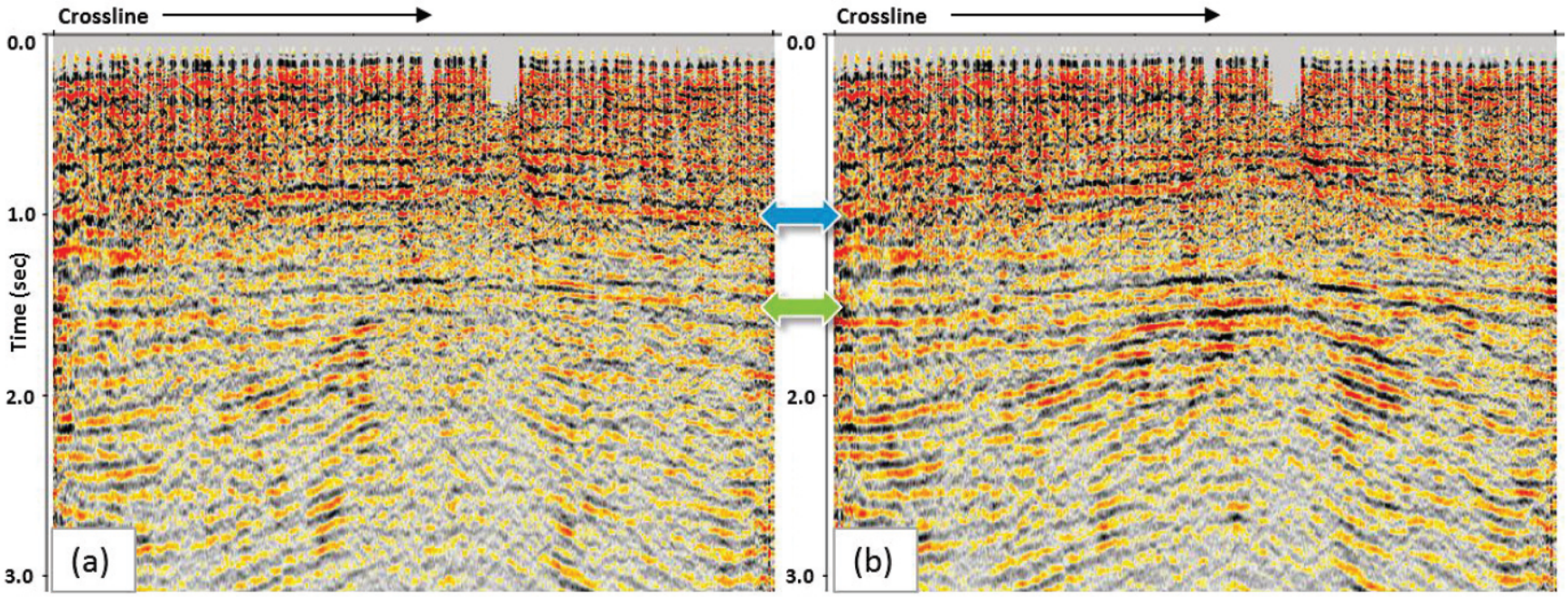
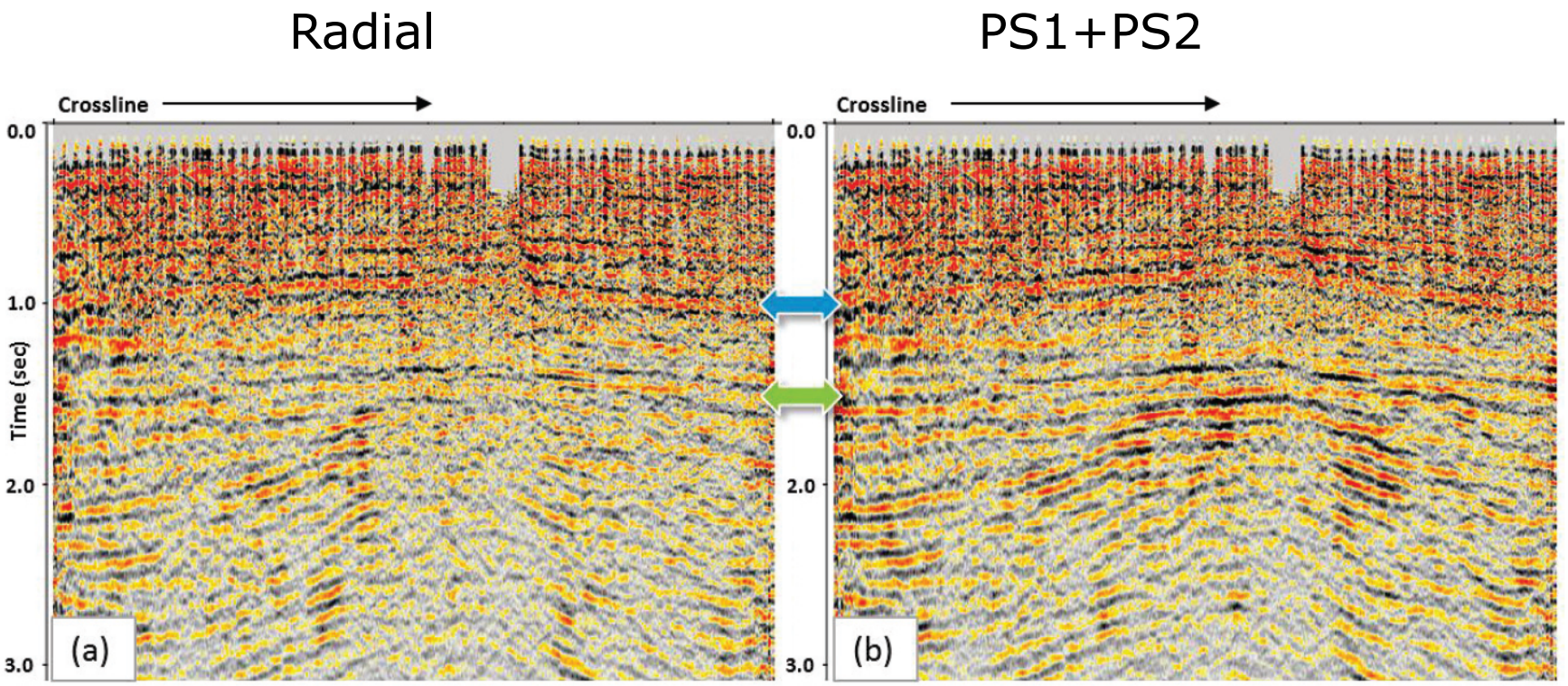


Figure 3: *Radial ACP Stack (a) Before, and (b) After over-burden, H1 and A/W corrections to the level of the Aruma-Wasia unconformity, indicated by the green arrow. The blue arrow indicates the base of the Rus layer used for the overburden correction (see also Fig.1). Note the improved resolution below the unconformity after compensation for the shear-wave splitting in the layers above it. Location is indicated by the red line in Figure 2c.*

Shear wave splitting: Khafji (Holden, 2014)



It takes time and effort but *it can be done

***it = imaging with PS under azimuthally anisotropic overburden**

Azimuthal anisotropy (Shatilo, Piceance basin)

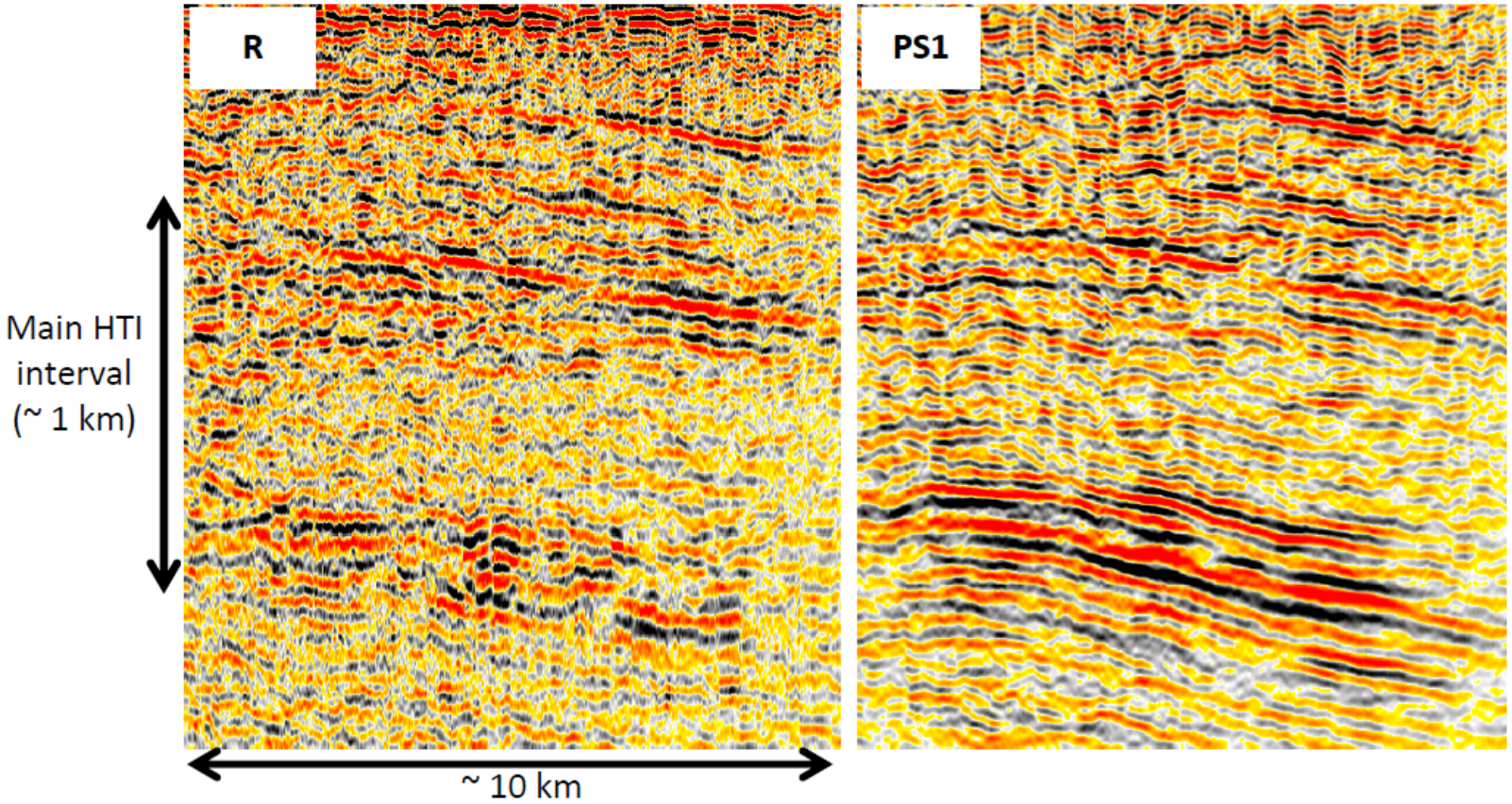


Figure 2. *PS Pre-stack migrated images for the radial (on the left) and the fast shear (PS1, on the*

A039

Piceance 3C 3D Survey - Processing of Converted-wave Data in an Area with Azimuthal Anisotropy

A.P. Shatilo* (ExxonMobil Upstream Research Co.), R. Bansal (ExxonMobil Upstream Research Co.), J. Hefti (ExxonMobil Exploration Co.) & C.Rochette (ExxonMobil Production Co. EAGE 2012

… but maybe it was also Pre/Post-stack migration, velocity?

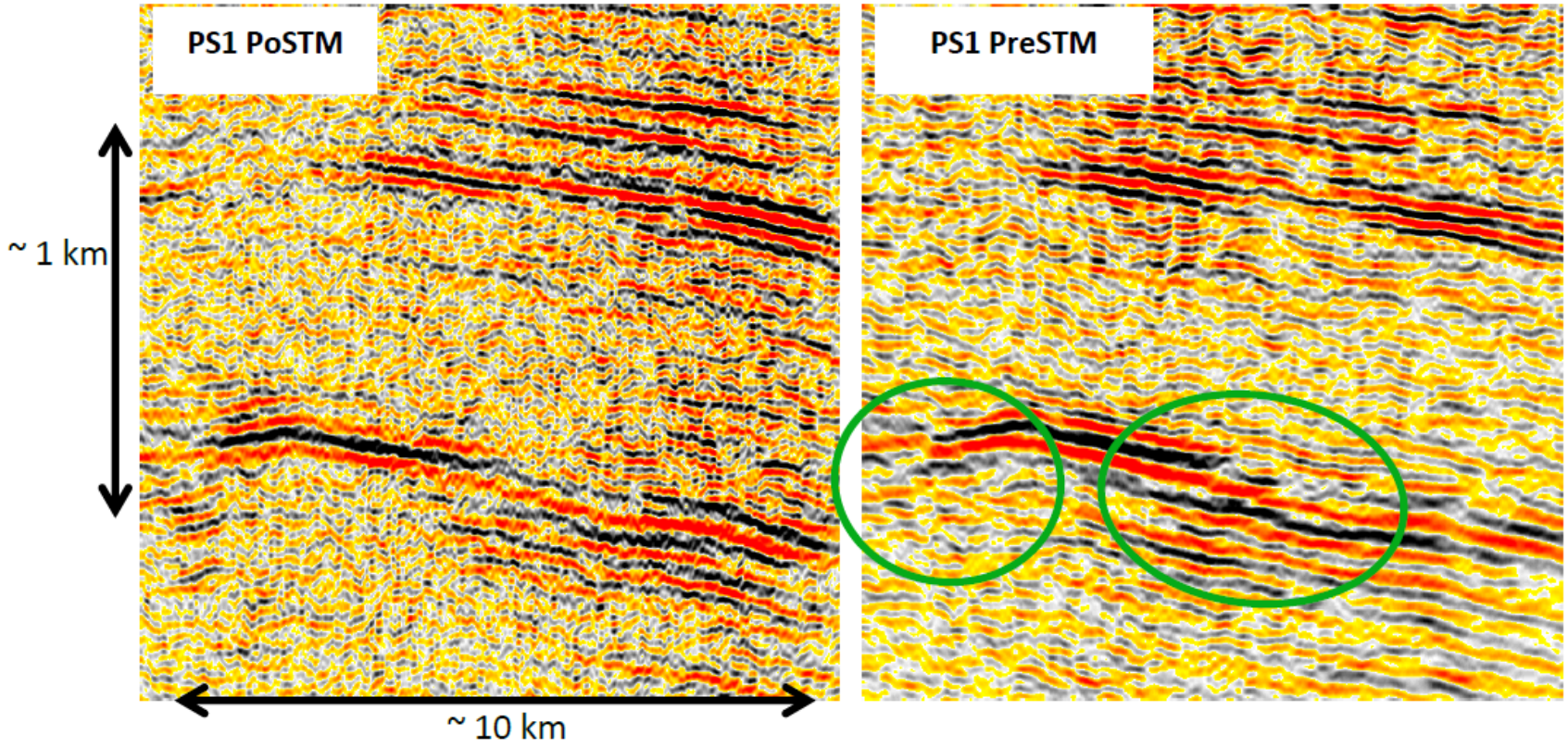


Figure 3. *PS1 migrated images obtained using the post-stack (on the left) and pre-stack (on the right) migration flows.*

A039

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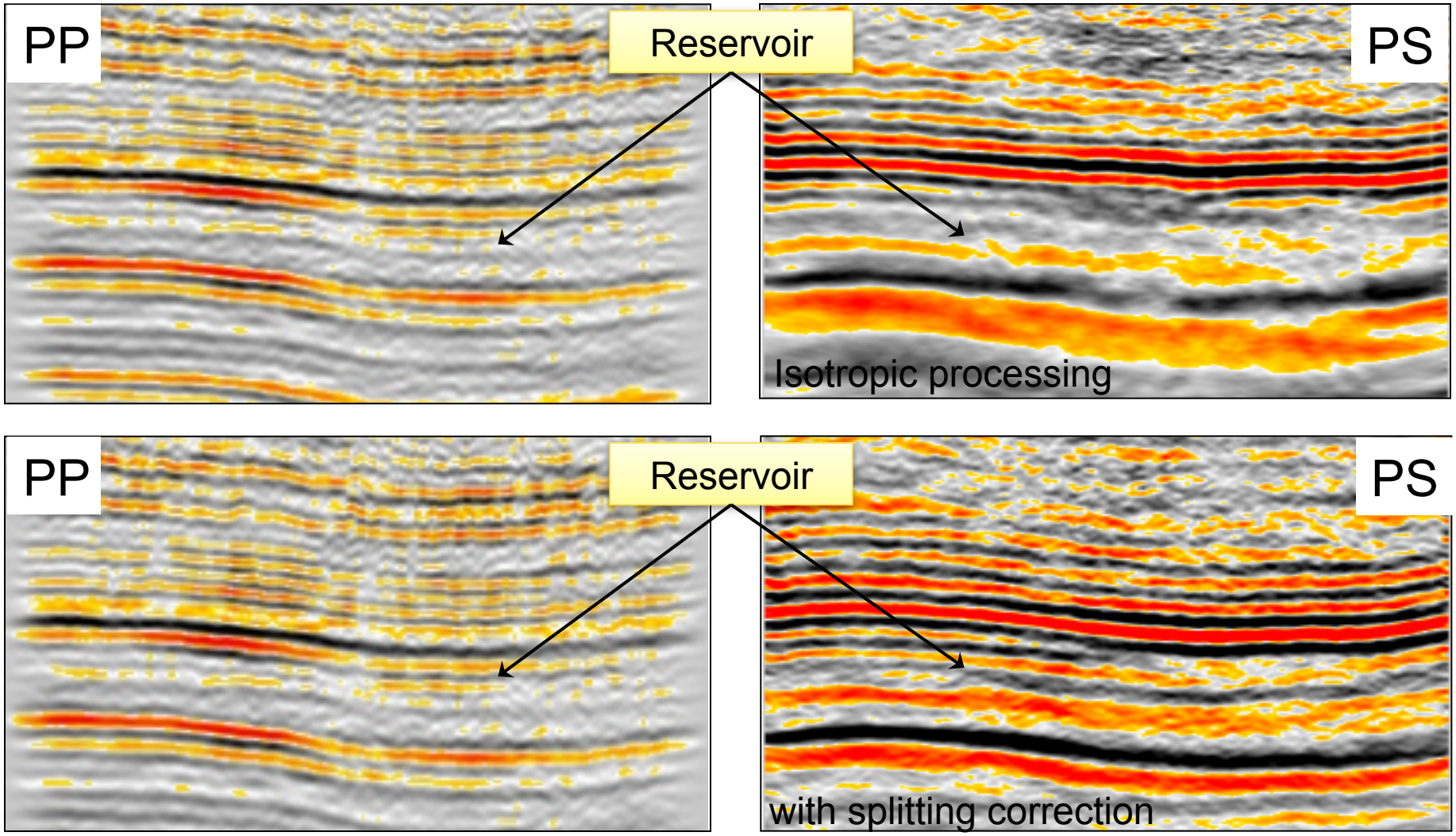
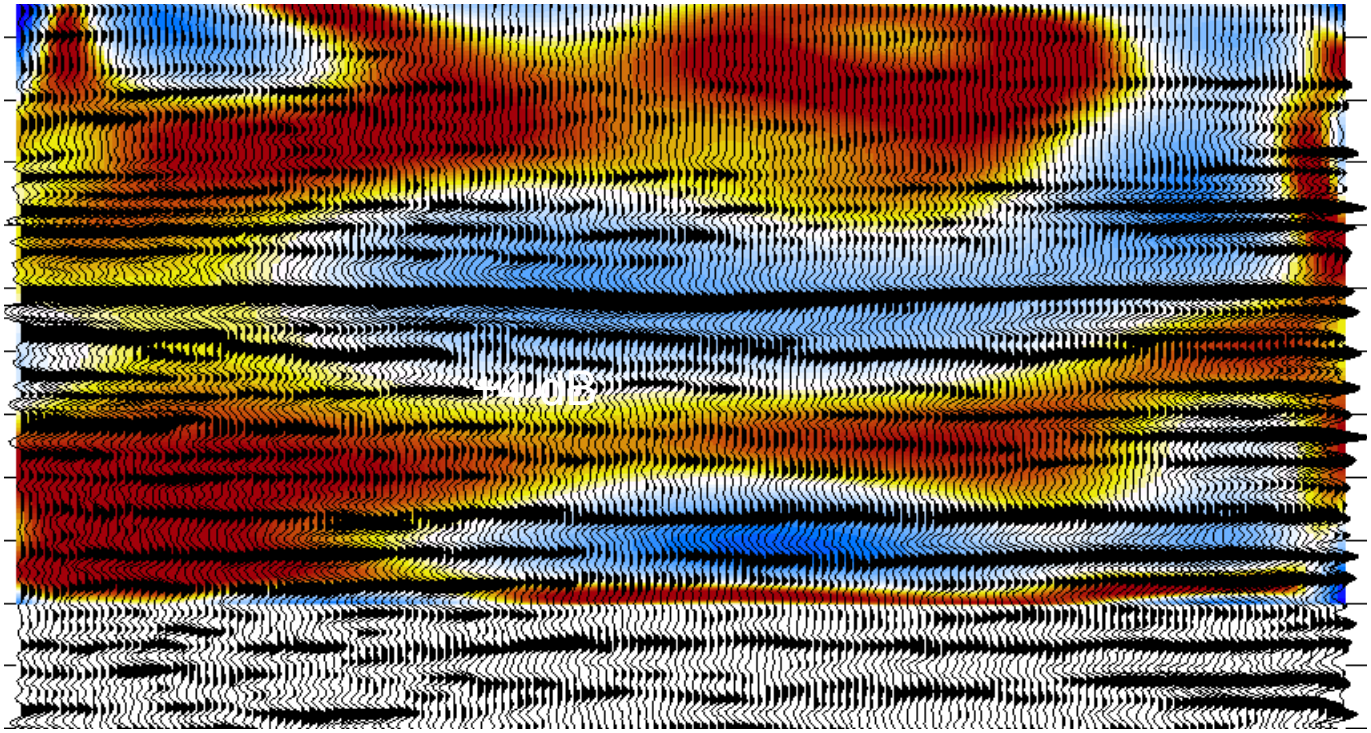
Shear wave splitting: Dowitcher Heavy Oil (Bale, 2010)



Courtesy of Chevron

Shear wave splitting: Dowitcher Heavy Oil (Bale, 2010)

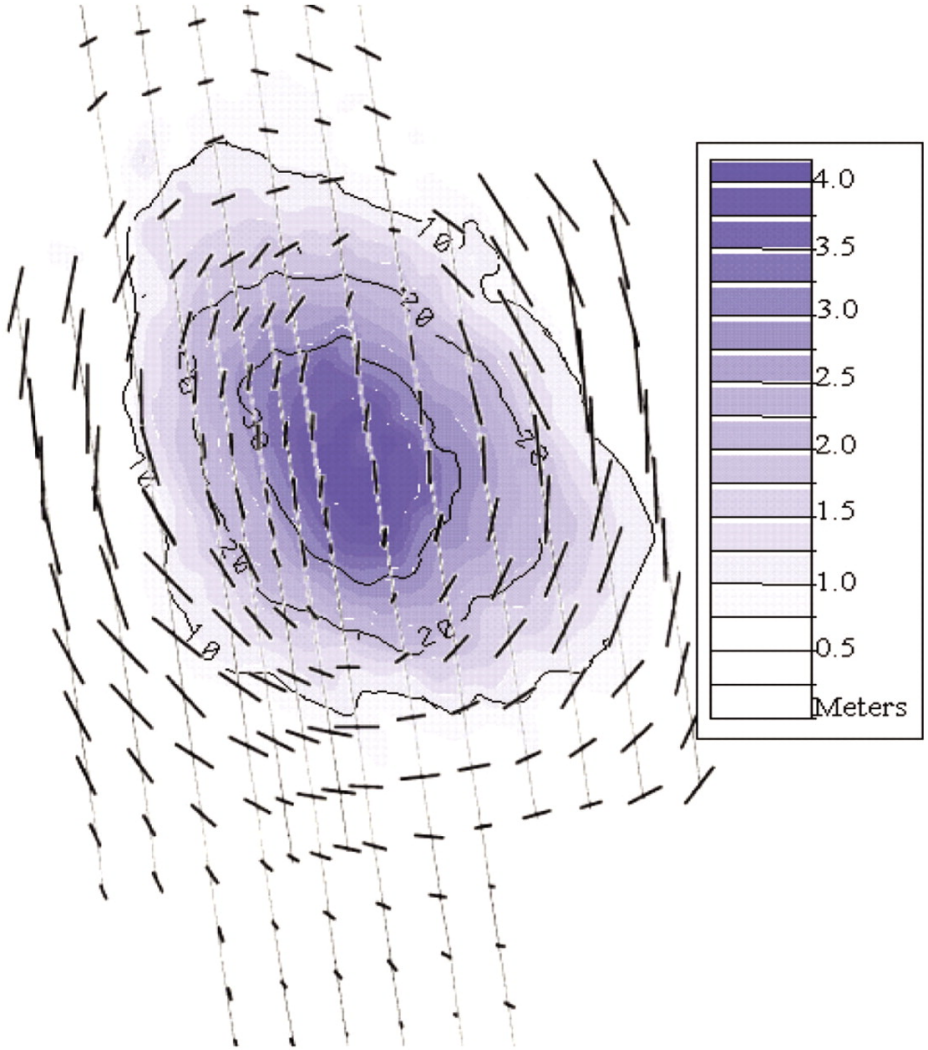
Operator gain at 10Hz



***It is not only the imaging but also deriving useful attributes from the azimuthal anisotropy amount, direction, and attenuation**

Courtesy of Chevron

Shear waves splitting: Valhal



Azimuthal anisotropy from the Valhall 4C 3D survey

Olofsson, Probert, Kommedal, Barkved

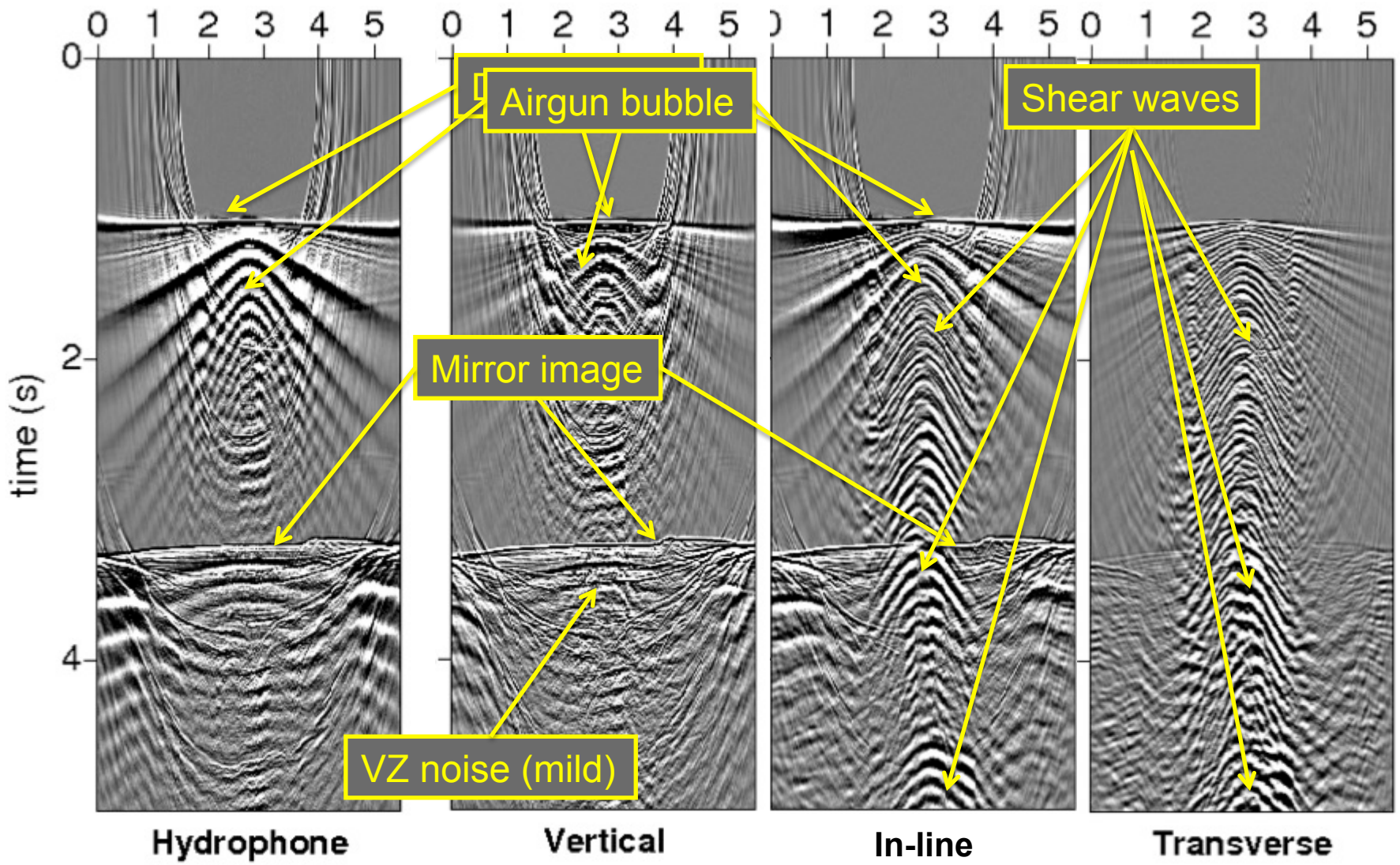
TLE December 2003

Shear waves processing

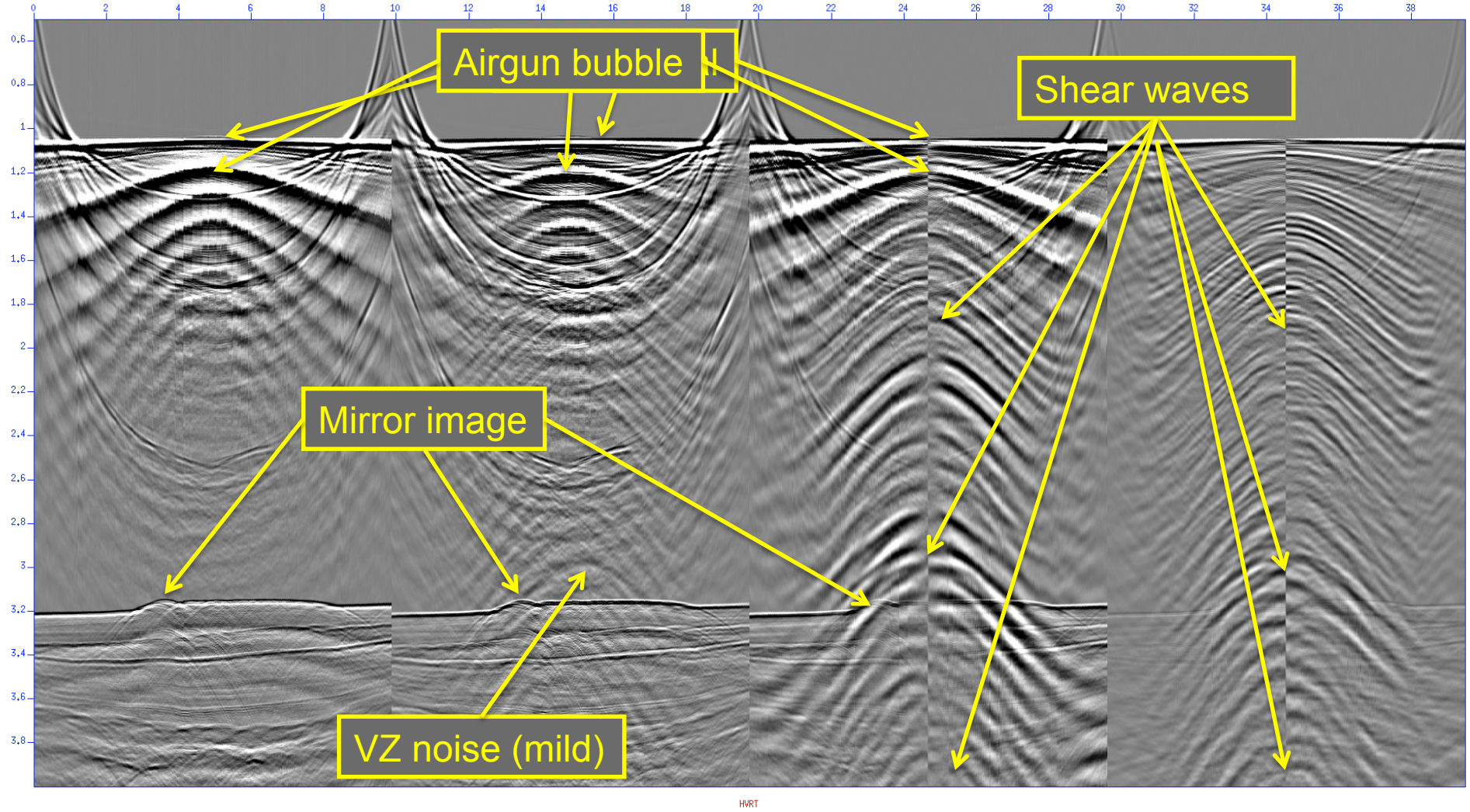
- Processing issues…
- Have to process and image the data properly
  - Shear wave statics? It can be done
  - Shear wave splitting? It can be done and it provides added information: initially a curse but then a blessing
  - Long turn around time? Yes, this is a big challenge!

- How about acquisition data quality?
  - VZ noise

Cross section after NMO QC



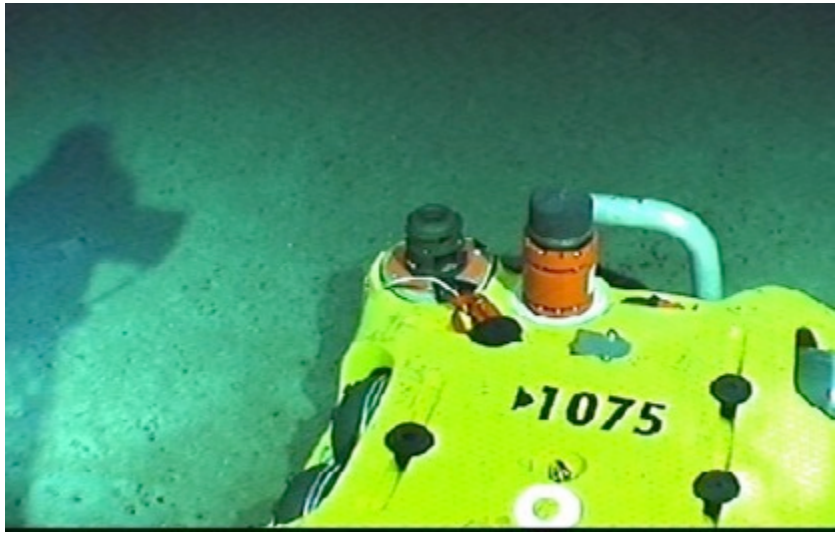
Cross section after NMO QC

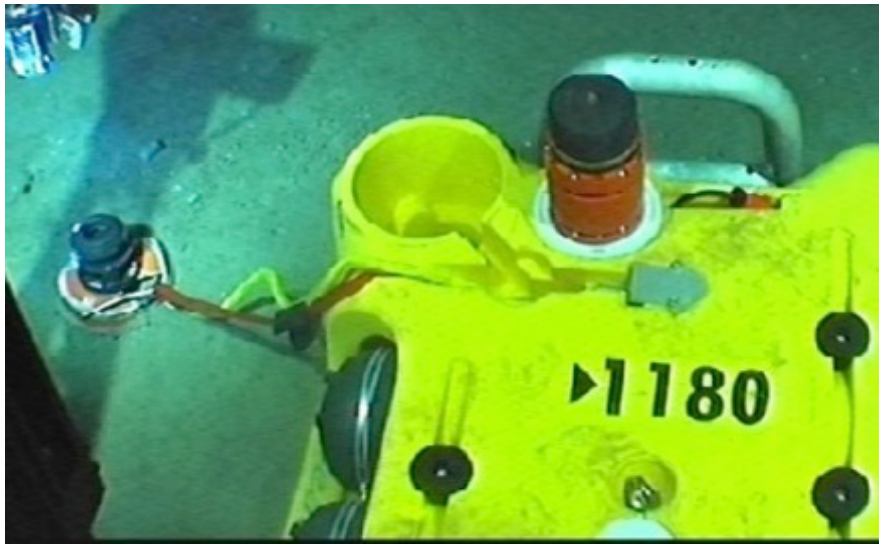


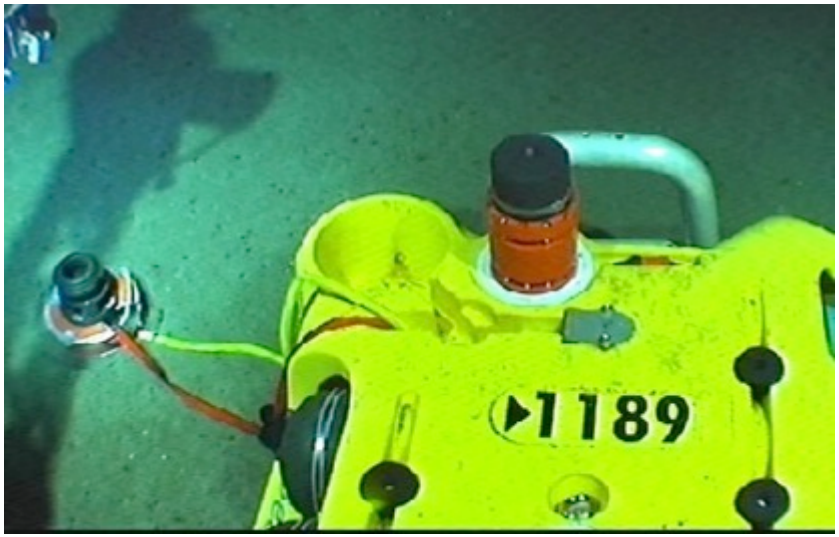
In-line

Severe VZ noise

- 2009 Atlantis sea trial
- CASE-Abyss nodes
- One node deployed with sensor not planted co located with two nodes deployed normally

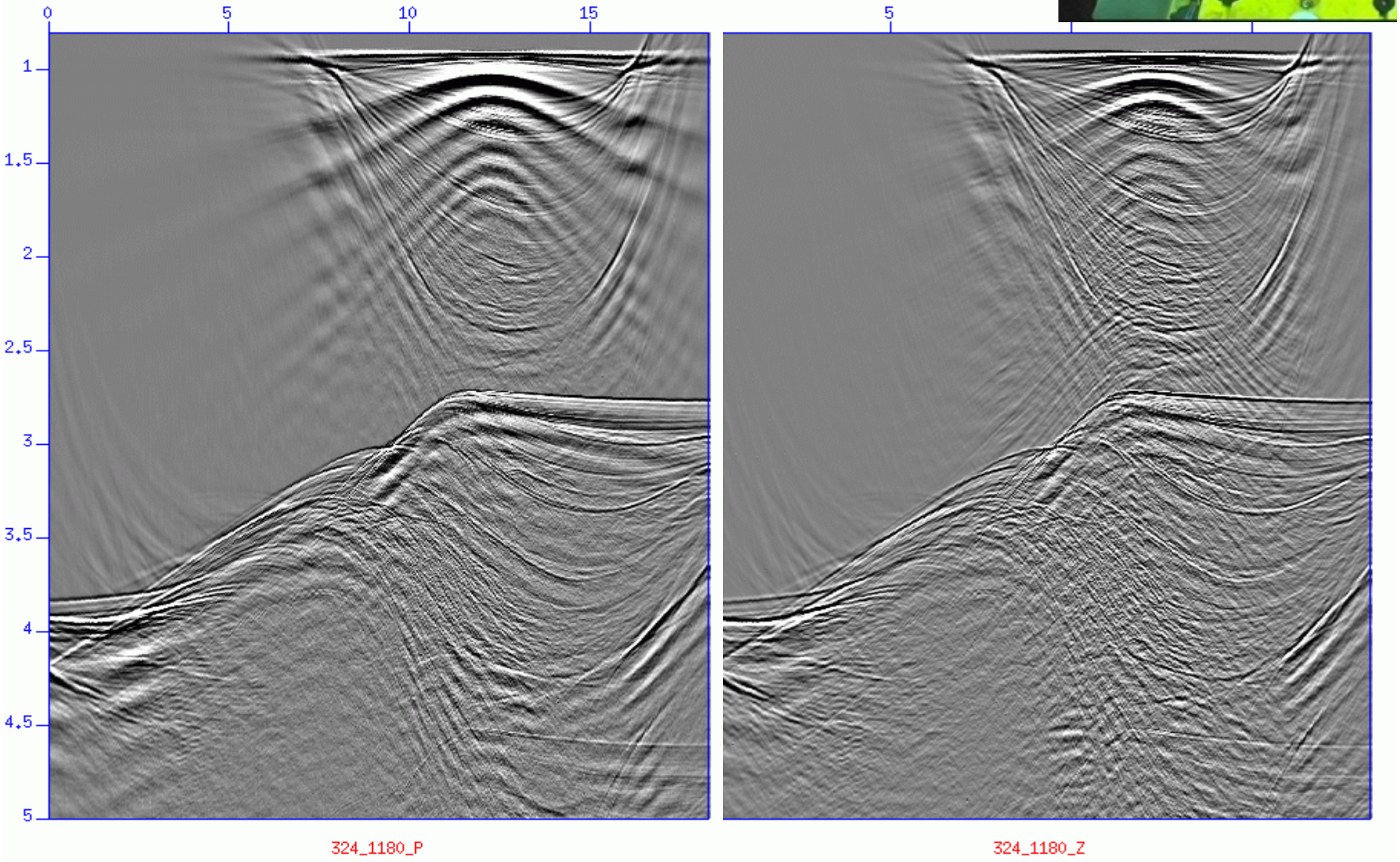






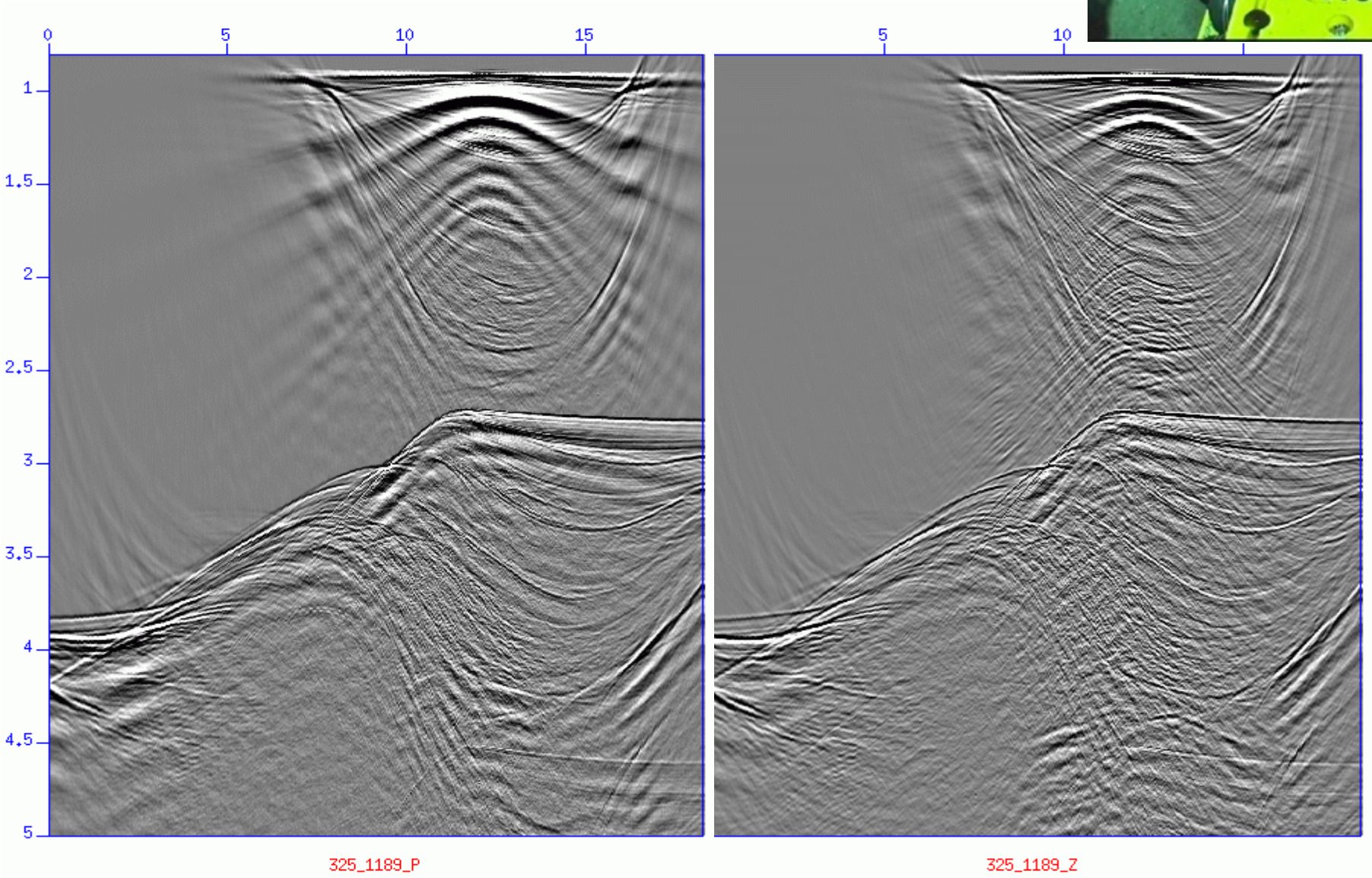
Good node P and Z





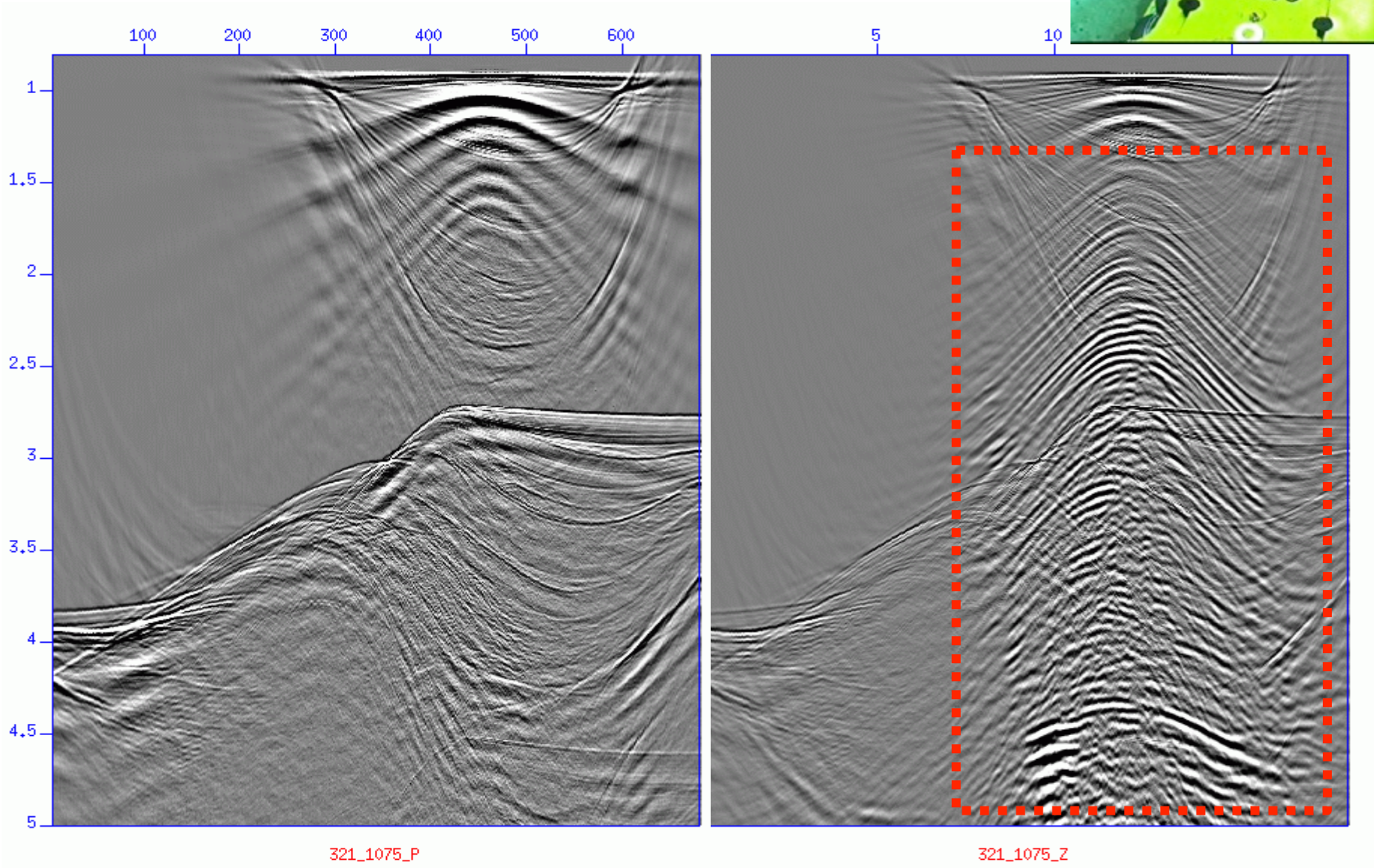
Good node P and Z



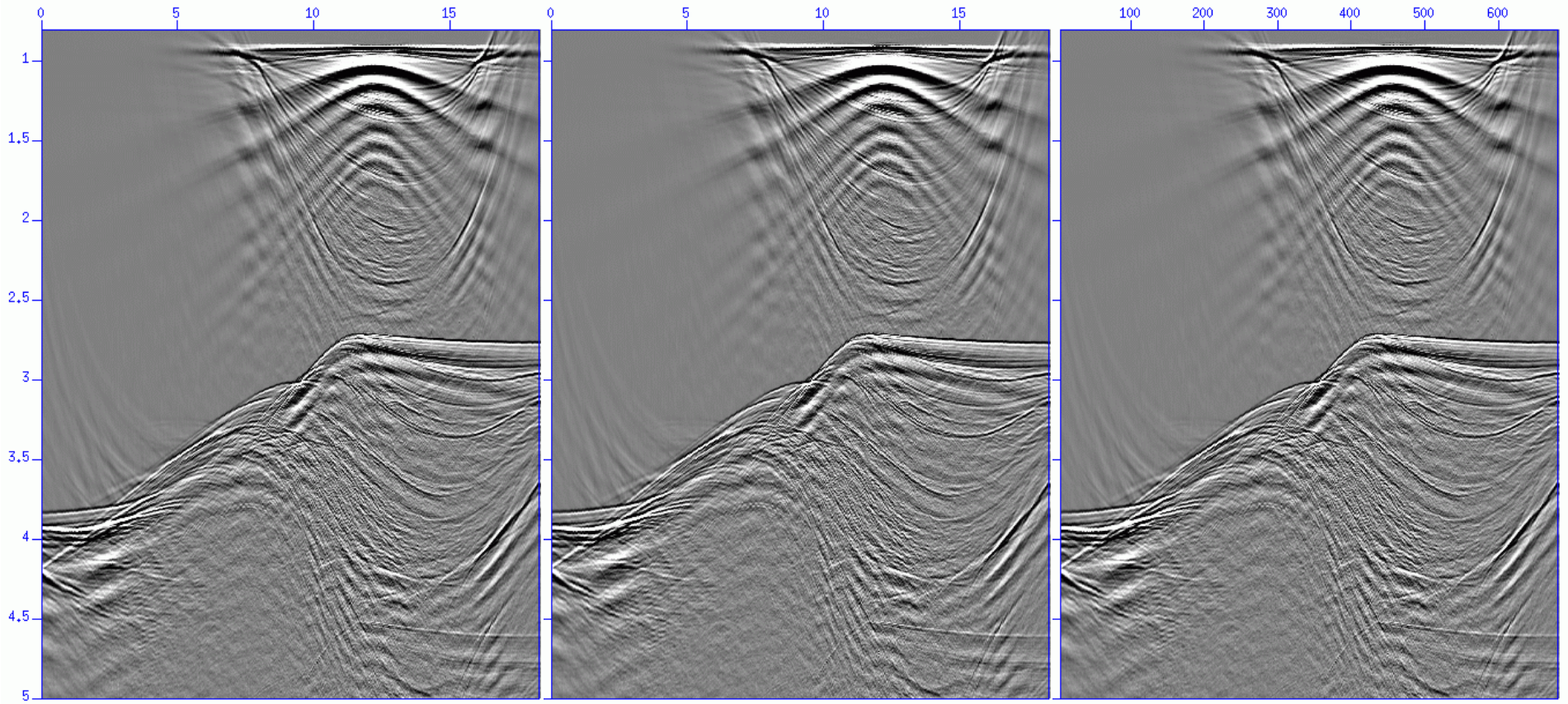


Bad node P and Z





Hydrophone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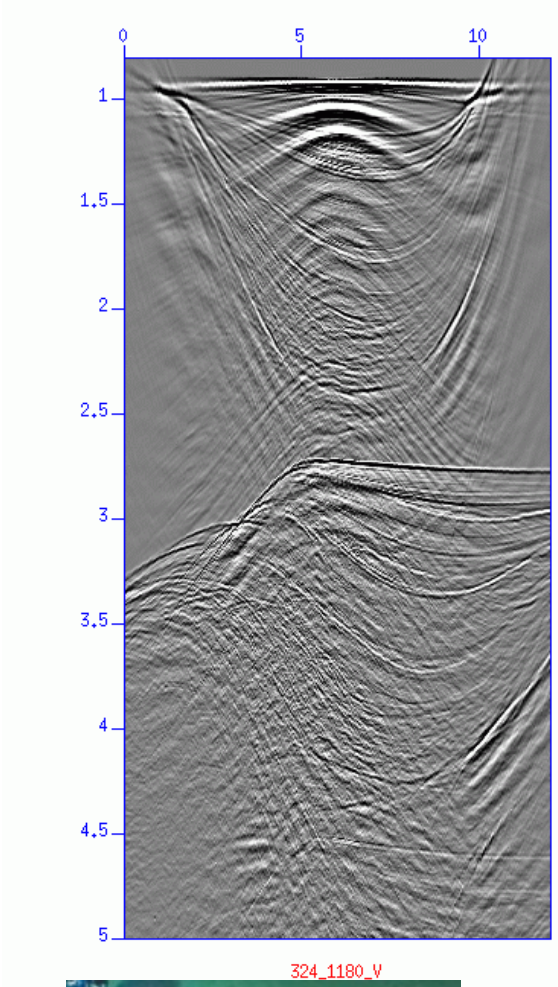
324_1180_P
1180


325_1189_P
1189


321_1075_P
1075

Vertical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324_1180_V
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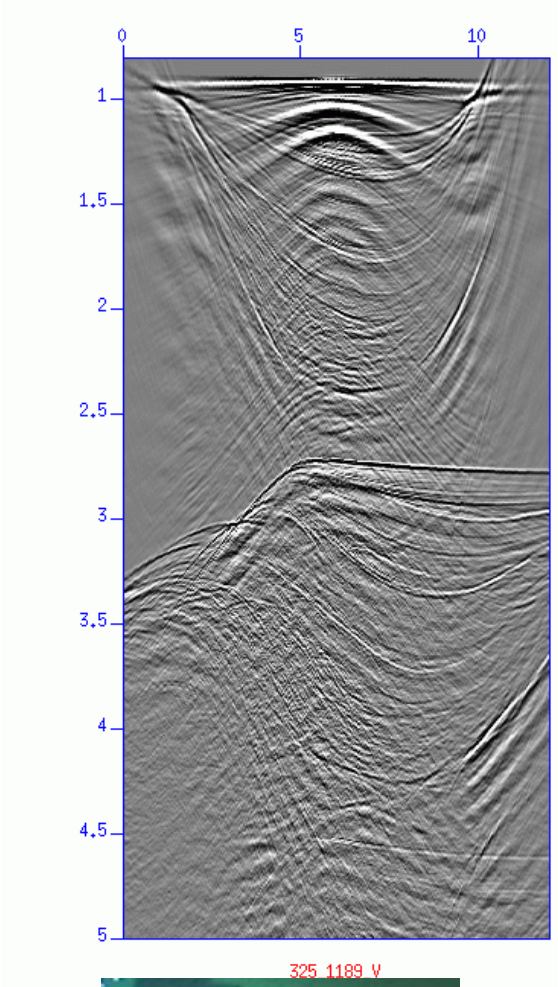
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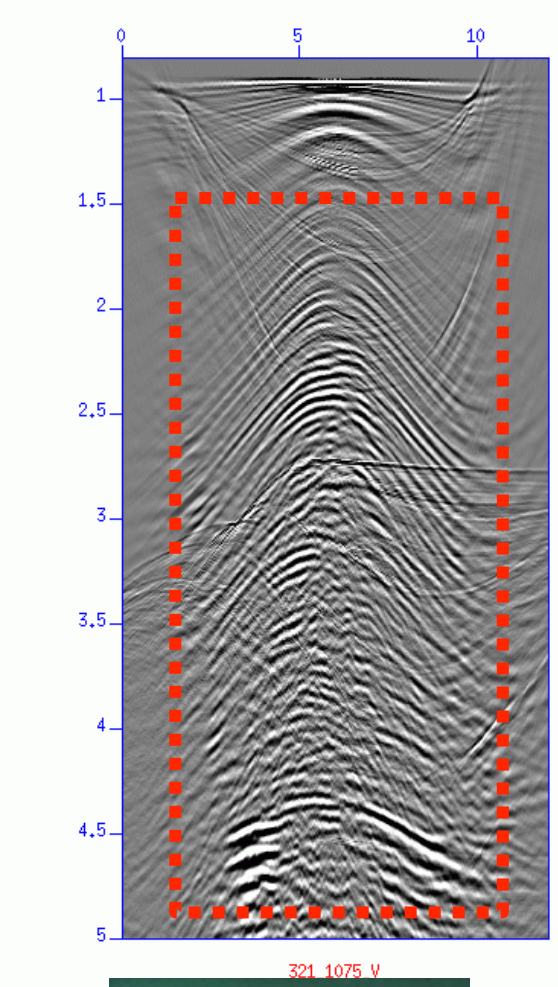
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321_1075_V
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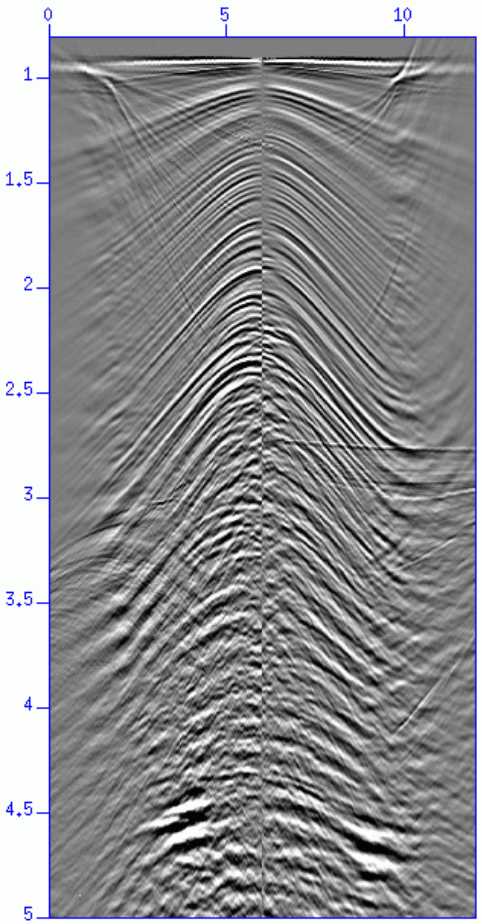
Radial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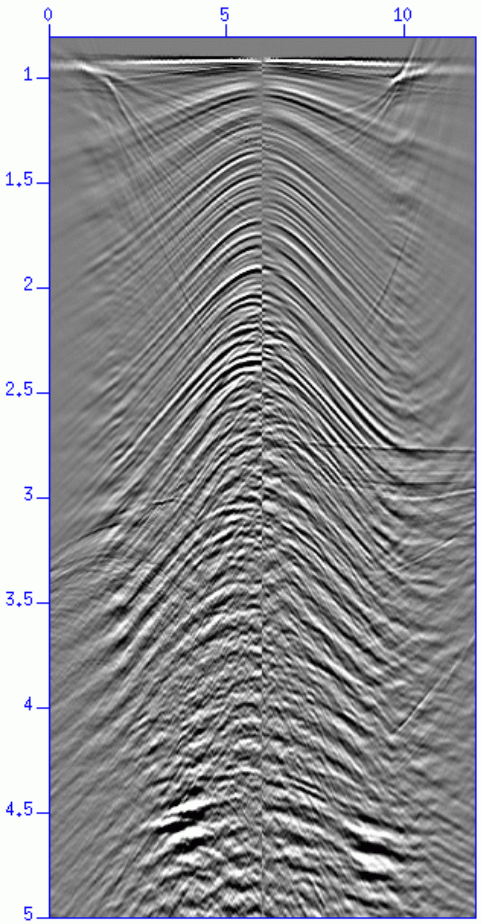
324_1180_R
1180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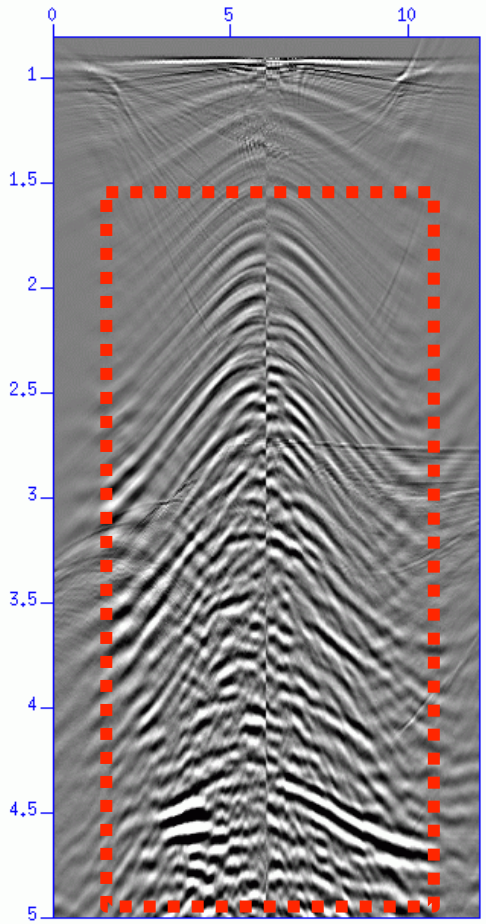
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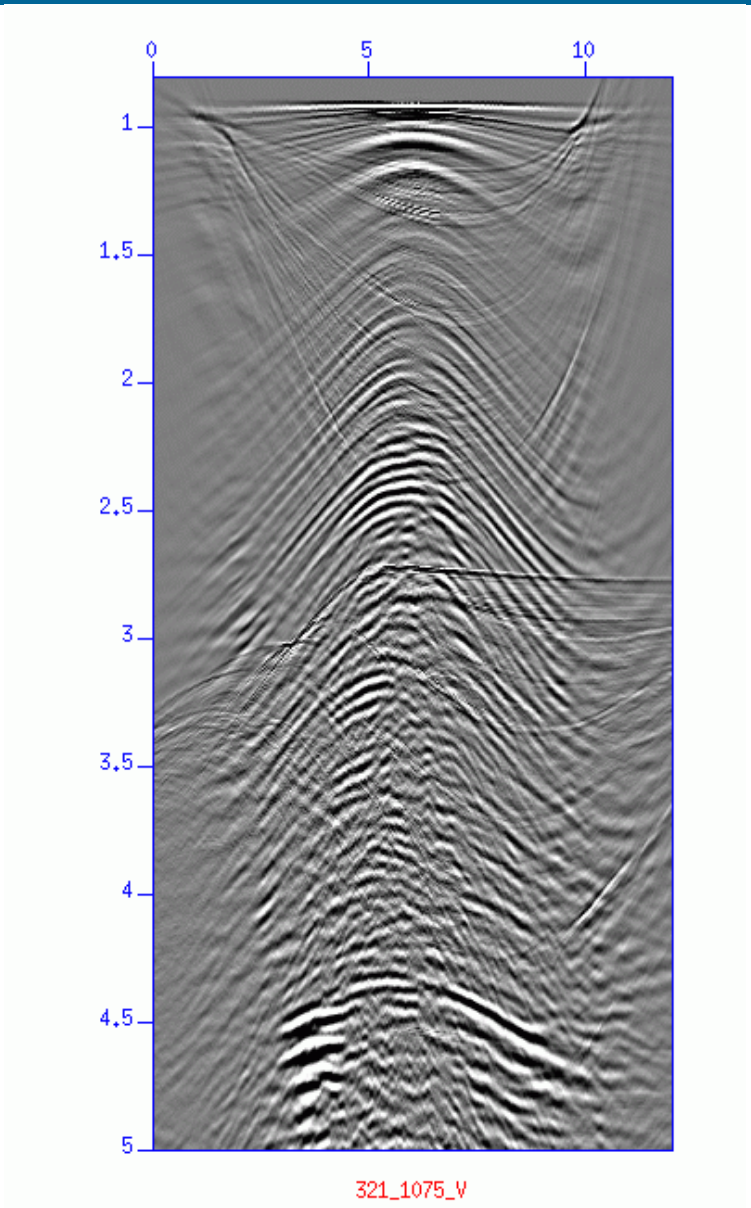
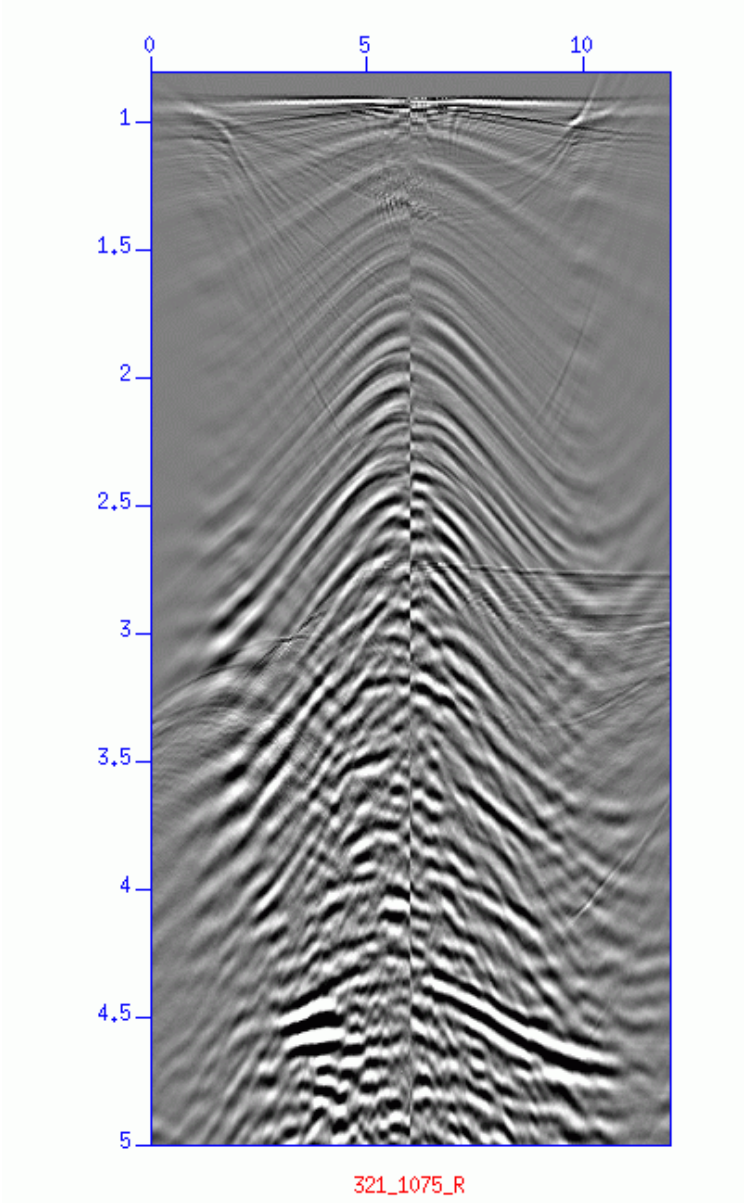
321_1075_R
1075

Shear waves acquisition problems



- There is almost always some VZ noise
  - Sometimes it is a big problem. Usually not.
- Data processing is pretty good cleaning the vertical from VZ noise: VZ noise has shear velocity ≠ P velocity
- However, VZ noise damages not only the vertical component but also the horizontal components: where there is shear on the vertical the horizontals are poor

Shear waves acquisition problems



- It is much more difficult to separate shear induced noise from shear signal—they have the same velocity!
- Must not rely on velocity filtering: must either avoid the noise by better node design, or use other processing methods to attenuate VZ noise

Shear waves processing

- Processing issues…
- Have to process and image the data properly
  - Shear wave statics? It can be done
  - Shear wave splitting? It can be done and it provides added information: initially a curse but then a blessing
  - Long turn around time? Yes, this is a big challenge!
- How about acquisition data quality?
  - VZ noise
- Interpretation challenges
  - Joint inversion

Interpretation: joint inversion

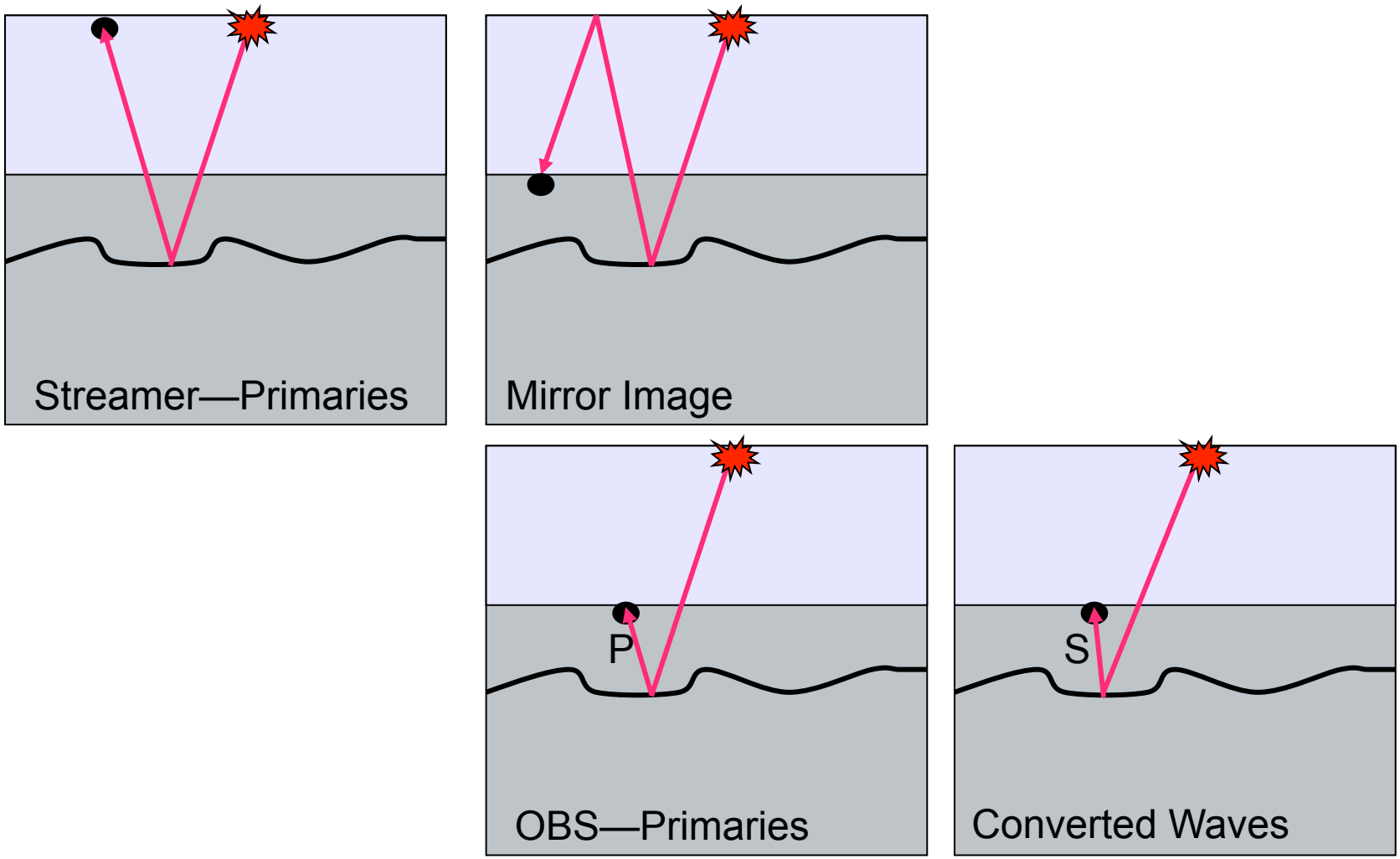
- We should not see shear waves as an alternative to P waves
- We should see them as an opportunity to add value
  - Explain the P data

    P Data = P Forward Modeling (Earth Model)
  - Explain the PS data

    PS Data = PS Forward Modeling (Earth Model)
  - Invert (3 equations, one unknown)

$$\begin{bmatrix} P \\ PS1 \\ PS2 \end{bmatrix} = \begin{bmatrix} PP & F \\ PS1 & F \\ PS2 & F \end{bmatrix} [M]$$

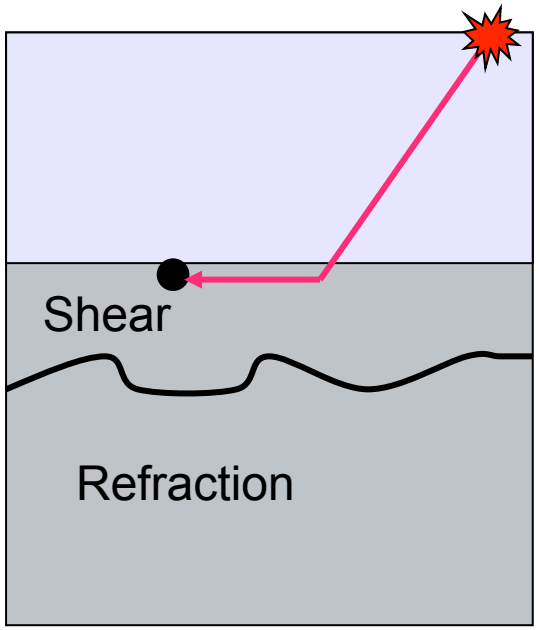
Multi-mode seismic imaging



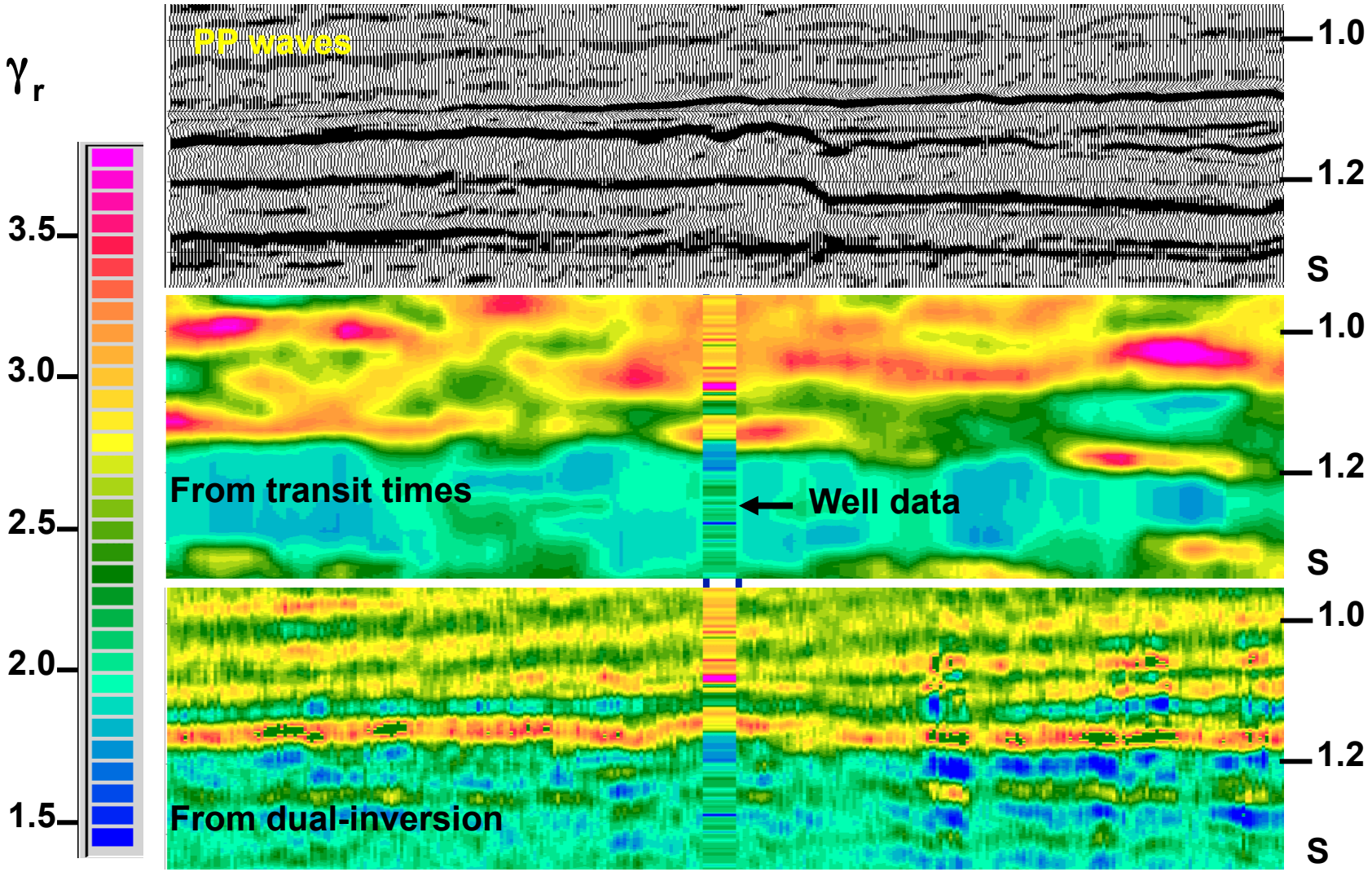
Valhal

FWI

Refraction

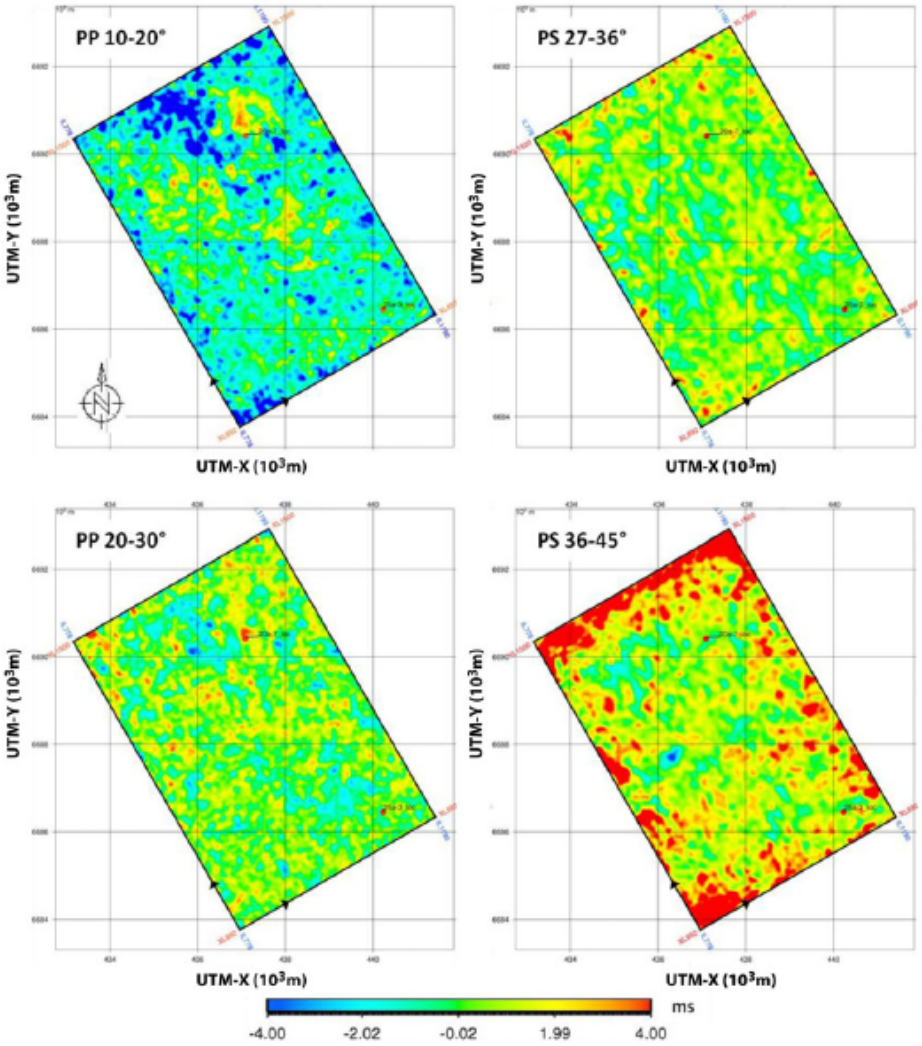


PP-PS joint inversion, 2002

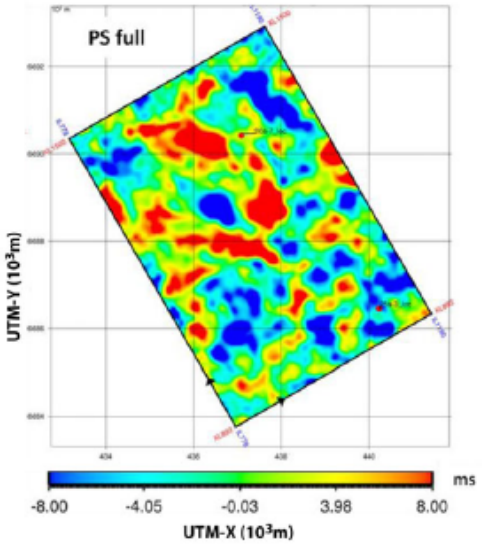


Granger, Garotta and Dariu, 2002

PP-PS joint AVO inversion, 2014

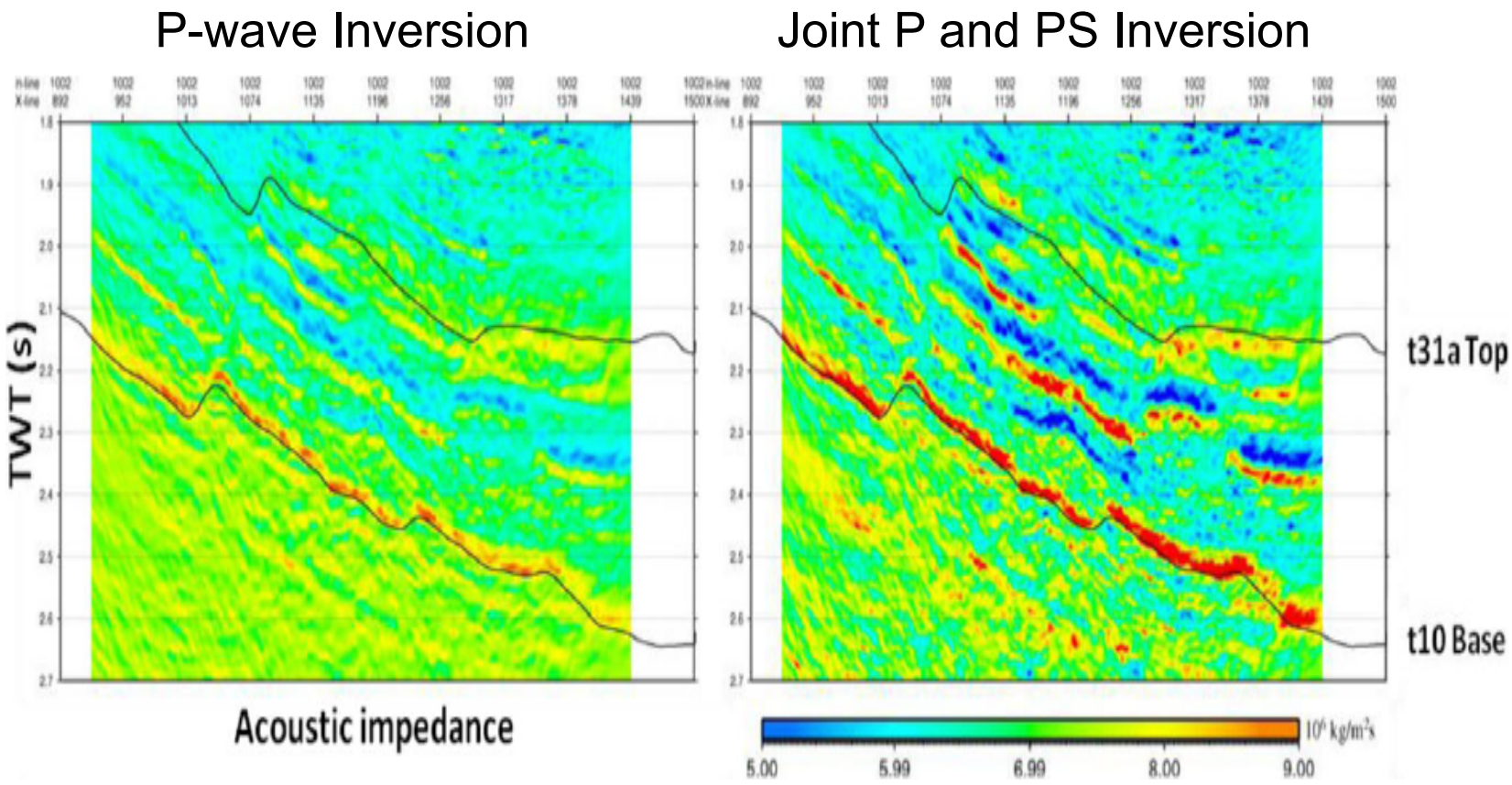


Angles stacks and time shifts



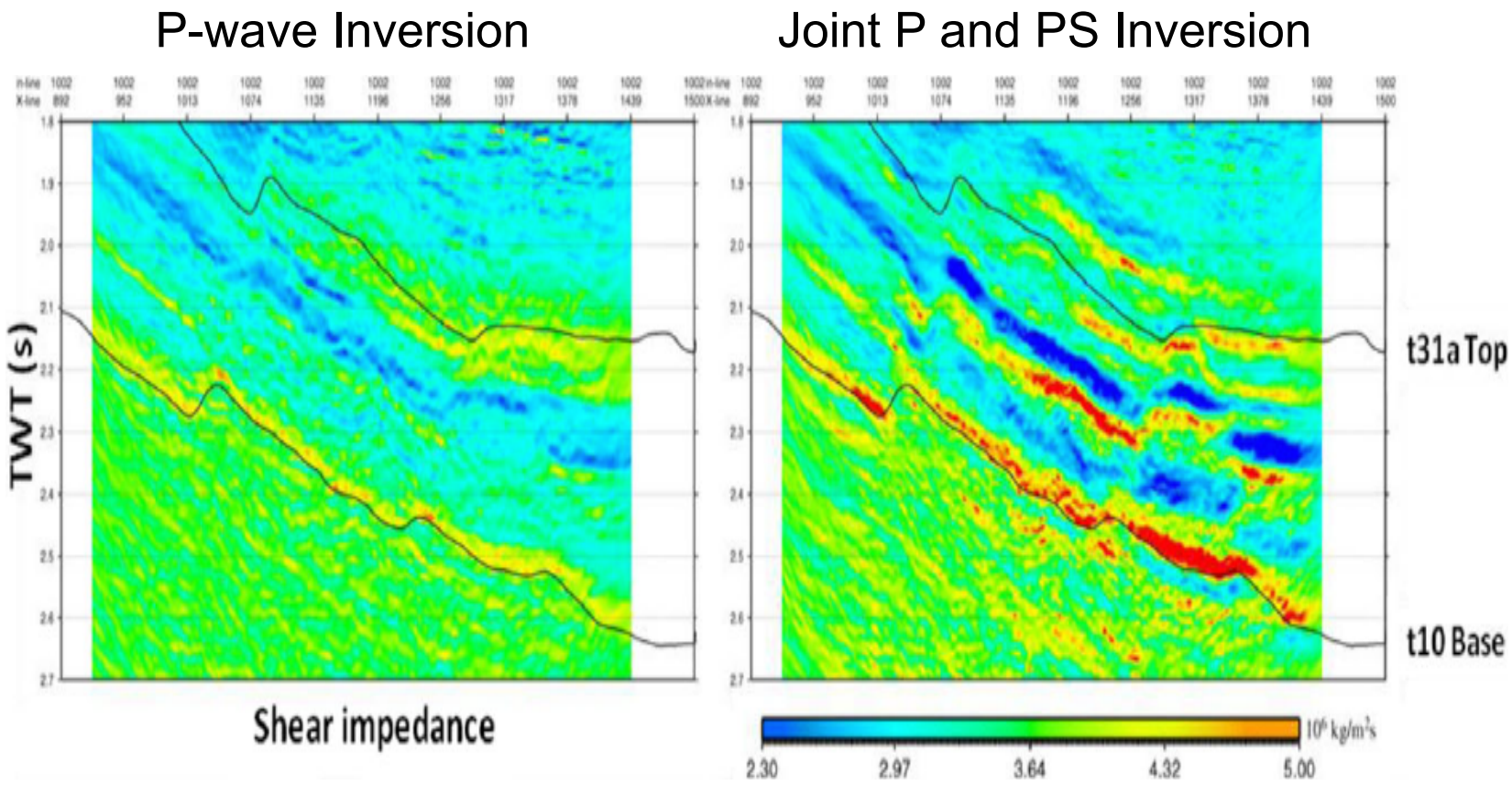
Barnola and Ibram, 2014. Clair OBC data. BP and WG

PP-PS joint inversion (Clair OBC, 2014)



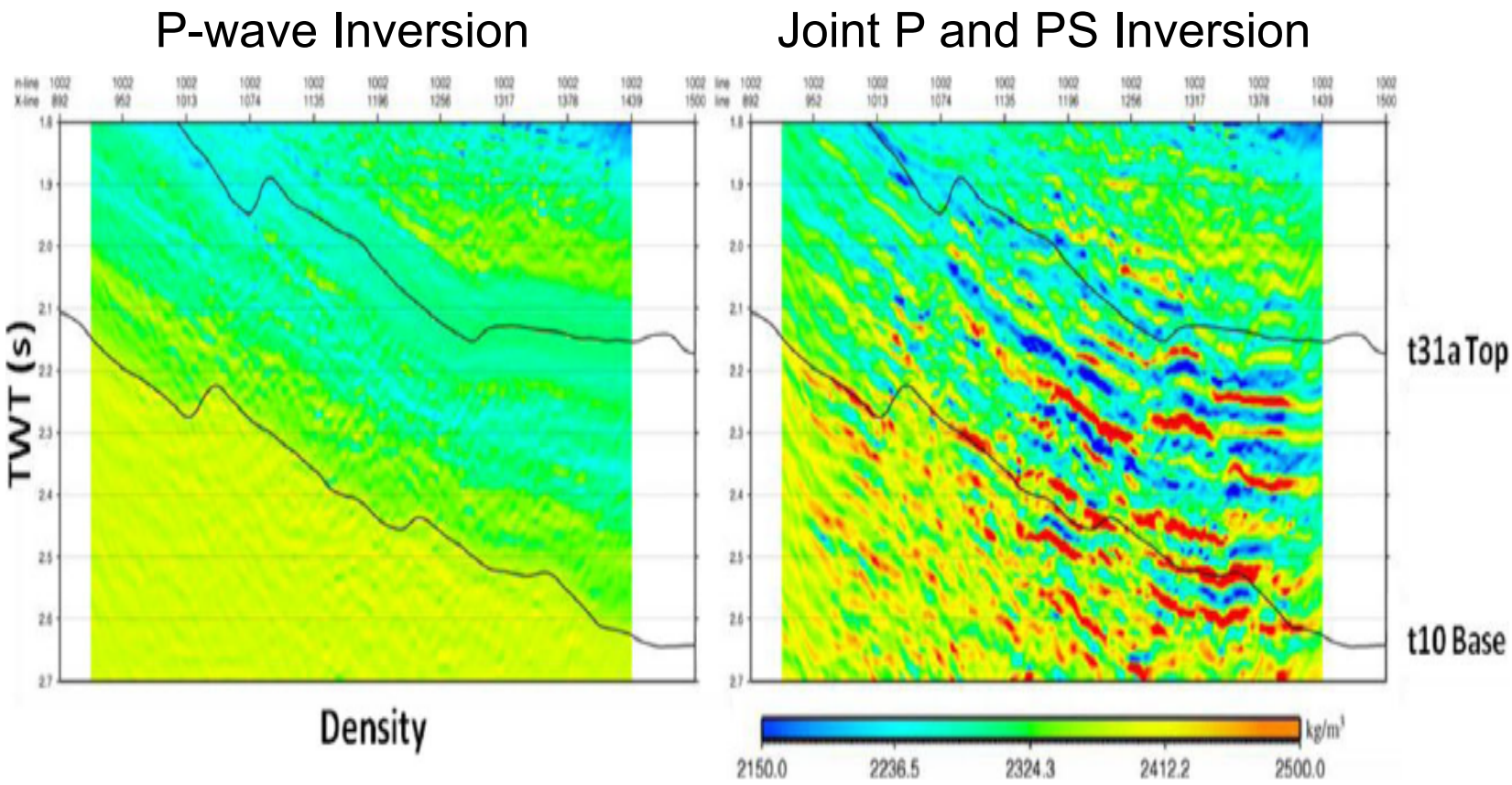
Barnola and Ibram, 2014

PP-PS joint inversion (Clair OBC, 2014)



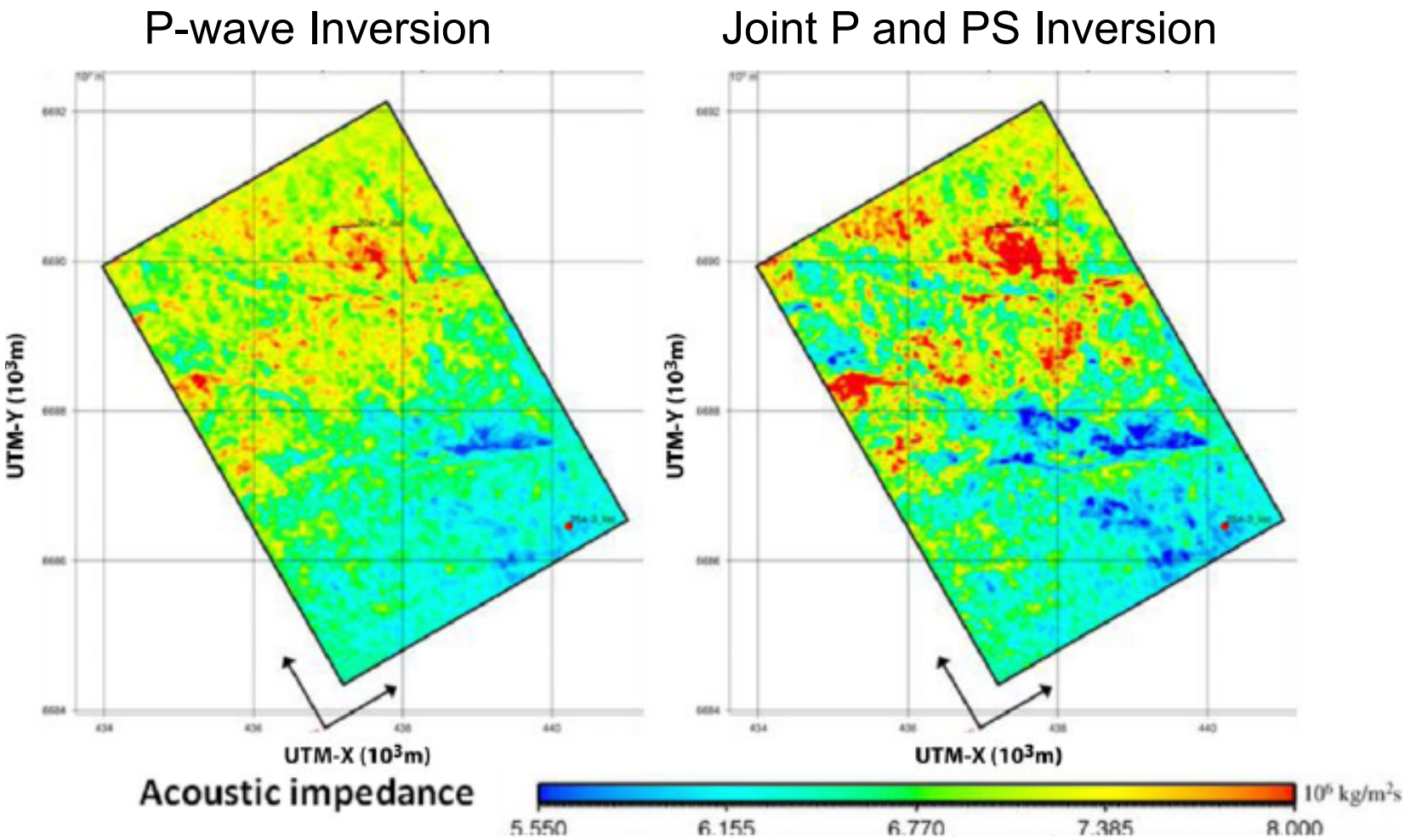
Barnola and Ibram, 2014

PP-PS joint inversion (Clair OBC, 2014)



Barnola and Ibram, 2014

PP-PS joint inversion (Clair OBC, 2014)

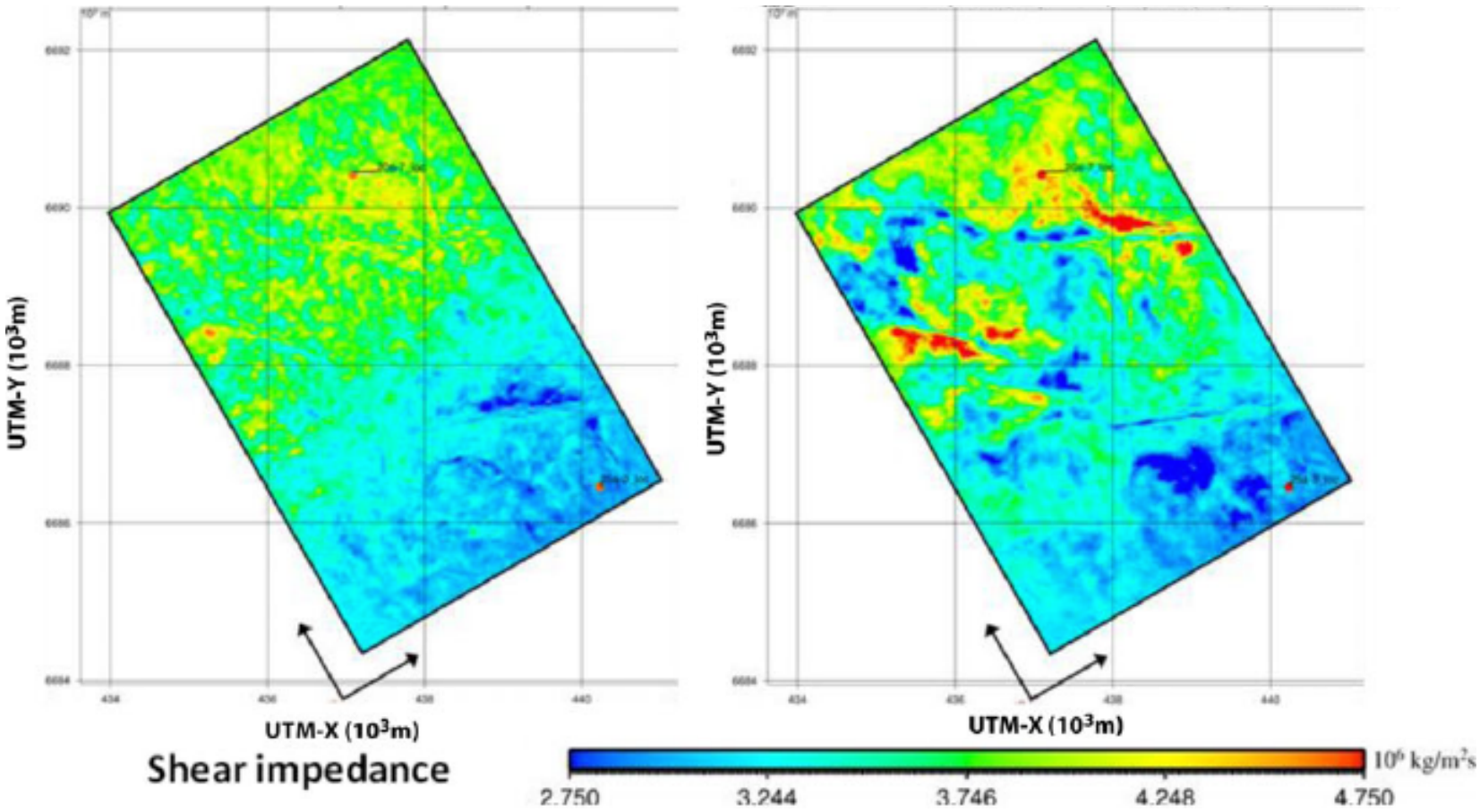


Barnola and Ibram, 2014

PP-PS joint inversion (Clair OBC, 2014)

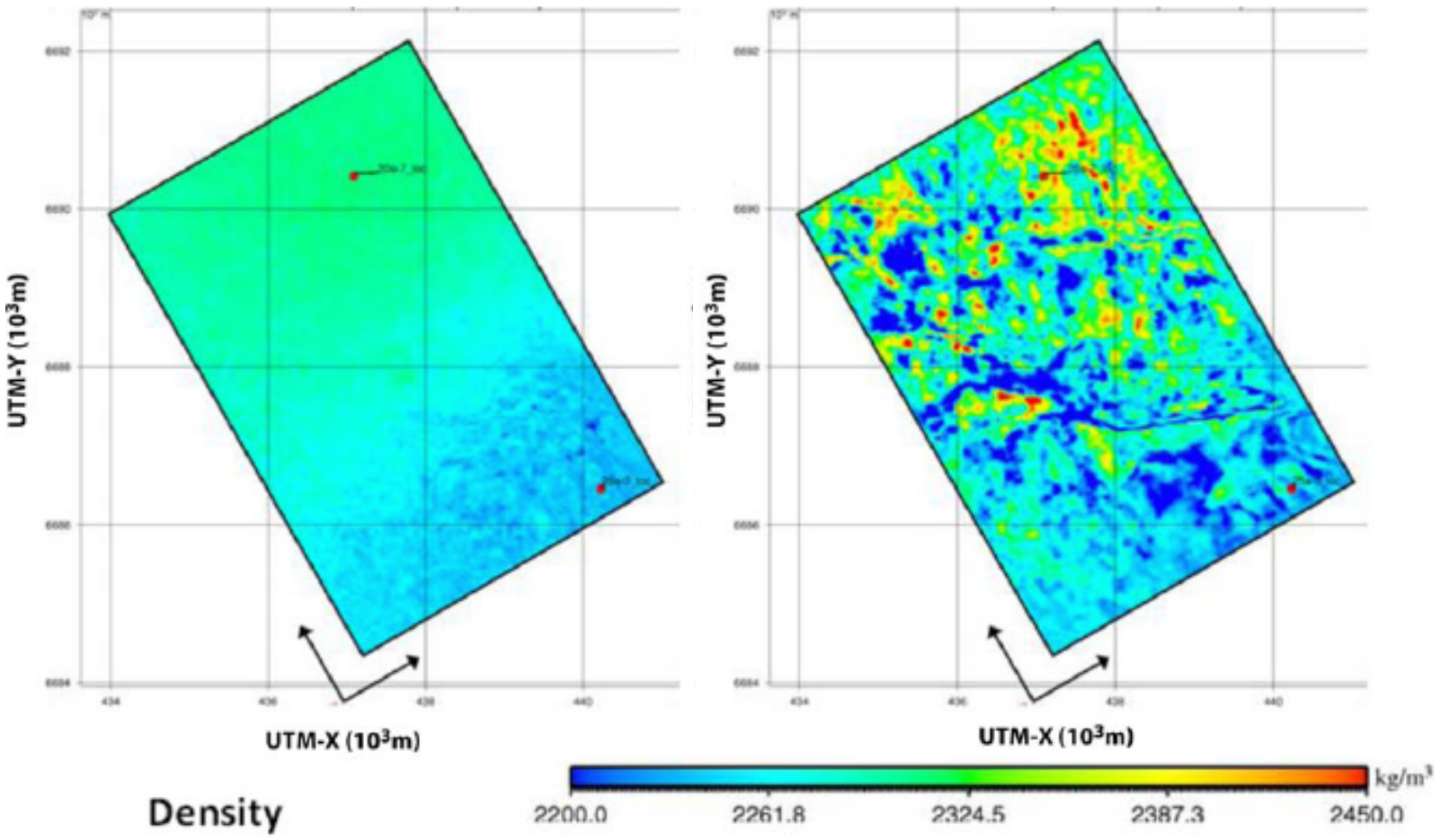
P-wave Inversion

Joint P and PS Inversion



Barnola and Ibram, 2014

PP-PS joint inversion (Clair OBC, 2014)



Barnola and Ibram, 2014

PP-PS joint inversion

- We are getting different results from PP only and from PP+PS
- Similarly we are getting different azimuthal anisotropy from wide azimuth PP-AVO and from shear wave splitting

Question

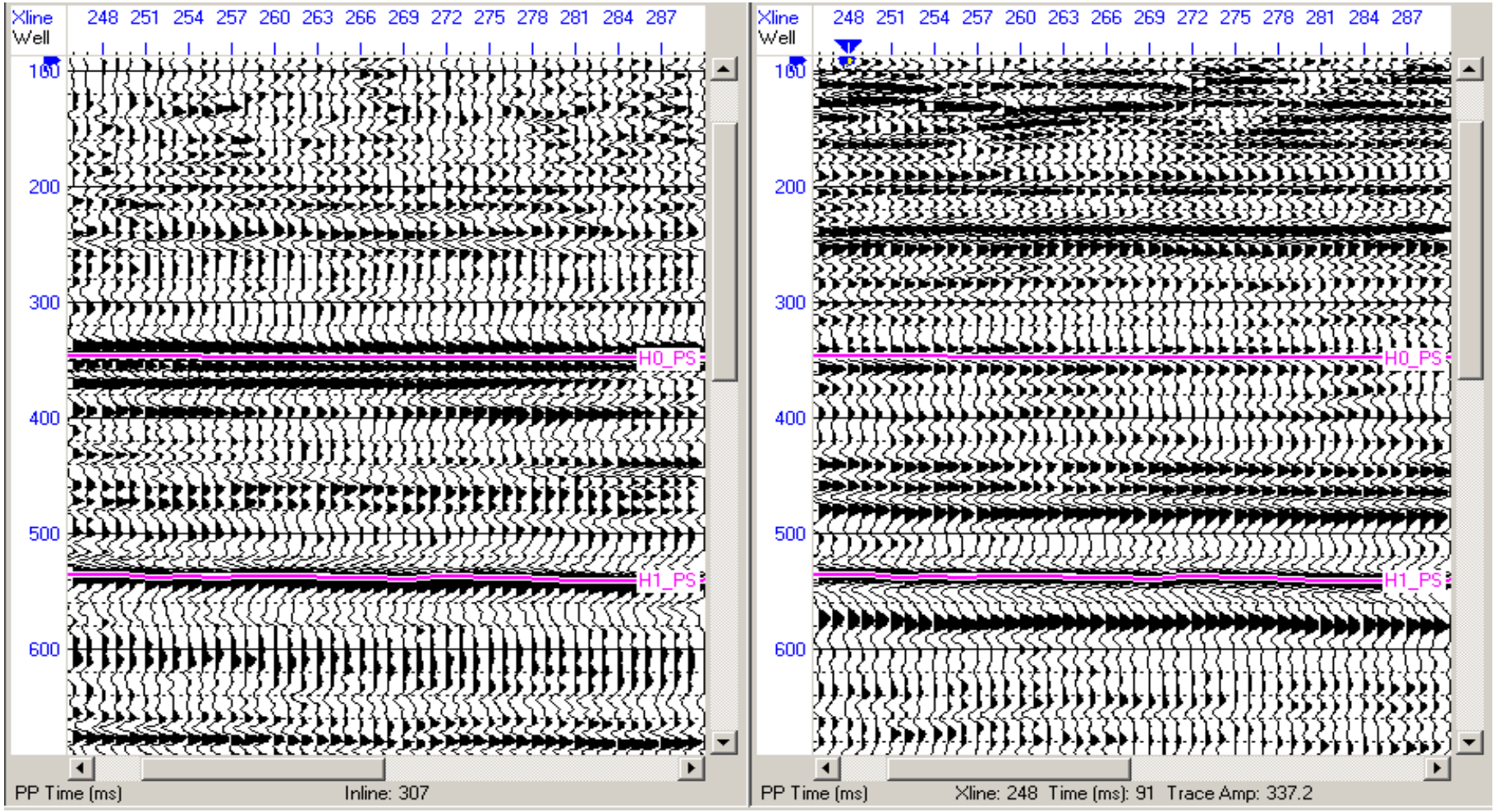
- Which one is better?

Answer:

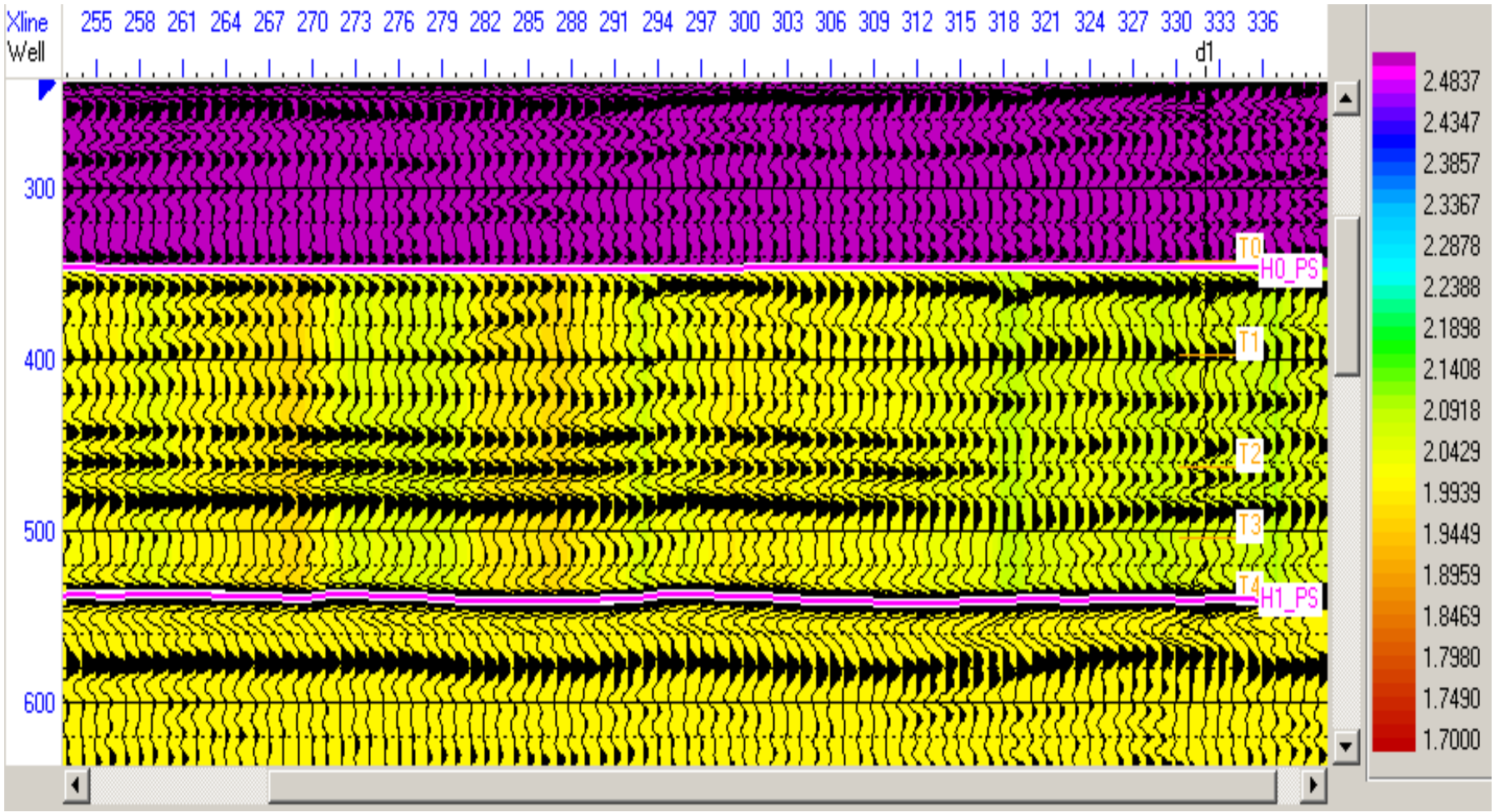
- The products of inversion are seismic attributes
- They should be calibrated against well logs
- Wells are using in the inversions (well tie and more)…
- Use blind test with “leave one out”

Barnola and Ibram, 2014

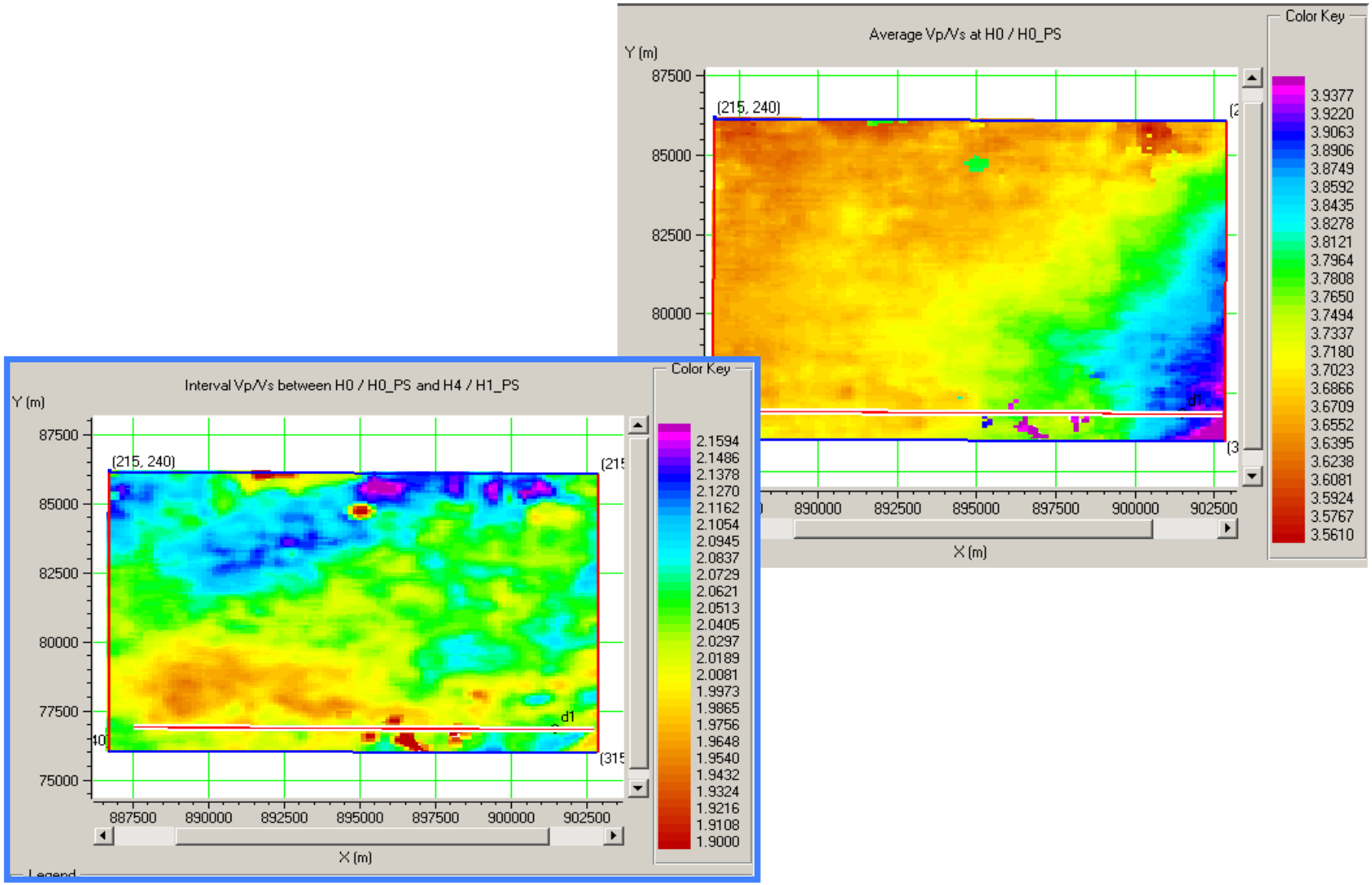
Well tie driven PP-PS event registration (Canada)



Vp/Vs ratio derived from the PP-PS event registration



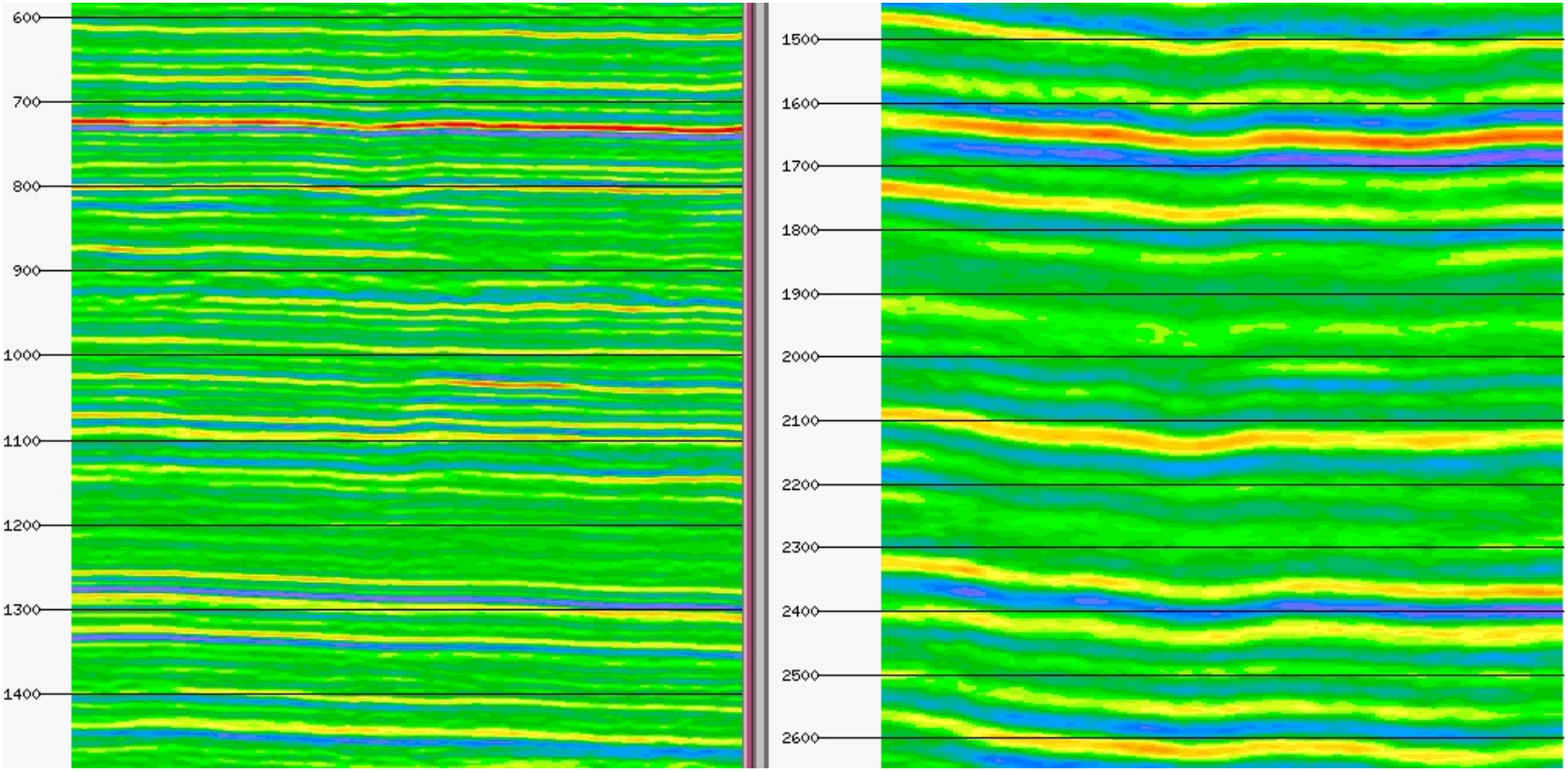
Vp/Vs ratio derived from the PP-PS event registration



A dog that did not bark

P-waves

C-waves

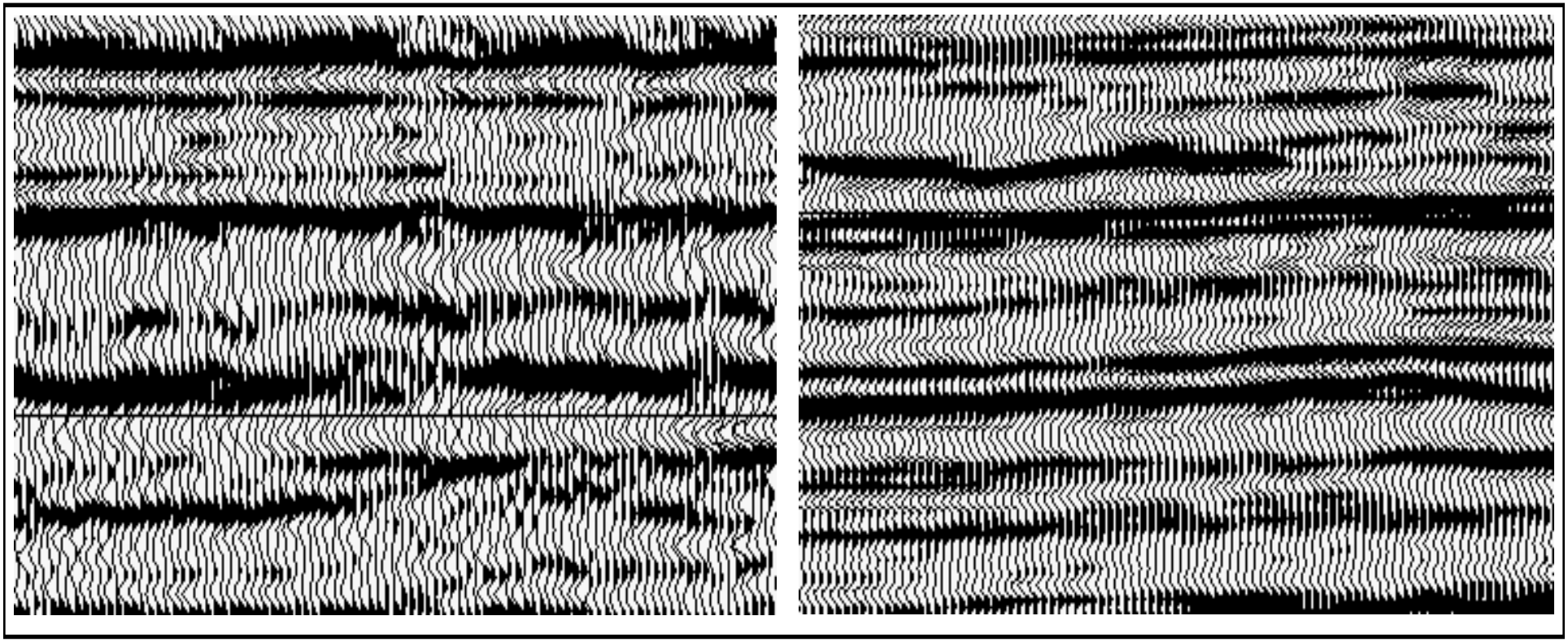


Fluid Identification (DHI) : Weyburn, Saskatchewan

Which one is better?

PS

P

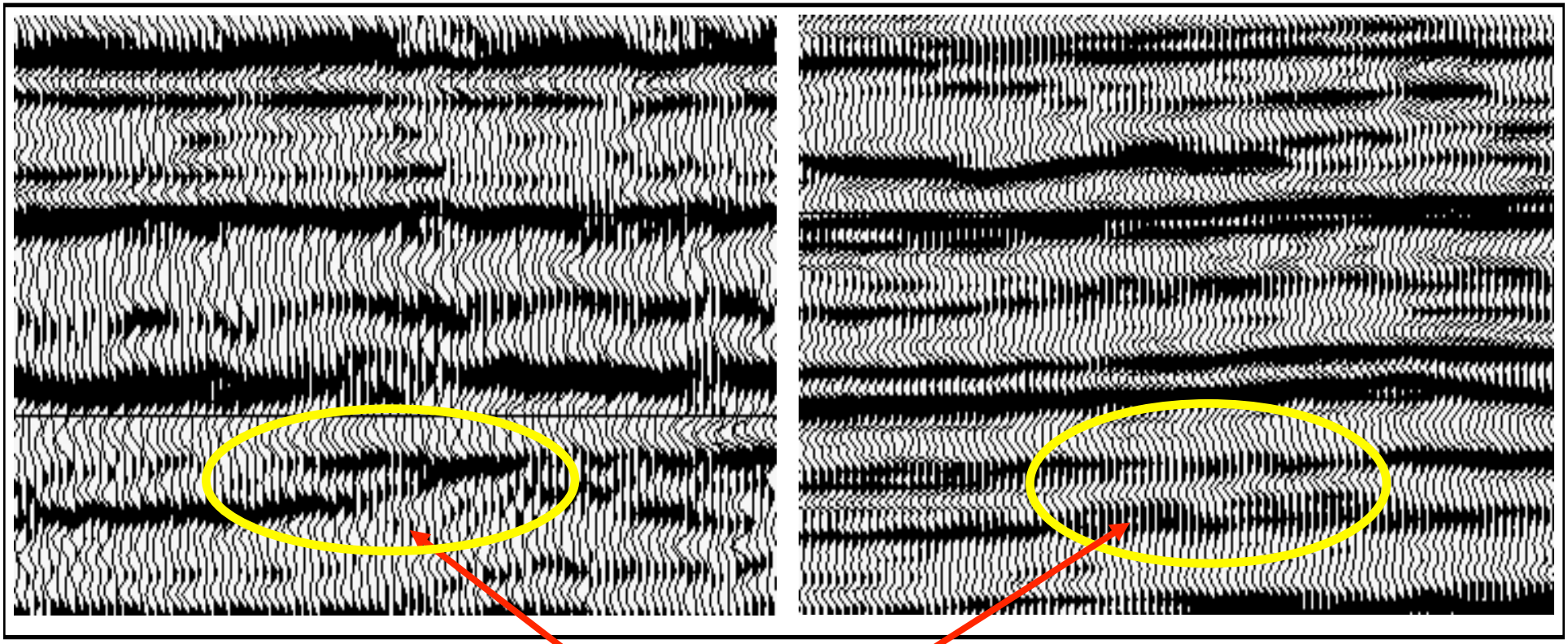


Arcola, Canada

Which one is better?

PS

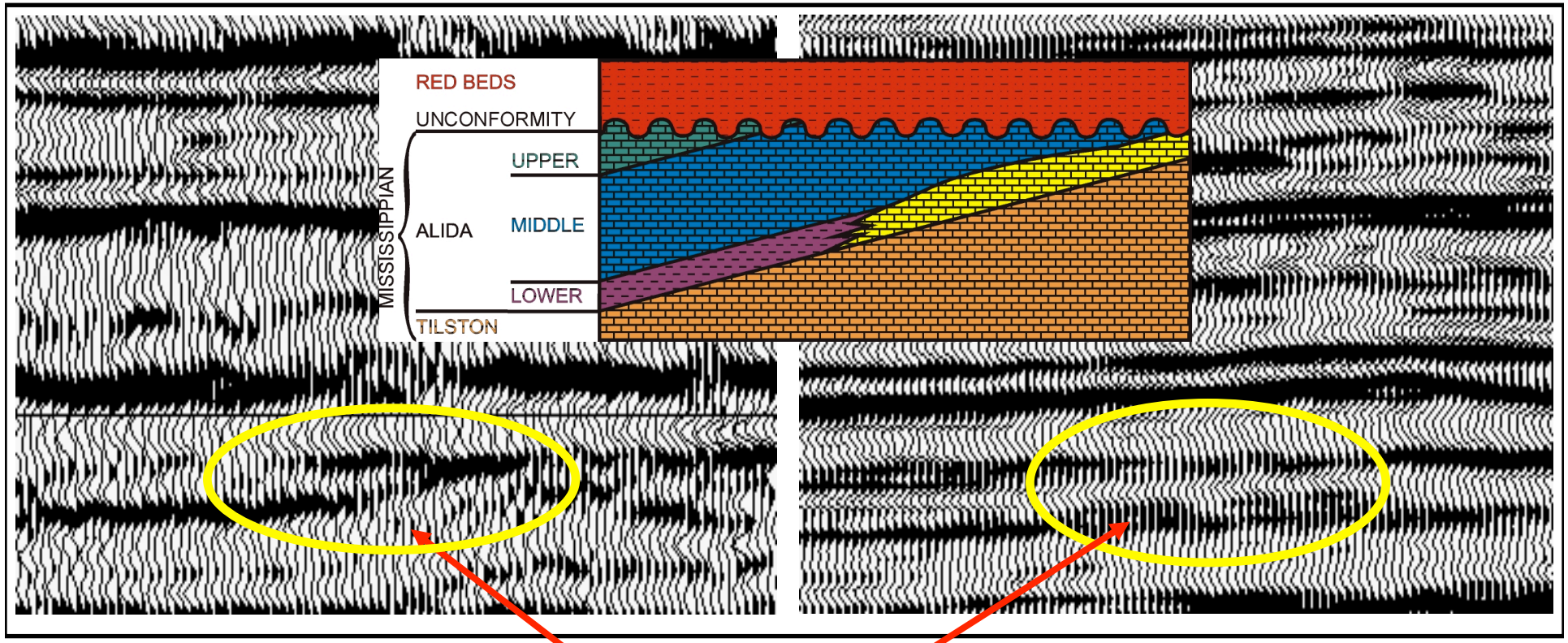
P



Arcola, Canada

Does PS add value to P alone?

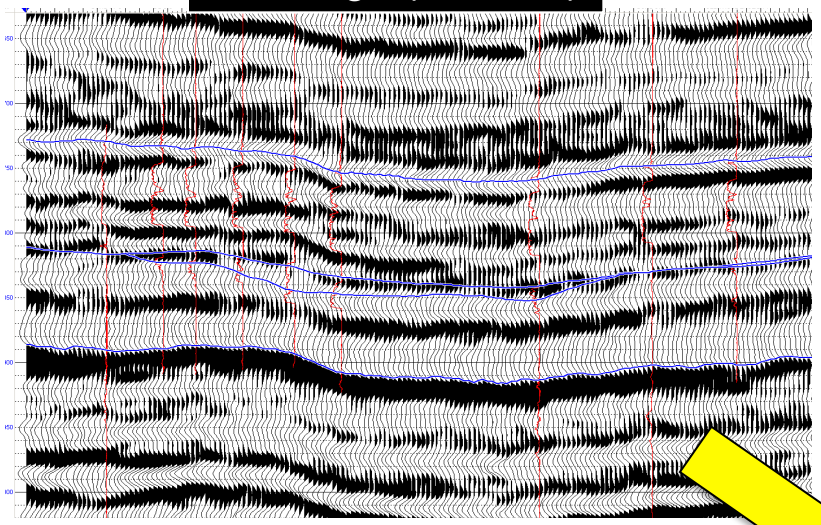
PS P



Arcola, Canada

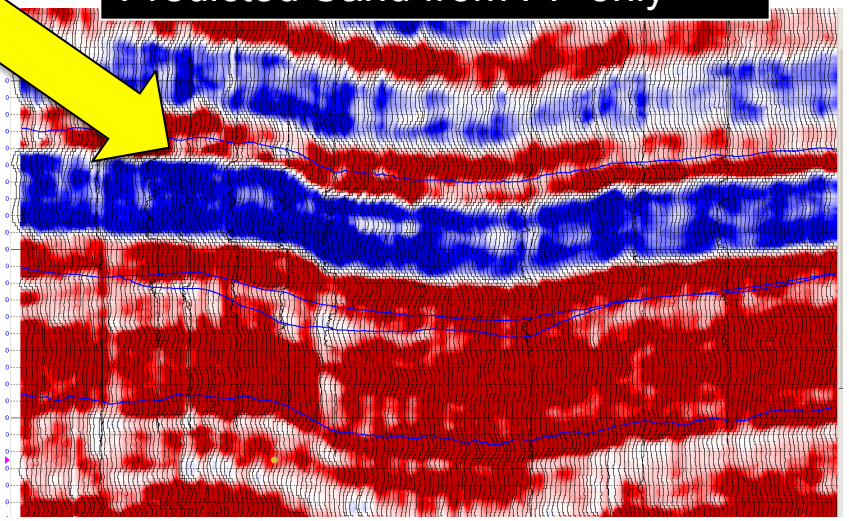
Harvest (Roche et al) onshore Texas

PP image (PP time)



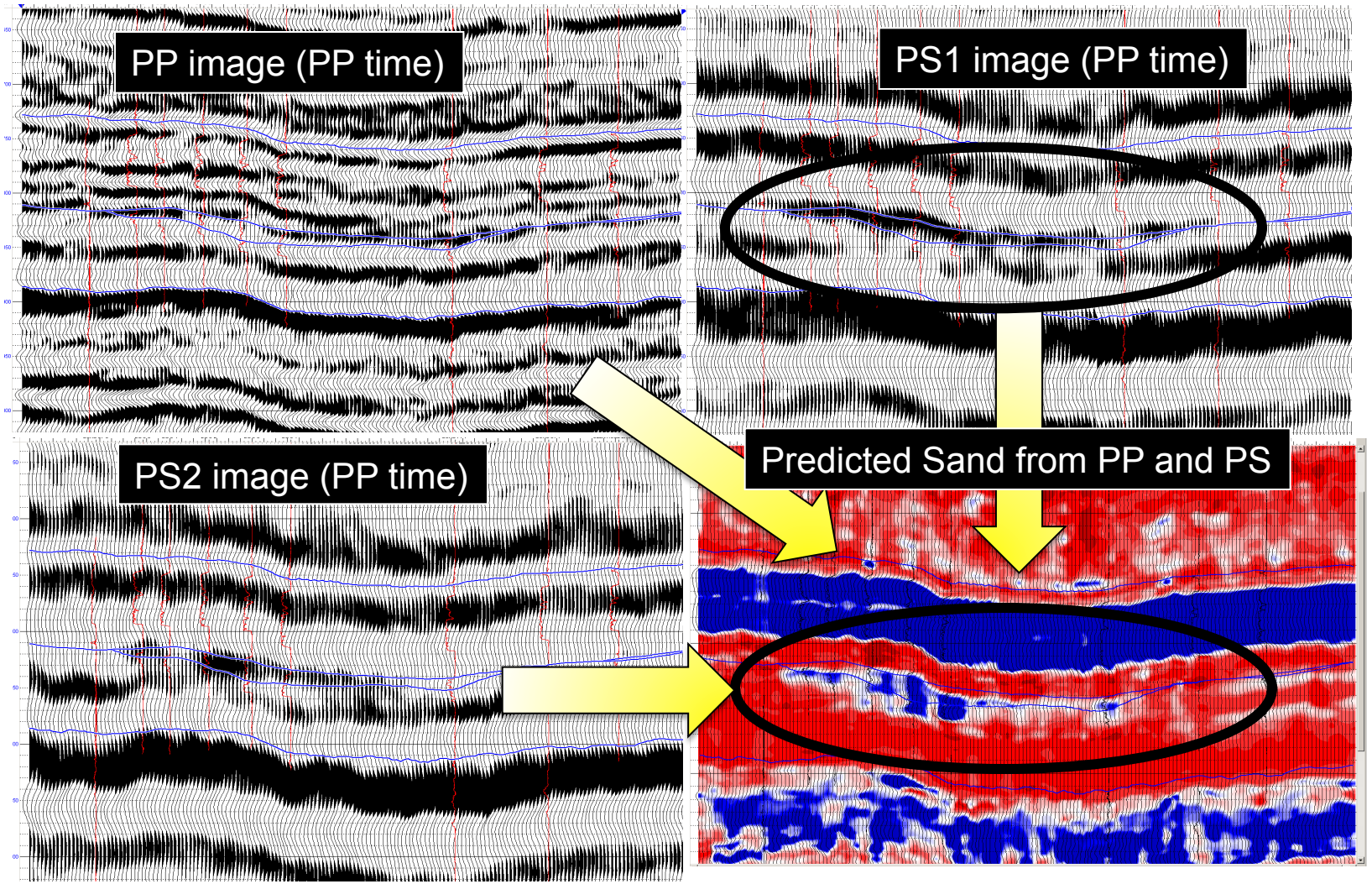
Seismic guided estimation of Sand from PP attributes including AVO and VSND logs (using Emerge™)

Predicted Sand from PP only



Harvest (Roche et al) onshore Texas

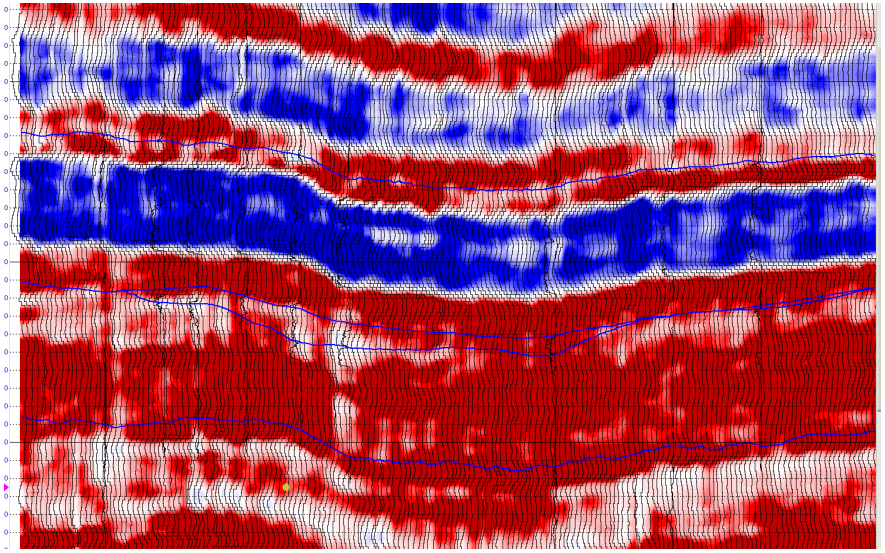
PS waves have Poor resolution but they add information and value



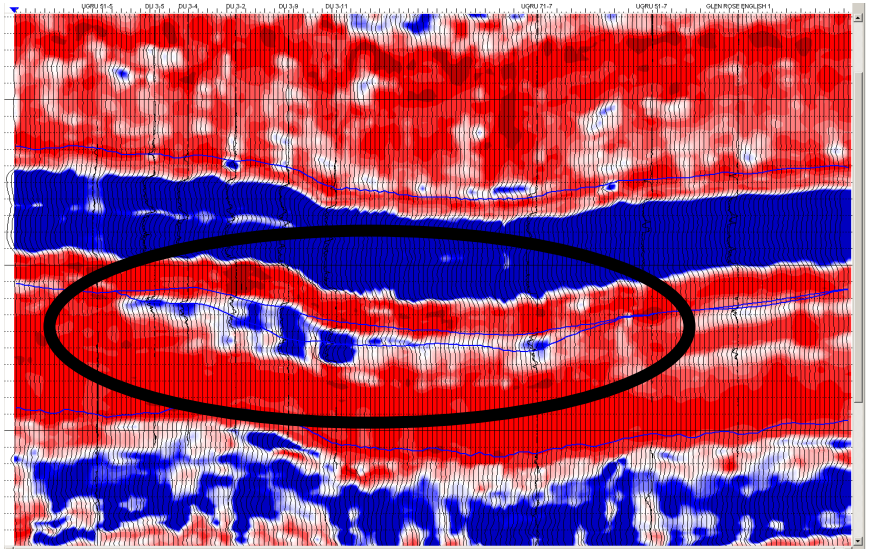
Harvest (Roche et al) onshore Texas

PS waves have Poor resolution but they add information and value

Predicted Sand from PP only



Predicted Sand from PP and PS



What can we do with the shear waves

- Acquisition
  - Some room for improved quality. Espeically reduce VZ noise. Perhaps rotation sensors
- Processing
  - Shear wave splitting, …
- Interpretation
  - Tools like joint inversion
- Management
  - Expectation management: reasonable but not zero
  - Project management: schedule!
  - Stop thinking either P or PS

The message is …

- The solid earth is visco-elastic
- It is also 3 dimensional and waves have multi components
  - 3 displacement + 1 pressure + 3 rotations … + …
- We were doing okay pretending that it is acoustic

The message is …

- We then (~1982) found that we could do *better if we allow AVO
  - – So we now let the earth be elastic
  - – Even if we keep recording only one component
  - * Better means we can reach higher hanging fruit
- The other components are additional information
  - – More equations. Same number of unknowns (as AVO)

The message is … (continued)

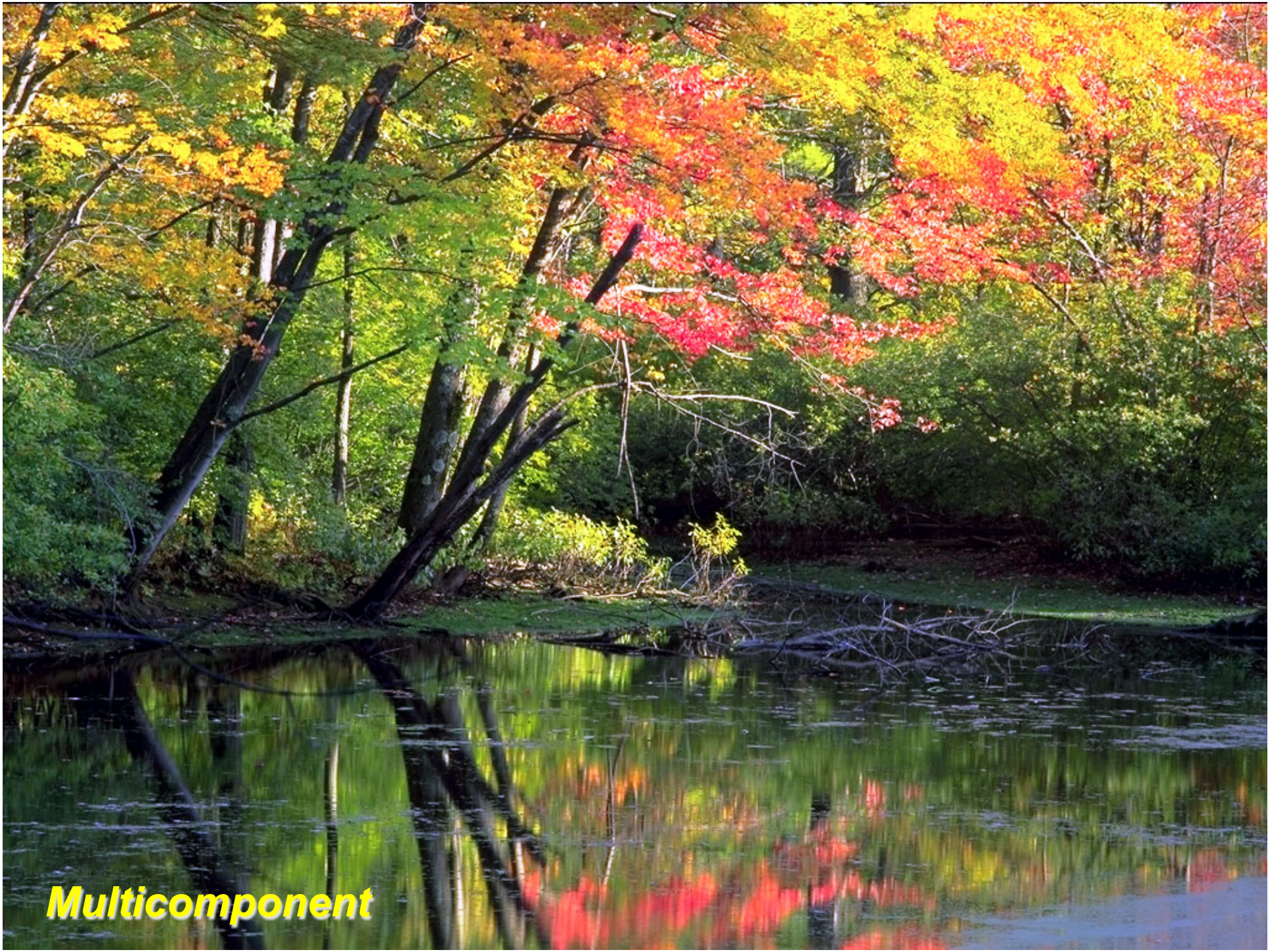
- We should not see shear waves as an alternative to P waves
- We should see them as an opportunity to add value
- Whenever we put receivers on solids (land, seabed) we record shear waves as well as P waves. Unless we have only hydrophones (not done since Foinaven).

The message is … (continued)

- All seabed systems record horizontal components. Some land systems too.
- It is up to us whether we use the additional data to build better visco-elastic earth models
- Better models that can explain our multi-component data using visco-elastic physics

If you had a color photograph

- Will you send it to a black and white printer?


Multicomponent


P-wave image

If you can record microwaves

- Will you trash them because optical light is higher resolution?

Multi-mode astronomy: Optical ~~*Vs*~~ *and* Microwave



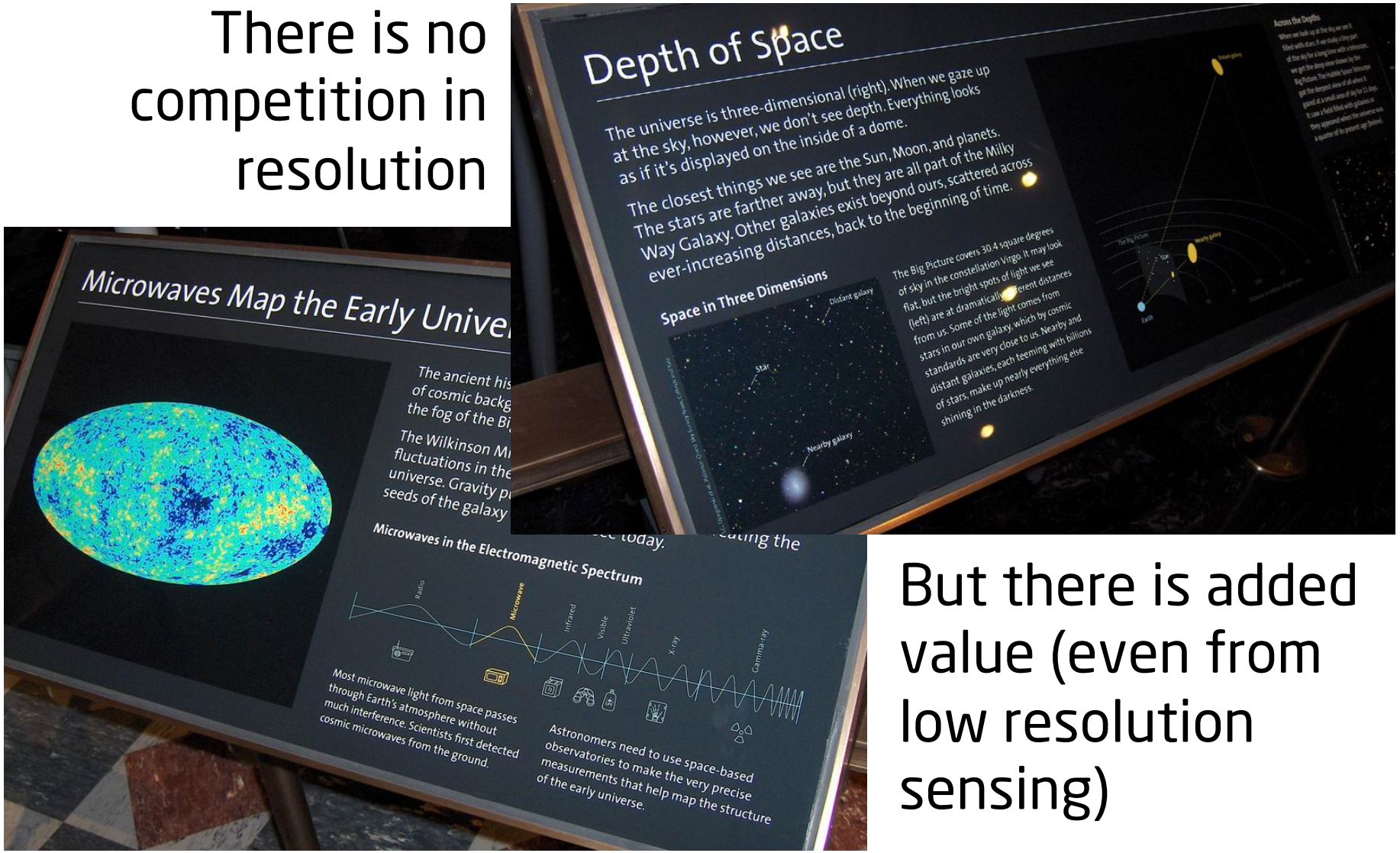


Penzias and Wilson, 1964

Cosmic Microwave Backgroud

Multi-mode astronomy: Optical *Vs* Microwave

There is no competition in resolution

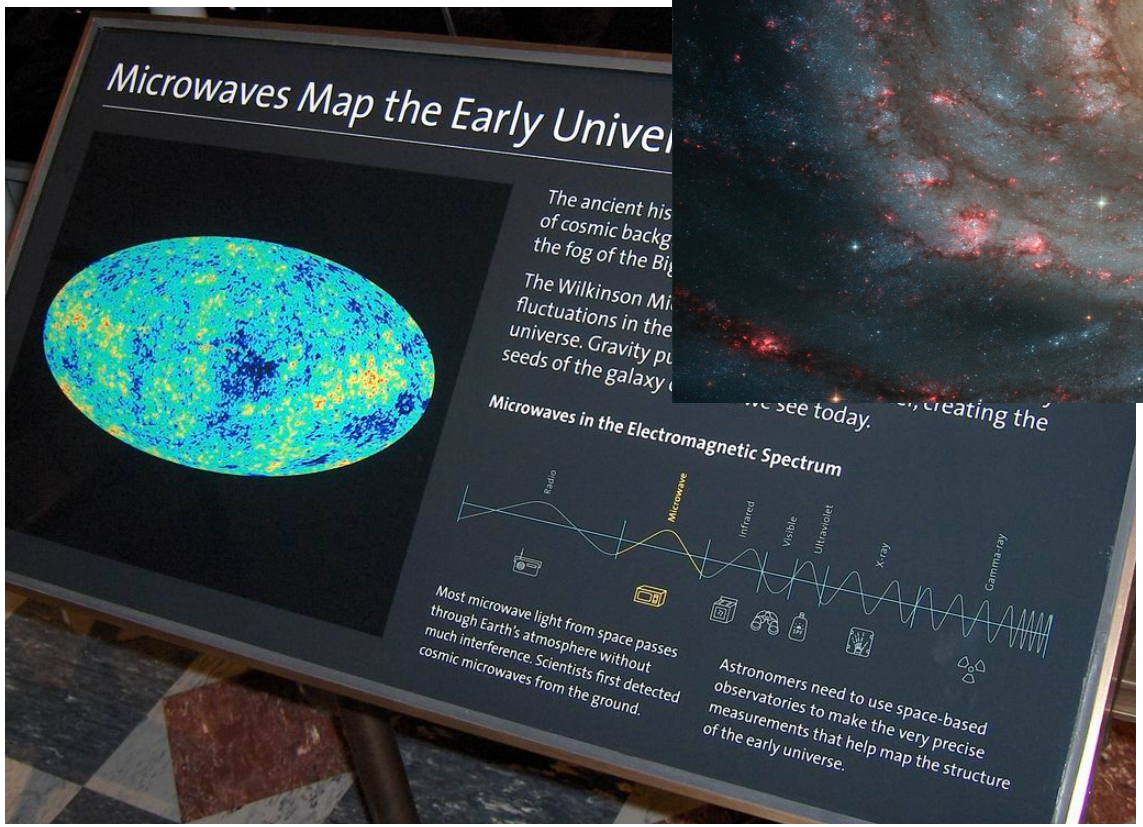


But there is added value (even from low resolution sensing)

Multi-mode astronomy: Optical ~~*Vs*~~ *and* Microwave

There is no competition in resolution





But there is added value (even from low resolution sensing)

The end