# From Incremental to Transformational Workflows: Contemporary Imaging and What Comes Next

*Presented by Ian Jones*

***NAPE UK/Europe Chapter's Technical Meeting, Chertsey***
***Thursday 29th March***

# Introduction

**Recent and ongoing research aims to push the limits of contemporary techniques, so as to sidestep the migration element, in order to directly deliver high resolution elastic parameter volumes, wherein the contributions of multiple reflections are exploited rather than suppressed.**

**We refer to these latter elements as being *transformational*, rather than *incremental*, workflows, involving ‘closed loop’, rather than ‘open loop’ solutions.**

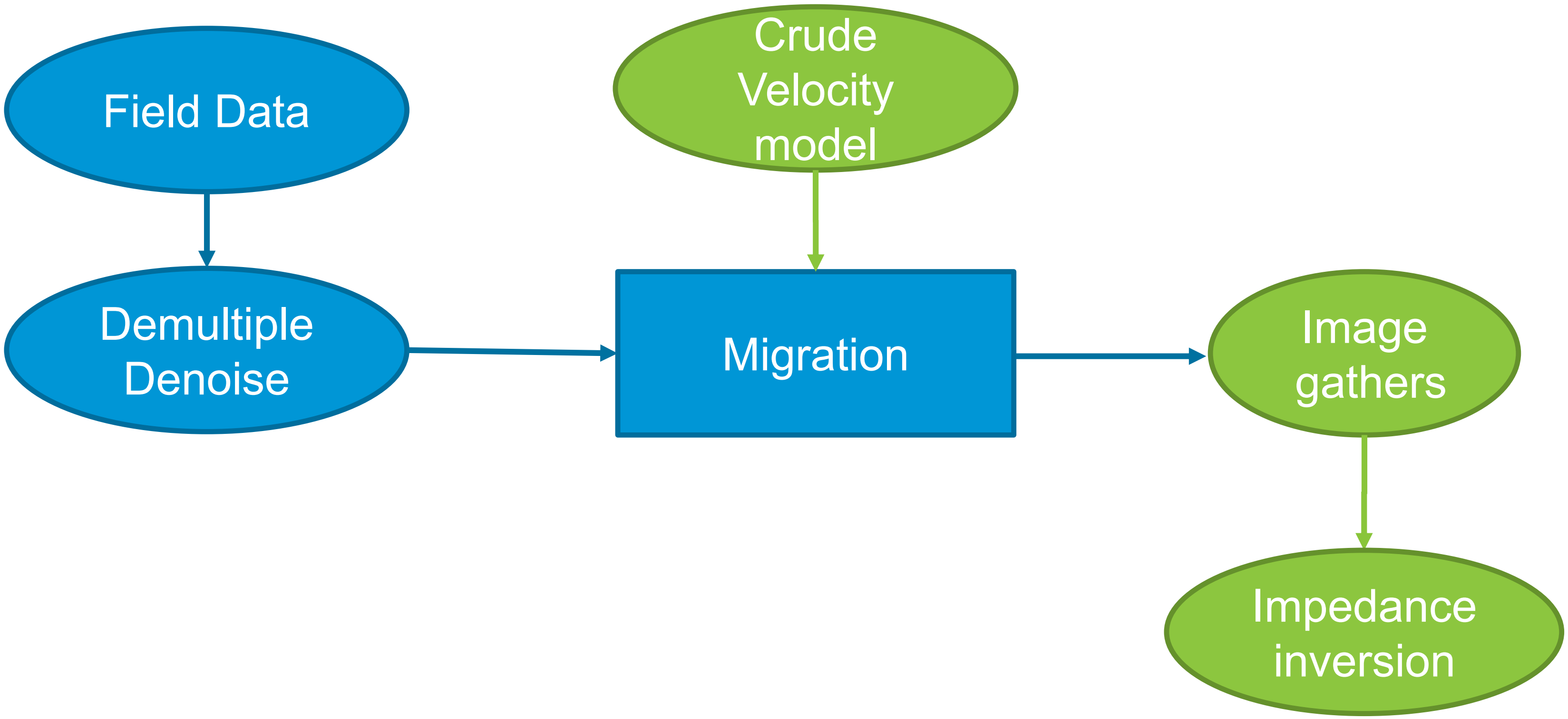
# Background

**Historically, seismic data processing workflows were purely linear….**

**Field data were ‘processed’, a velocity model was estimated from stacking velocity picking, using map migration to depth locate horizons, and migration was performed…..**

**These tasks happened just once.**

# Historical route

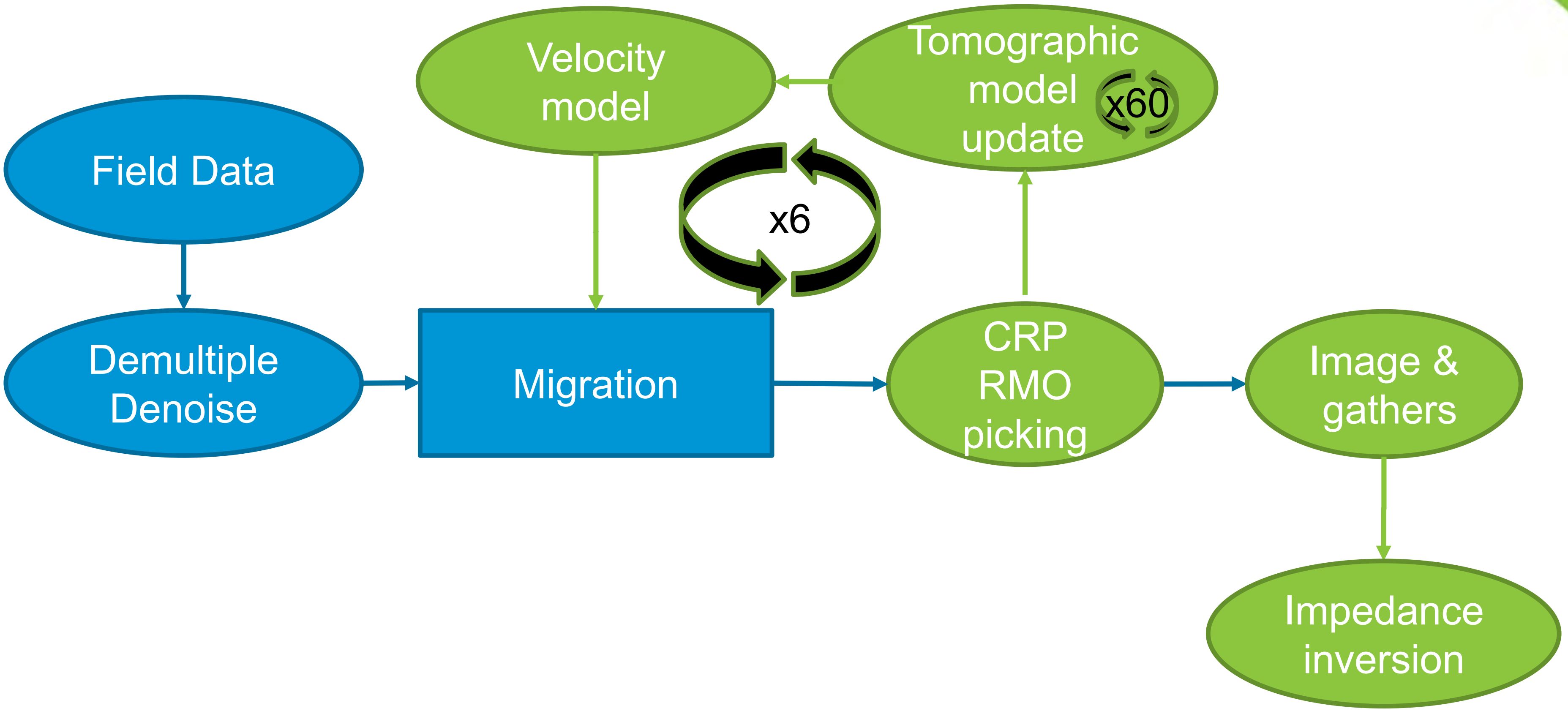


# Background

From about 1995 onwards, with the introduction of tomography, the model building element changed to become doubly iterative, in that repeated ray-trace modelling was utilized within an inversion scheme, so as to converge on a model that produced flat CRP gathers, after several iterations of migration.

However, this methodology does not ‘refer back’ to the raw input data.

# Tomographic model updates

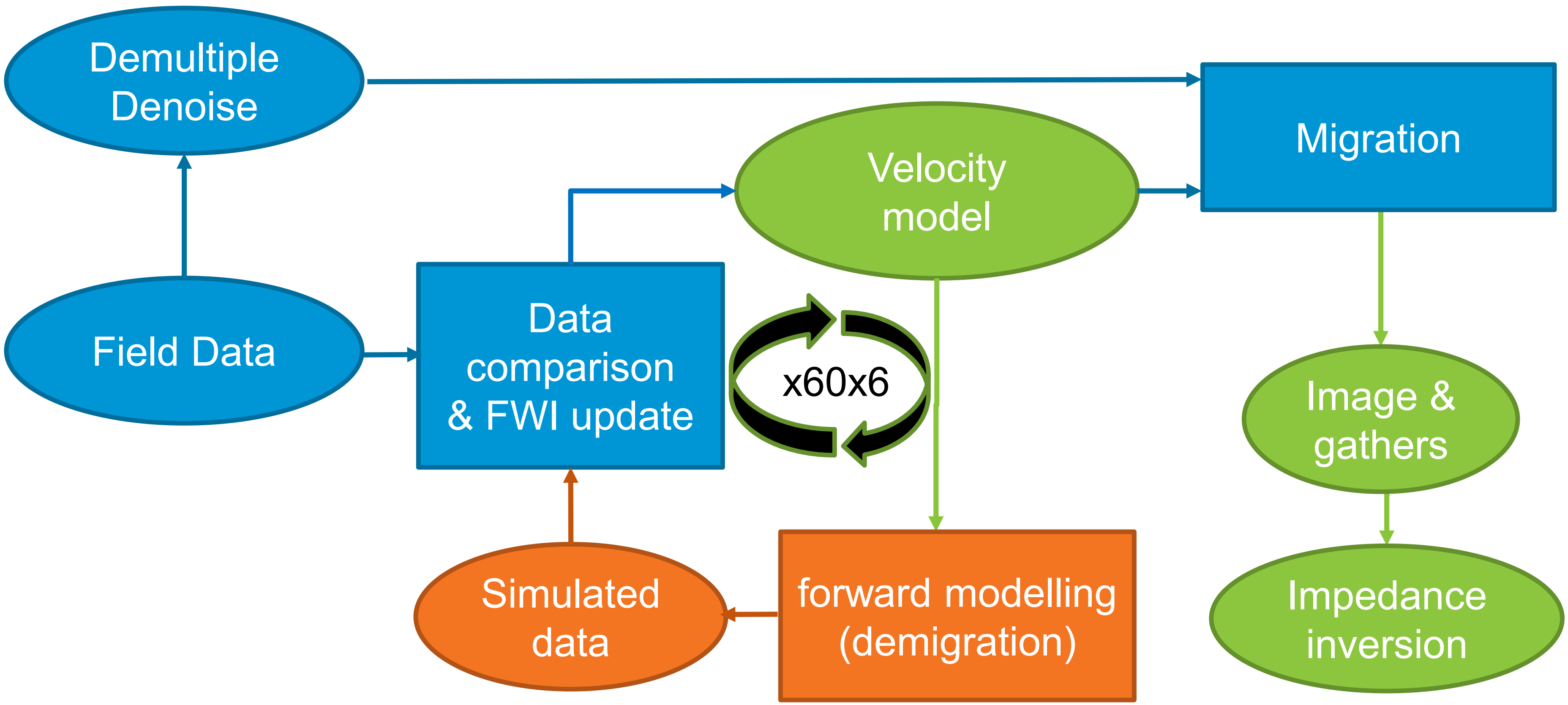


# Background

From about 2005 onwards, ‘full waveform inversion’ has been gradually introduced, modifying the tomographic solution so as to iteratively match forward modeled data with field data.

Hence, this methodology does ‘refer back’ to the raw input data, but as the inversion is performed in the ‘data domain’, and still has limiting assumptions, the resulting model is not guaranteed to produce ‘flat gathers’.

# Waveform inversion model for migration



# Background

In addition to the limitations just mentioned, none of these approaches attempted to compensate for the underlying ‘bad physics’ or ‘bad data’ that we were employing.

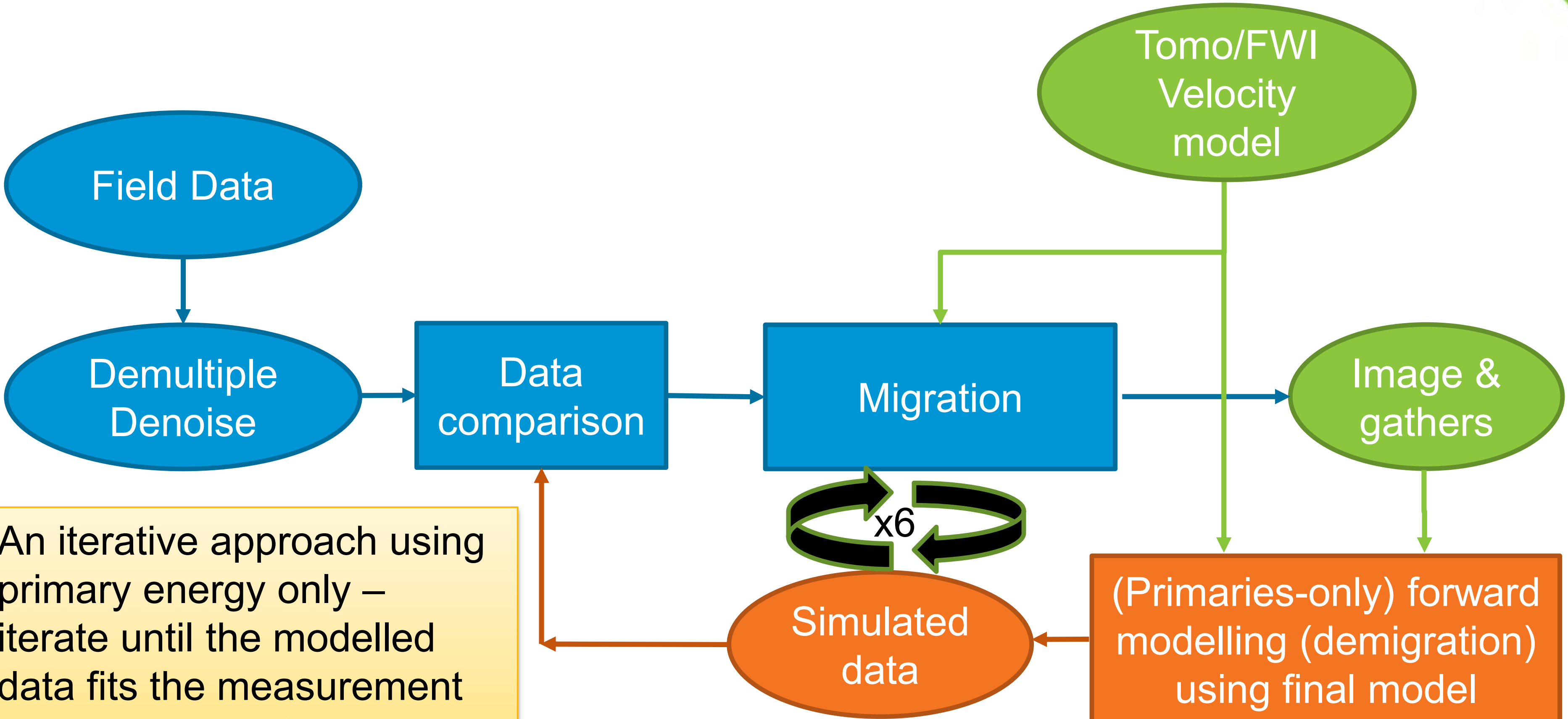
For example, using a one-way acoustic wave equation, and with field data that are poorly sampled.

# Background

Least-squares migration aims to compensate for some of these issues, in that another iterative inversion loop is introduced so as to form an image consistent with the input field data.

However, this does not simultaneously try to modify the subsurface model, and still assumes that data are multiple-free.

# (Primaries only) Least-Squares Migration using final (tomo or FWI) model




An iterative approach using primary energy only – iterate until the modelled data fits the measurement or you run out of money…

After Verschuur, 2015

# Background

**So what might come next?**

**A 'closed loop' solution, using a two-way elastic theoretical description, iteratively referring back to the field data, iteratively updating the model, and at each step iteratively constraining image gathers to be flat.**

**And ultimately, inversion for high frequency elastic Earth parameter models, having made use of the full wavefield (including multiples and elastic mode conversion effects).**

## Let’s recap the current situation…

## the ‘state of the art’

# Contemporary methodology …..

## In seismic data processing we aim to:

- Separate ‘signal’ from ‘noise’
- Build an anisotropic velocity model
- Migrate the data, producing ‘true amplitude’ angle classes
- Estimate elastic parameters via impedance inversion

# Contemporary methodology …..

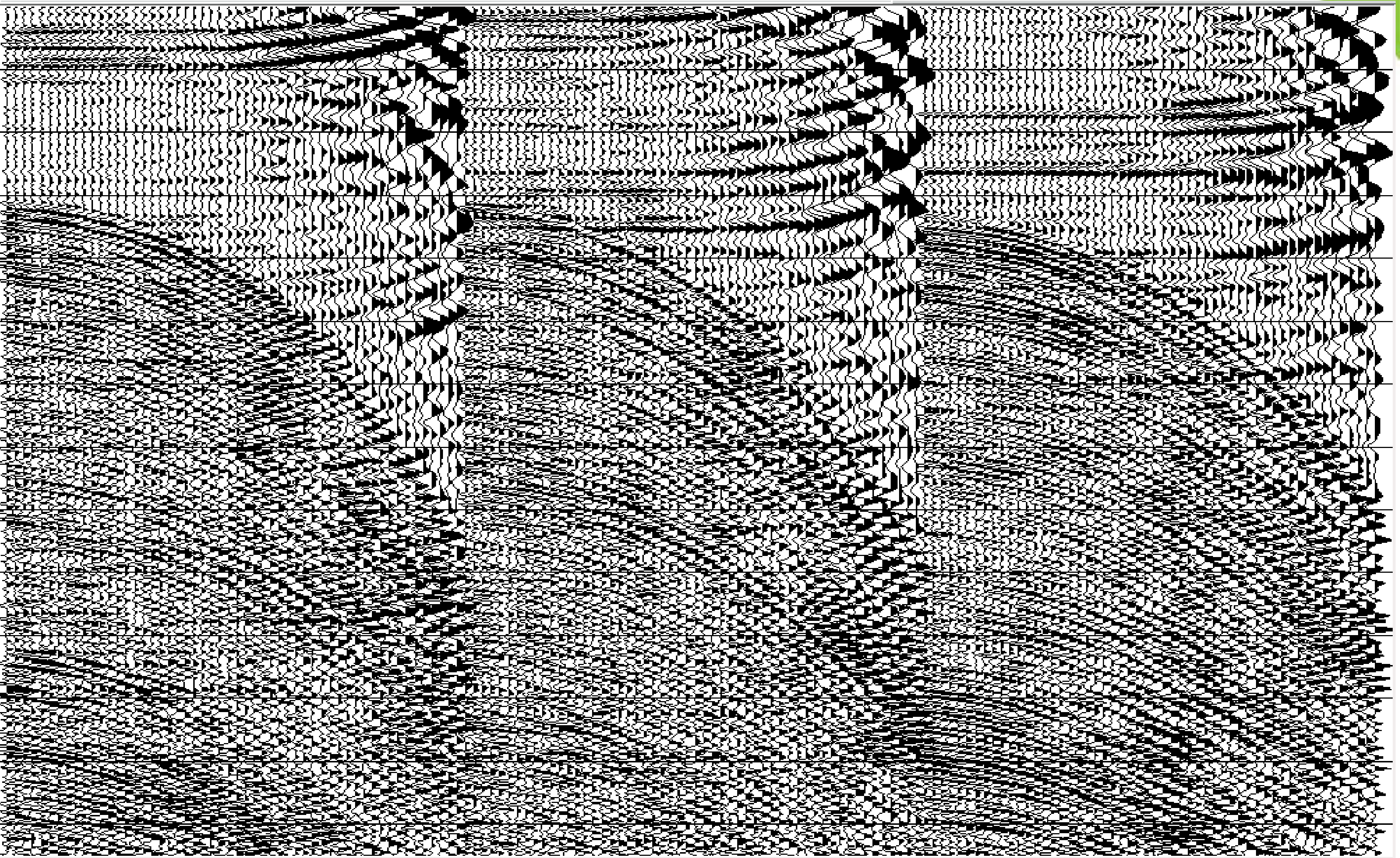
## In seismic data processing we aim to:

- Separate ‘signal’ from ‘noise’

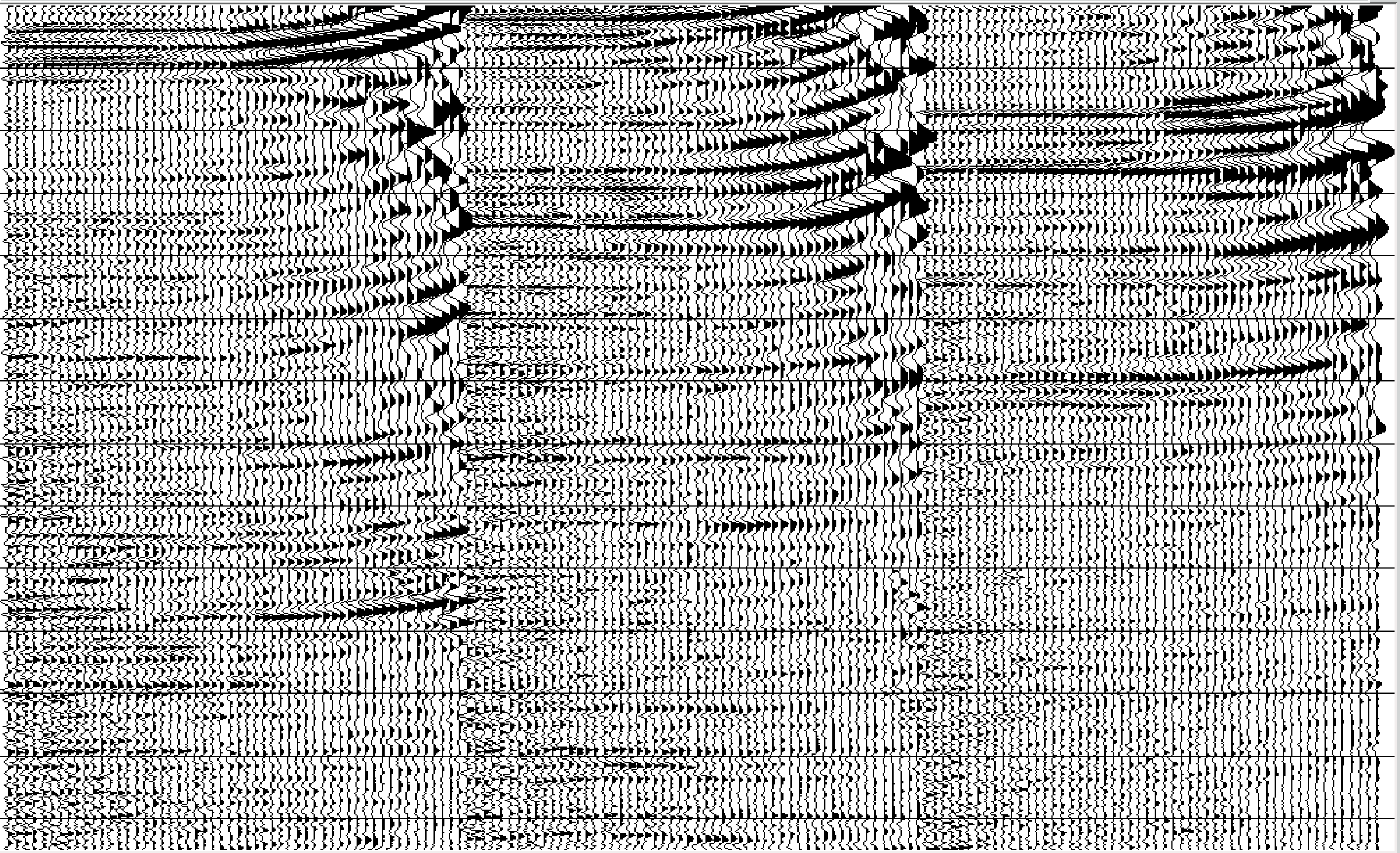
By ‘noise’, we mean anything that does not meet the assumptions of our (visco) acoustic migration theory, such as:

- Multiples
- Energy scattered from small heterogeneities
- Mode converted (shear) energy
- Plus ‘real’ noise from swell, cable tug, birds & buoys, etc

# Deep water CMP gathers without  Radon



# Deep water CMP gathers with **“BeamRadon”** (no interpolation)



# Contemporary methodology …..

## In seismic data processing we aim to:

- Separate ‘signal’ from ‘noise’
- Build an anisotropic velocity model

We are modest in what parameters we try to estimate tomographically, at best obtaining a smooth anisotropic velocity field suitable for migration, with features with lateral scales > ~500m.

# Contemporary methodology …..

## In seismic data processing we aim to:

- Separate ‘signal’ from ‘noise’
- Build an anisotropic velocity model

We are modest in what parameters we try to estimate tomographically, at best obtaining a smooth anisotropic velocity field suitable for migration, with features with lateral scales > ~500m.

Many excellent results have been obtained with ray methods, and developments (such as well and structural constraints) continue to improve them.

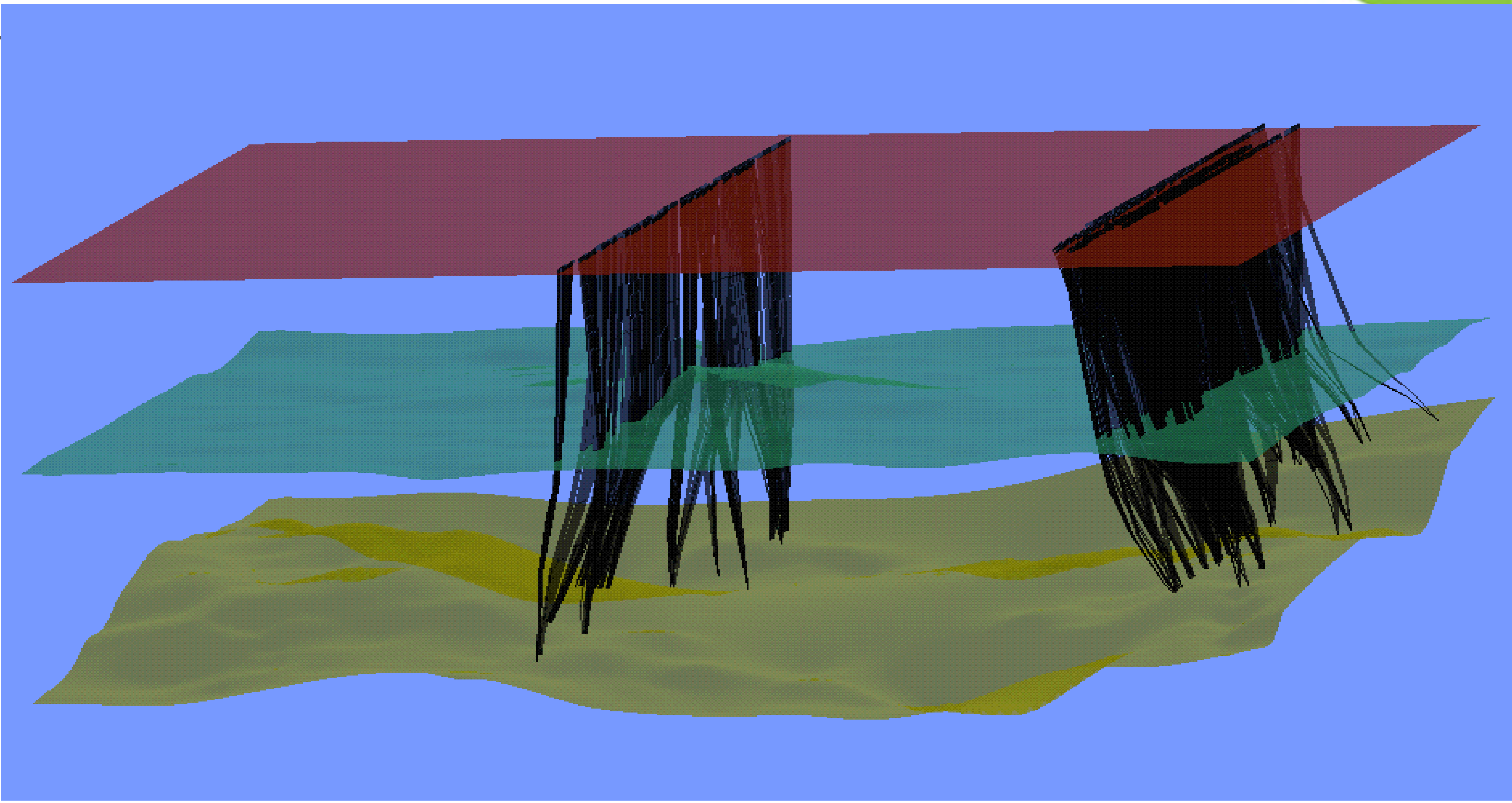
# Third time lucky?
# Imaging the Dentale formation offshore Gabon


Anton Pavlov[1], Juergen Fruehn[1], Mick Sugrue[1], Beth Cox[2] & John Price[3]

*1: ION Geophysical; 2: Monarch Geophysical; 3: Harvest Natural Resources*

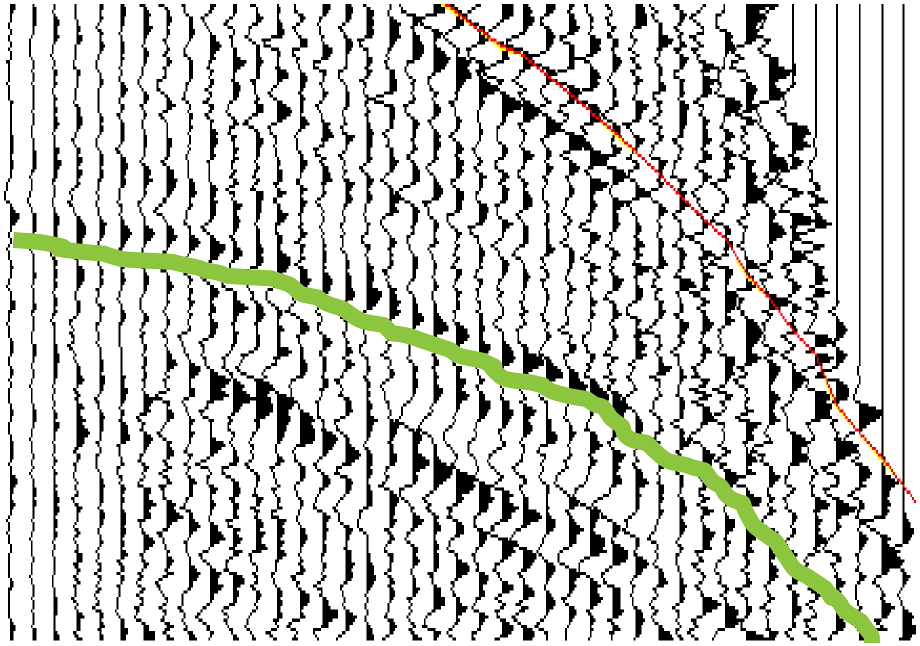

EAGE 2016

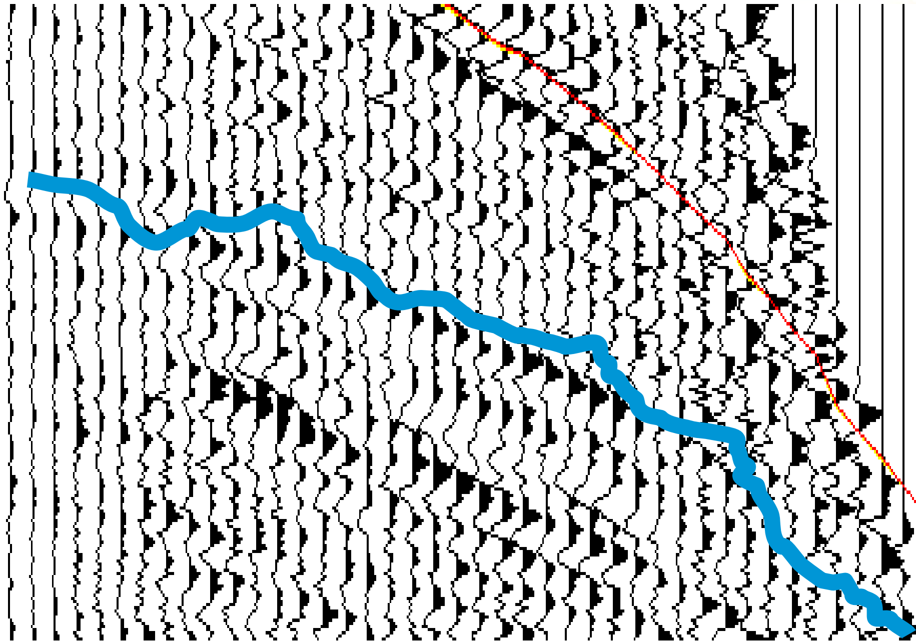
# Tomographic velocity update…..



Trace raypaths through the current version of the model and note arrival times

# Tomographic velocity update…..





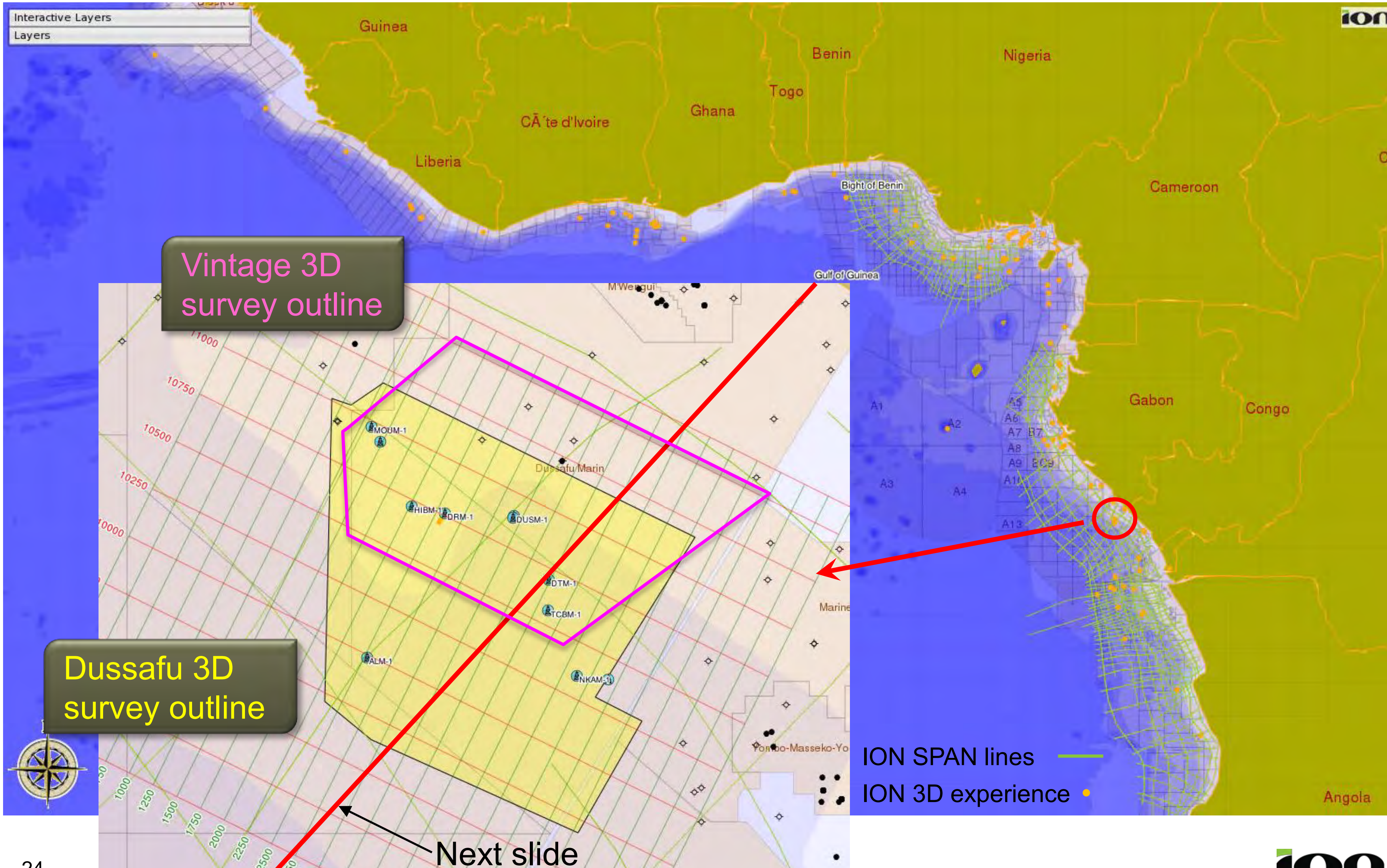
Picks of reflection event arrival times from the real data

arrival times synthesized from ray tracing through the current velocity model

# Tomographic velocity update…..

Limited by the ray-theory 'scattering limit' to a resolution of perhaps 5x the available sound-wavelength

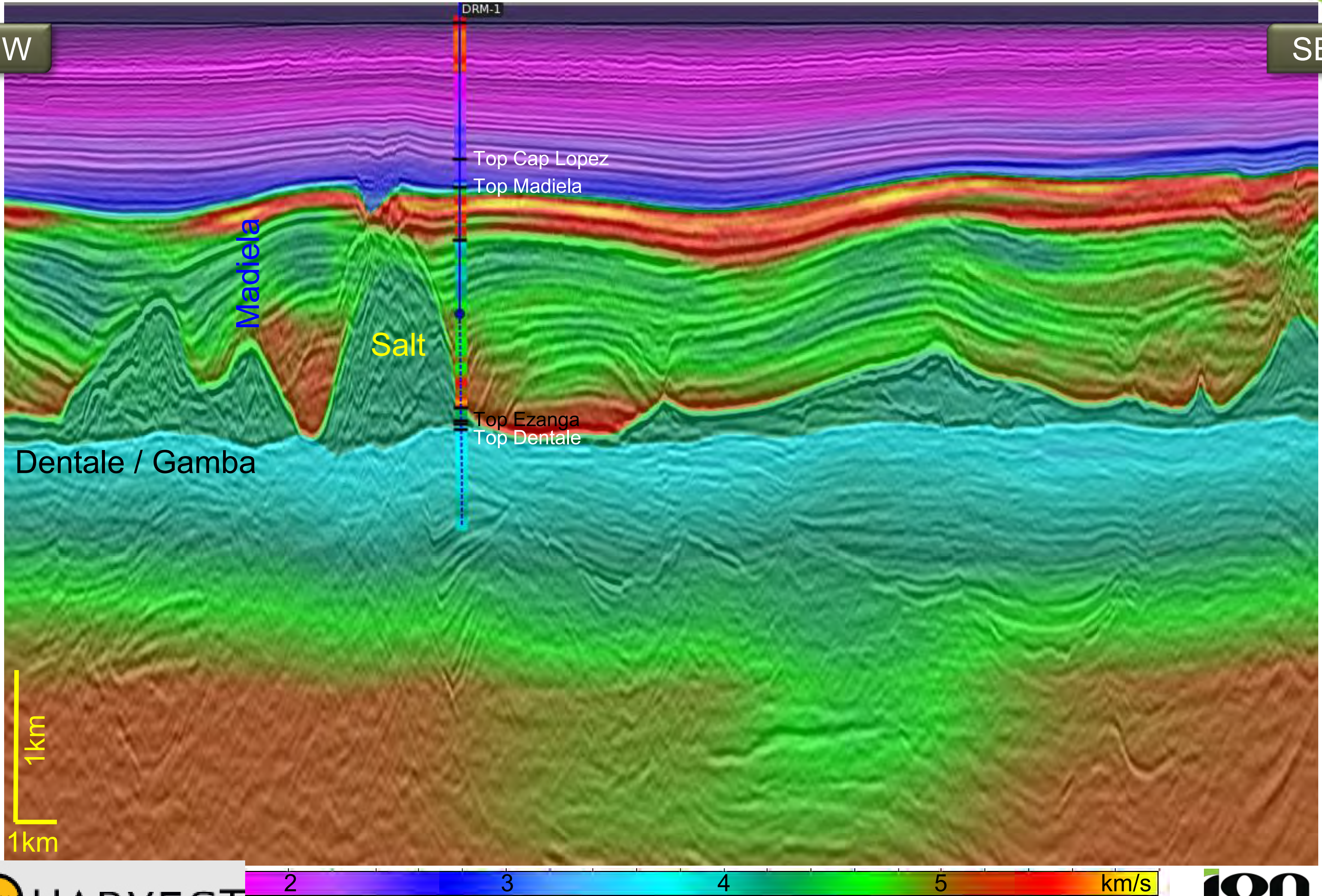
# Survey location map



# Final model – strike line



showing main lithological units and good reflection continuity at Dentale / Gamba level

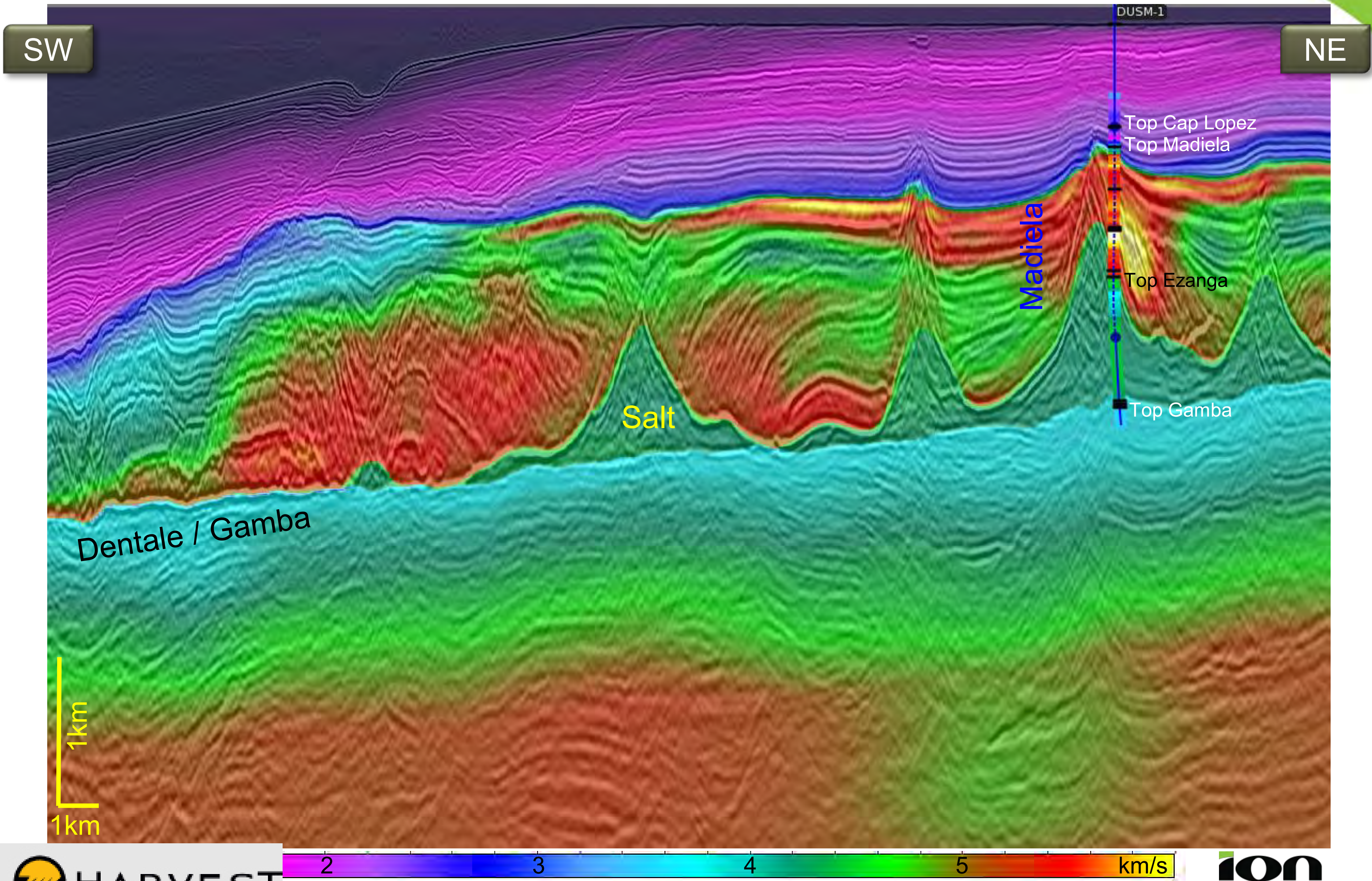



HARVEST

ion

# Final model – dip line

showing main lithological units and good reflection continuity at Dentale / Gamba level



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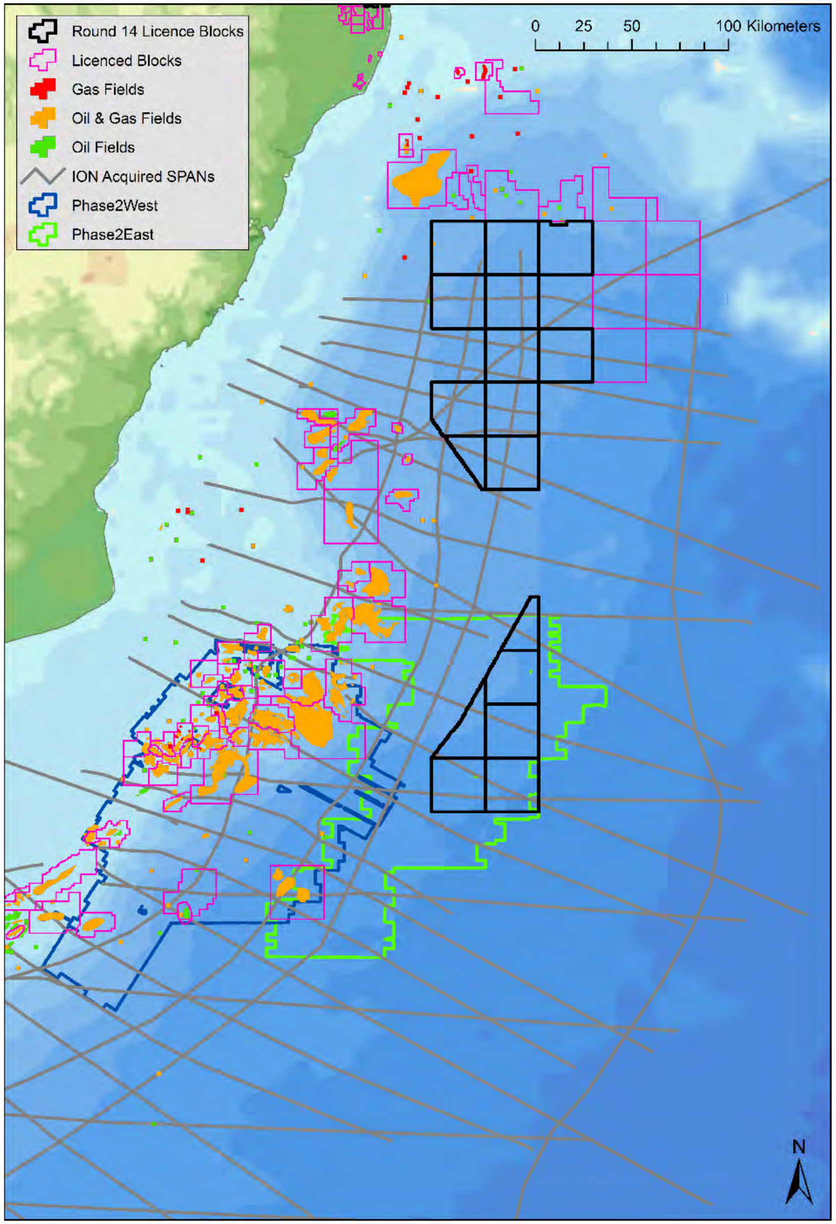
# Accelerated workflows using hi-res tomo and RTM

## A case study from the Campos Basin, Brazil: Picanha

# Introduction




Scenario

- Brasil 14th Licence Round
- Short time frame to evaluate blocks (2-3 months)

Challenge

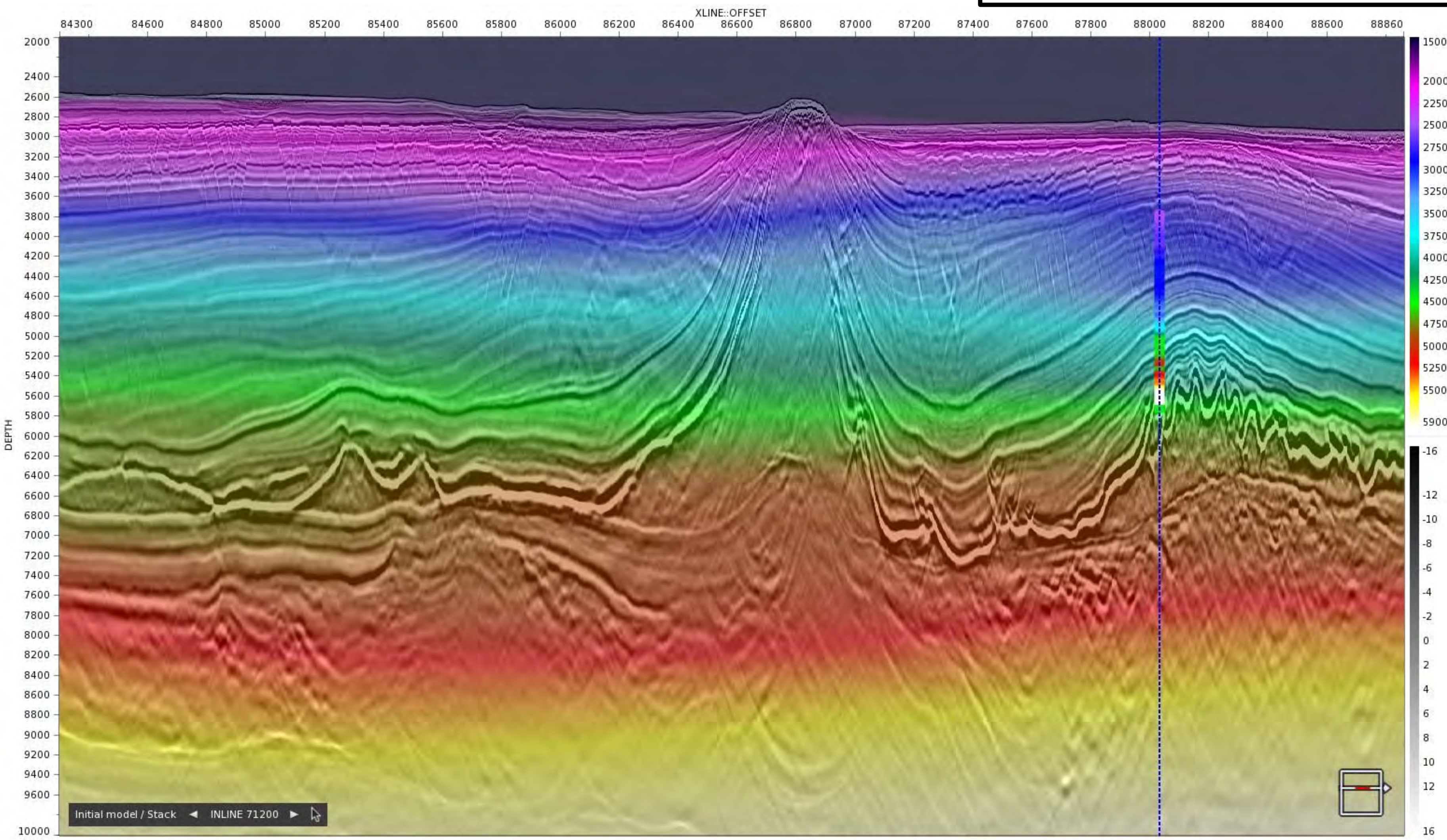
- To provide a time and cost efficient alternative to new 3D seismic acquisition

Solution

- ION Accelerated Imaging
  – Reprocessing of individual surveys into a single fully integrated 3D seismic dataset within a short timeframe

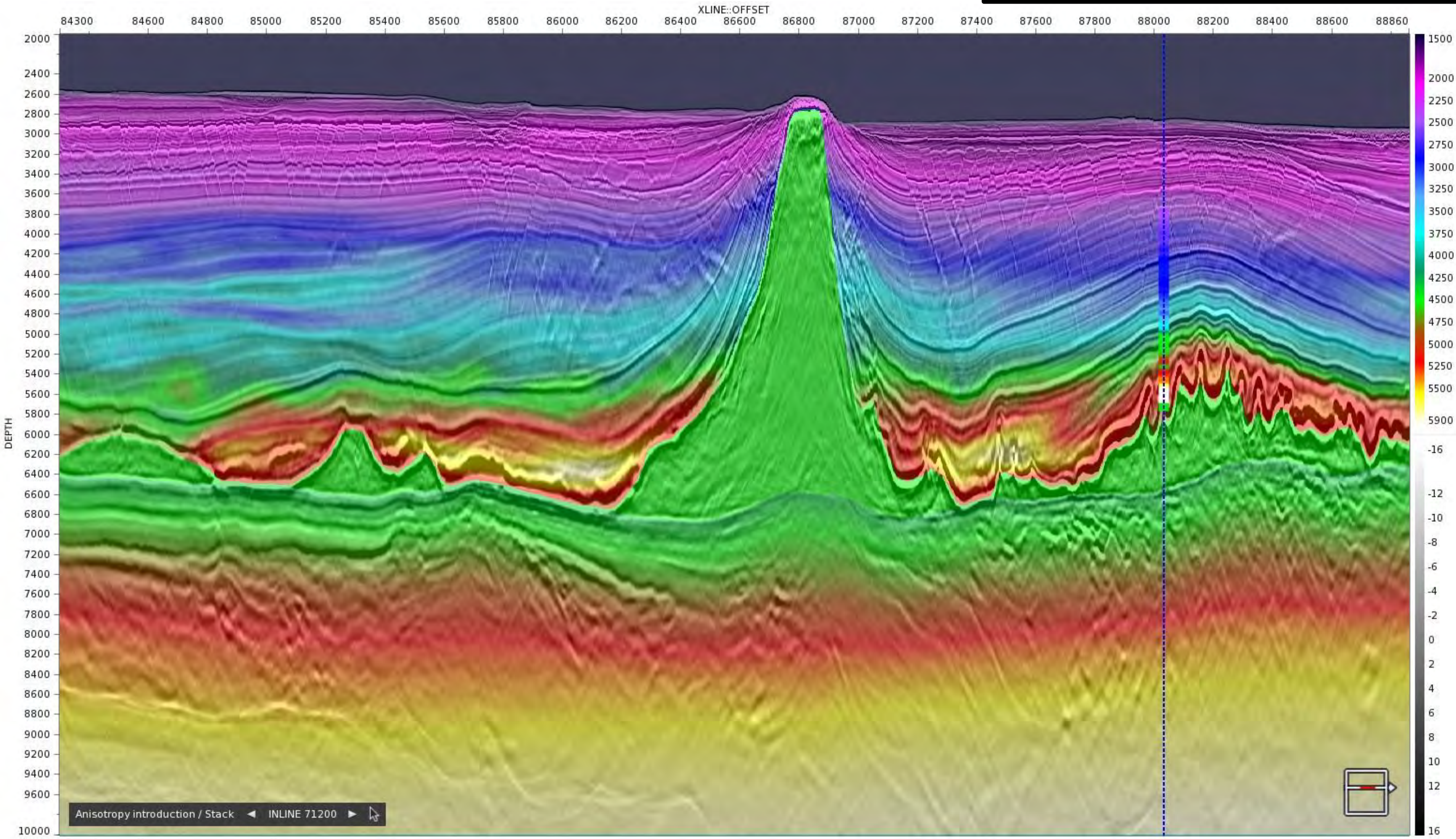
# Monday 3rd Apr
## Initial model

April 3 | April 4 | April 5 | April 6 | April 7



# Friday 7th Apr
## Pre-Salt Gradient and Anisotropy

| April | April | April | April | April |
|---|---|---|---|---|
| 3 | 4 | 5 | 6 | 7 |



# Contemporary methodology …..

## In seismic data processing we aim to:

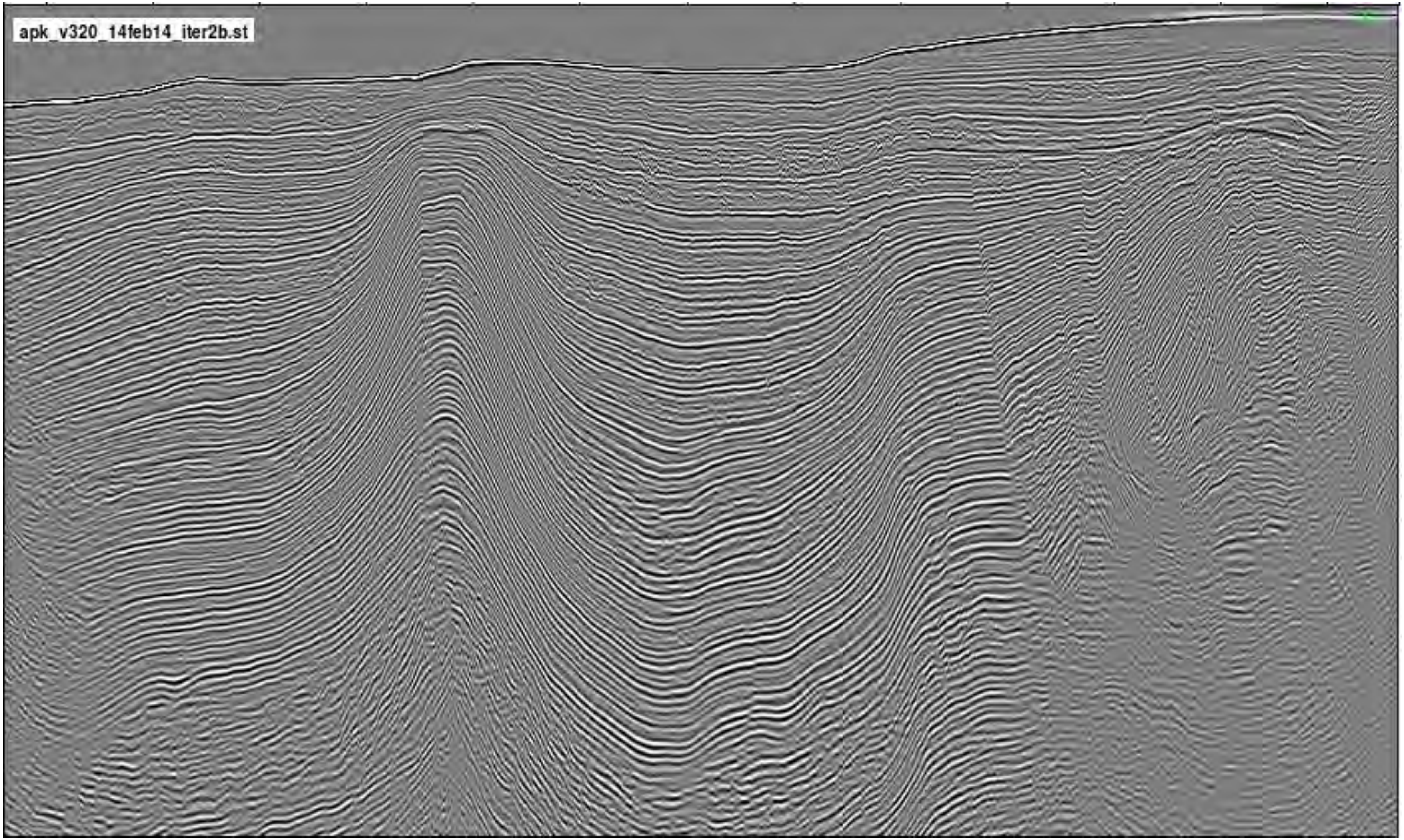
- Separate ‘signal’ from ‘noise’
- Build an anisotropic velocity model

We are modest in what parameters we try to estimate tomographically, at best obtaining a smooth anisotropic velocity field suitable for migration, with features with lateral scales > ~500m,

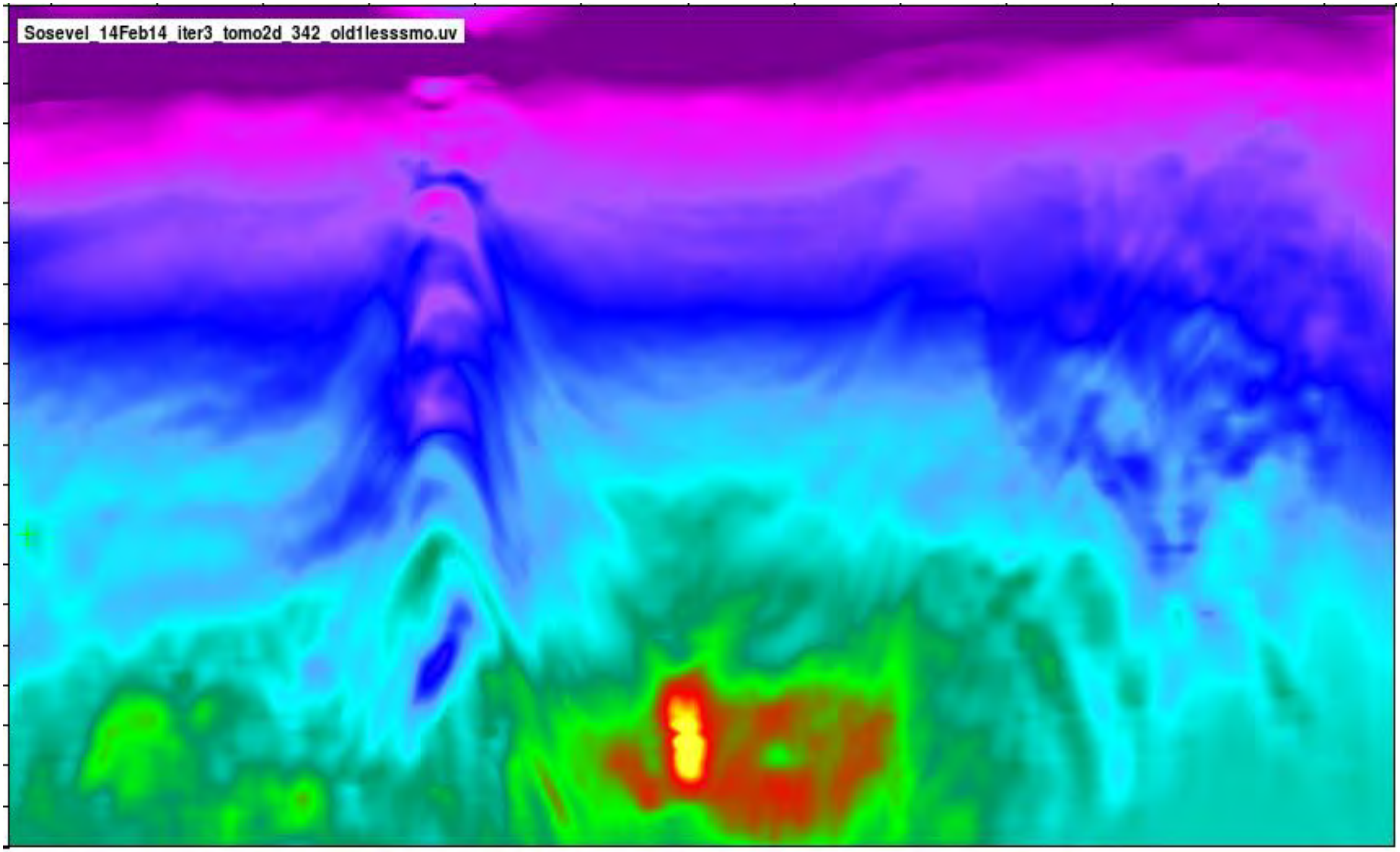
Adding interpretational constraints such as structural constraints in the tomography, picked horizons, and wells

And our anisotropic characterization is approximate (TTI or orthorhombic)

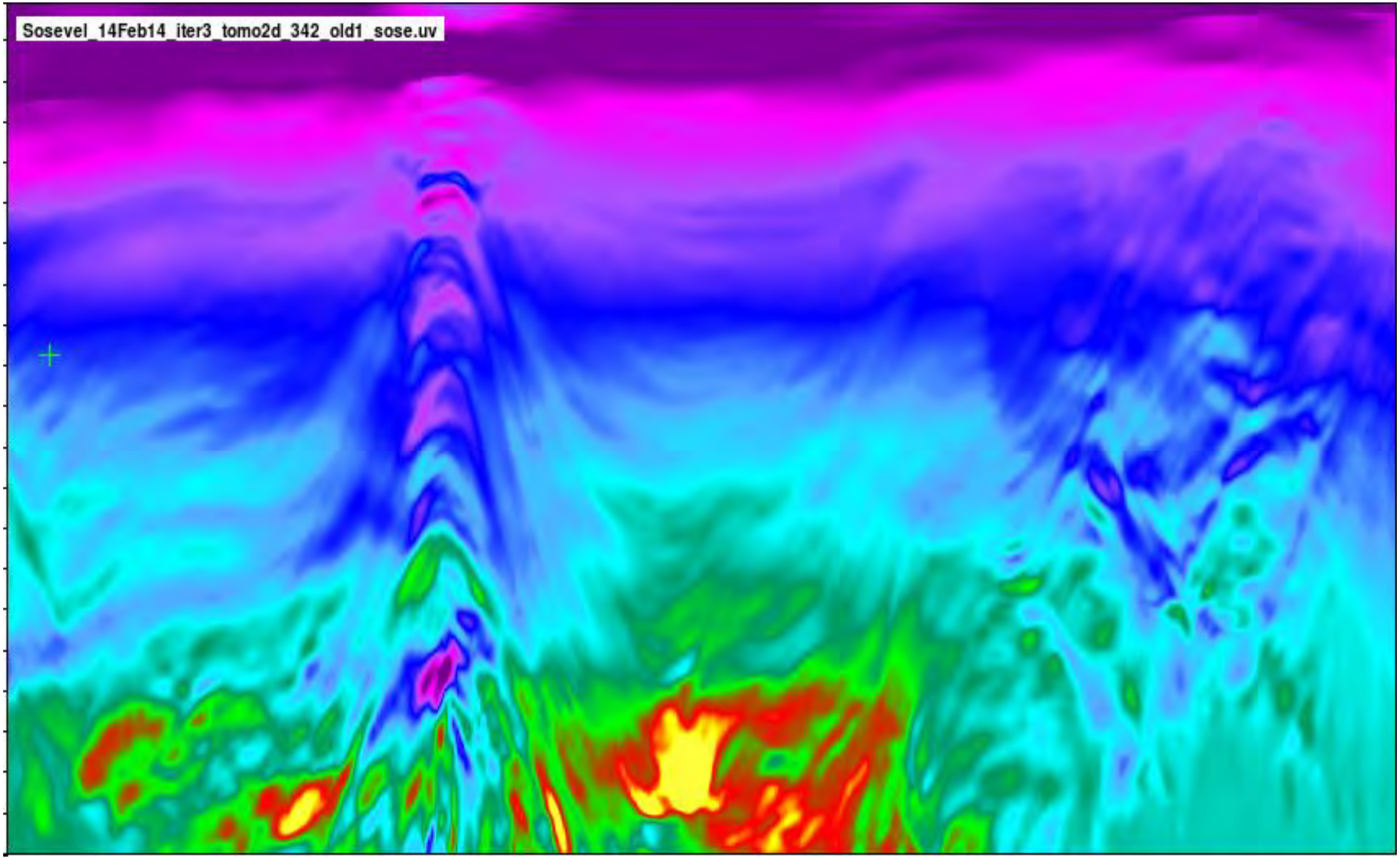
# Seismic image used to guide smoothing



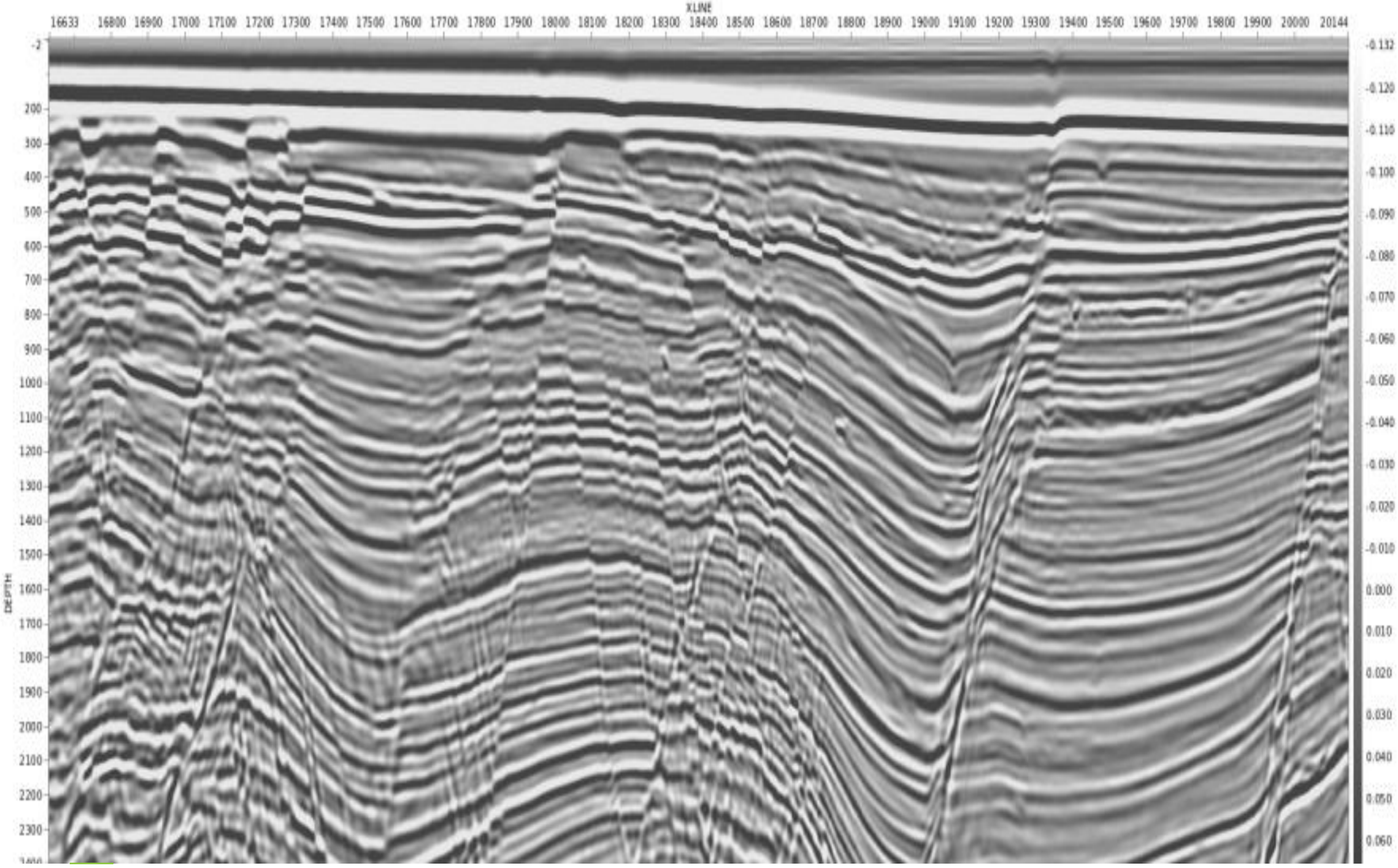
# BPAIT TTI sediment structural tomo constraints (no explicit fault handling)



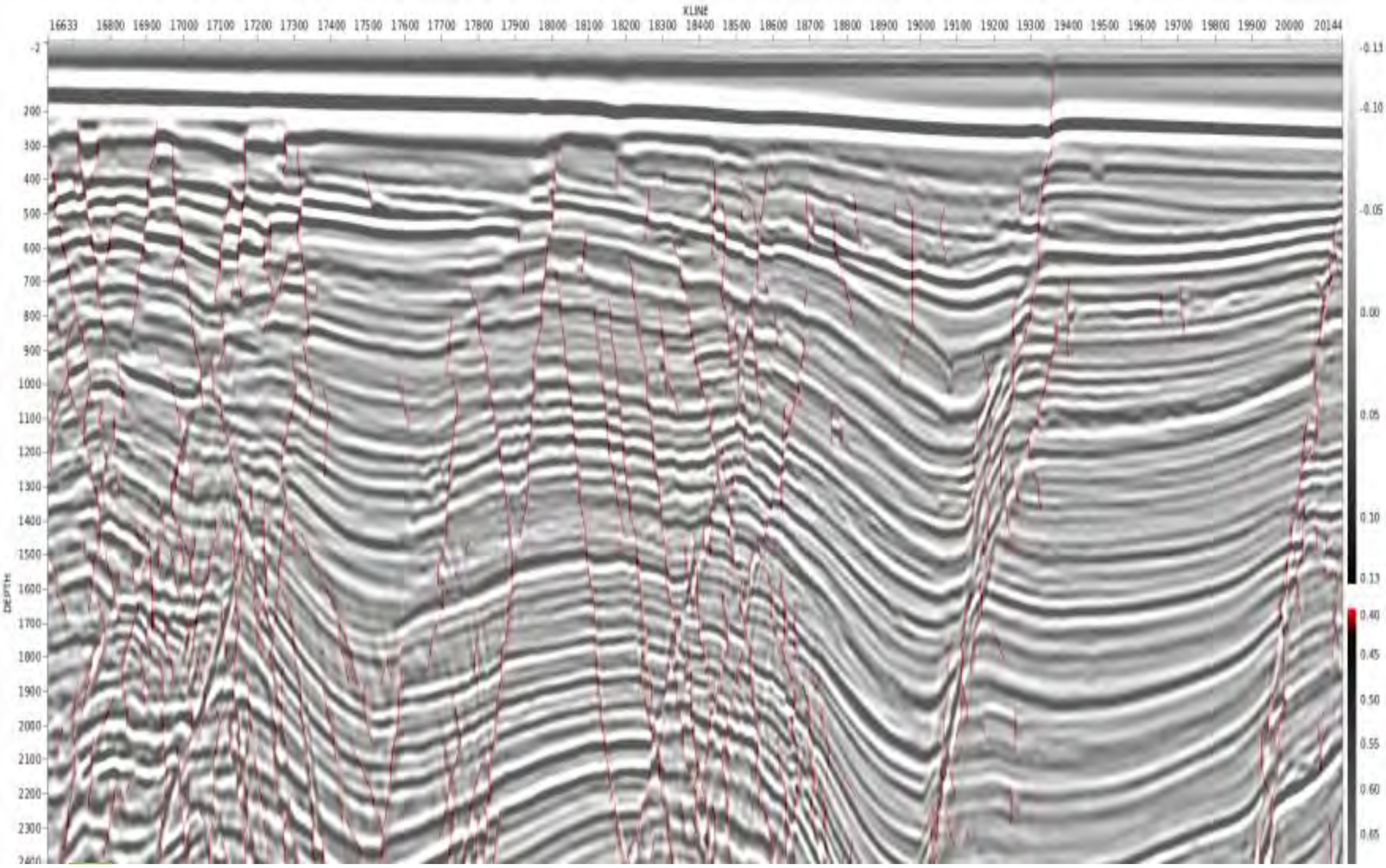
# Tomo result with implicit fault awareness



# RTM stack


XLINE
16633 16800 16900 17000 17100 17200 17300 17400 17500 17600 17700 17800 17900 18000 18100 18200 18300 18400 18500 18600 18700 18800 18900 19000 19100 19200 19300 19400 19500 19600 19700 19800 19900 20000 20144
DEPTH
-2 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300
-0.132 -0.120 -0.110 -0.100 -0.090 -0.080 -0.070 -0.060 -0.050 -0.040 -0.030 -0.020 -0.010 0.000 0.010 0.020 0.030 0.040 0.050 0.060

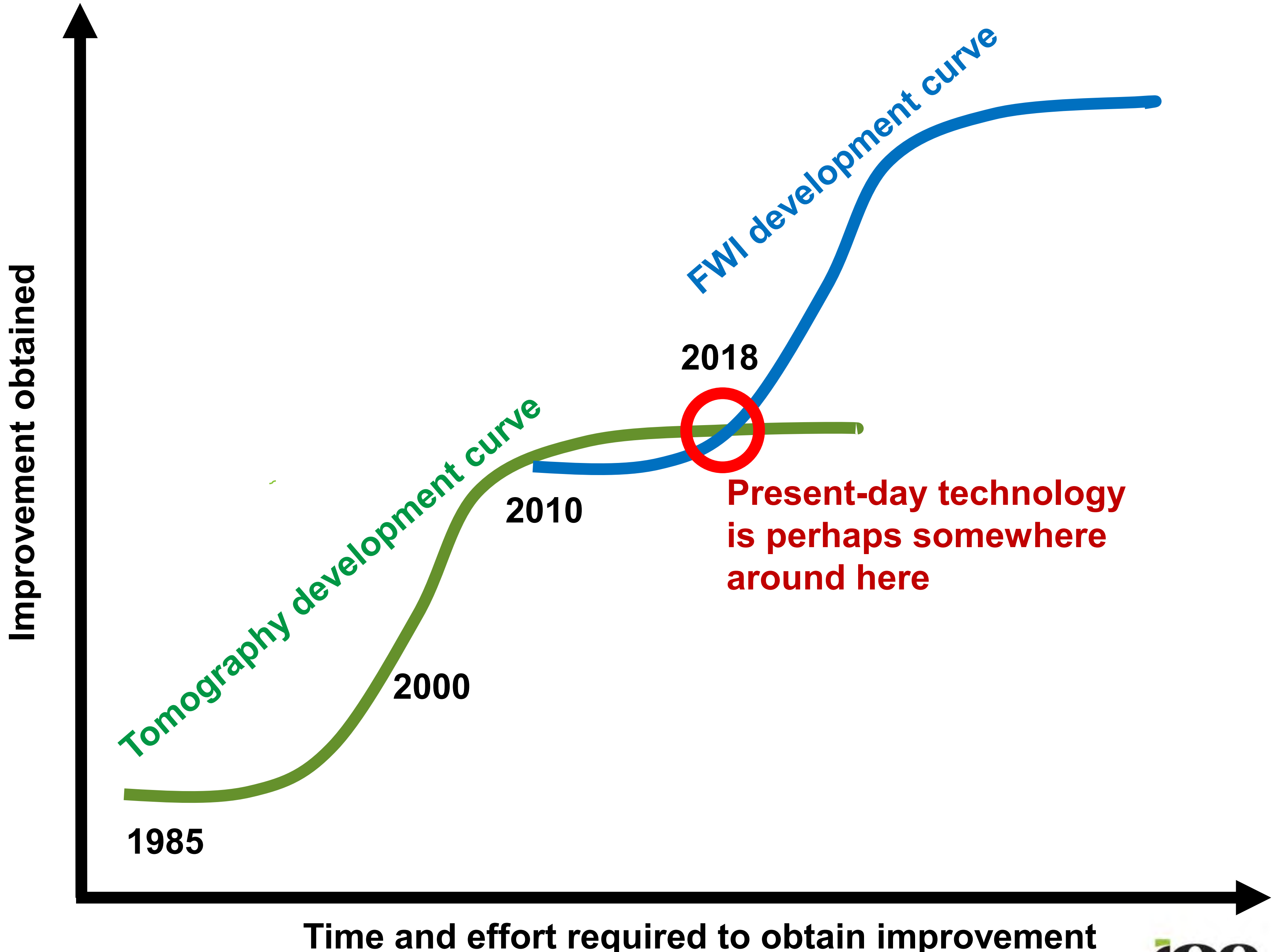
# Automated fault detection within tomography



# Tomographic versus FWI?

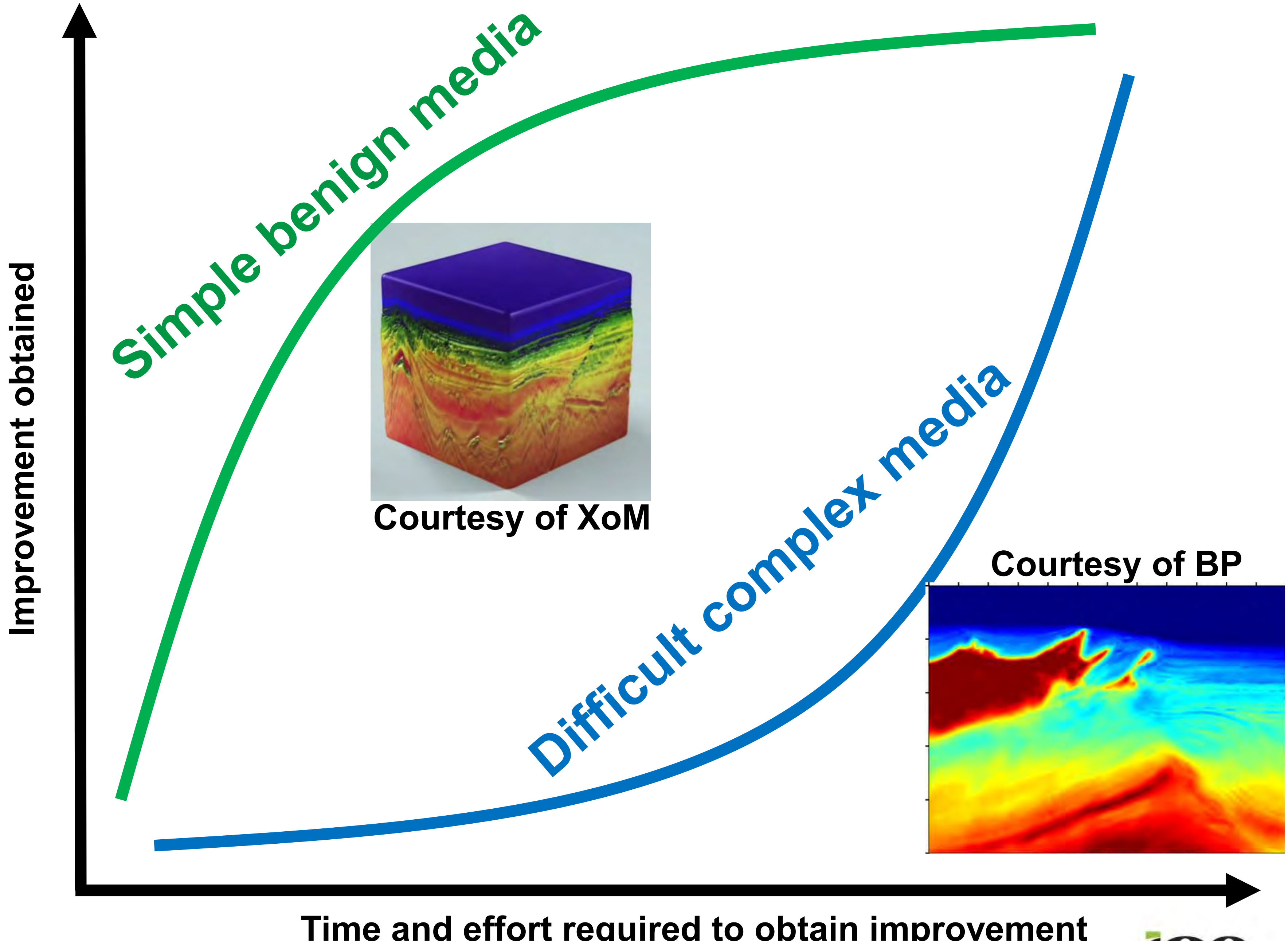
The industry is currently transitioning from a purely tomographic model building route, to one incorporating both refraction and reflection FWI.

What can we expect from this latest development?



Improvement obtained
FWI development curve
2018
Tomography development curve
2010
Present-day technology
is perhaps somewhere
around here
2000
1985
Time and effort required to obtain improvement

# What uplift is expected from FWI?



# Tomographic velocity update…..

**Limited by the ray-theory ‘scattering limit’ to a resolution of perhaps 5x the available sound-wavelength**

# FWI velocity update…..

Can perhaps deliver resolution of about half the available sound-wavelength, so theoretically perhaps 10x the resolution of ray methods

Primarily using the transmitted (refracted) rather than the reflected wavefield, and typically ignoring density contrast, Q, etc.

# HOWEVER…..

**For the majority of geological environments, building a model with FWI will not result in an image much different than that obtained using tomography**

**The exception to this observation would be in shallow water with small-scale anomalies (e.g. gas), or for deep salt (and then only if we have low frequencies and long offset)**

**The promise of FWI is in delivering high resolution attribute fields DIRECTLY and QUICKLY**
**(and perhaps with better depth ties)**

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# Benefits of re-processing using non-parametric model building for exploration and field development

## A case study from the Nyk High, Vøring Basin


Anton Pavlov[2], Josh Howsego[2], Marco Haverl[1], Victoria Valler[2], James Raffle[2], Bjarte Myhren[1], Hans Aronsen[1]



Presented at PETEX 2016

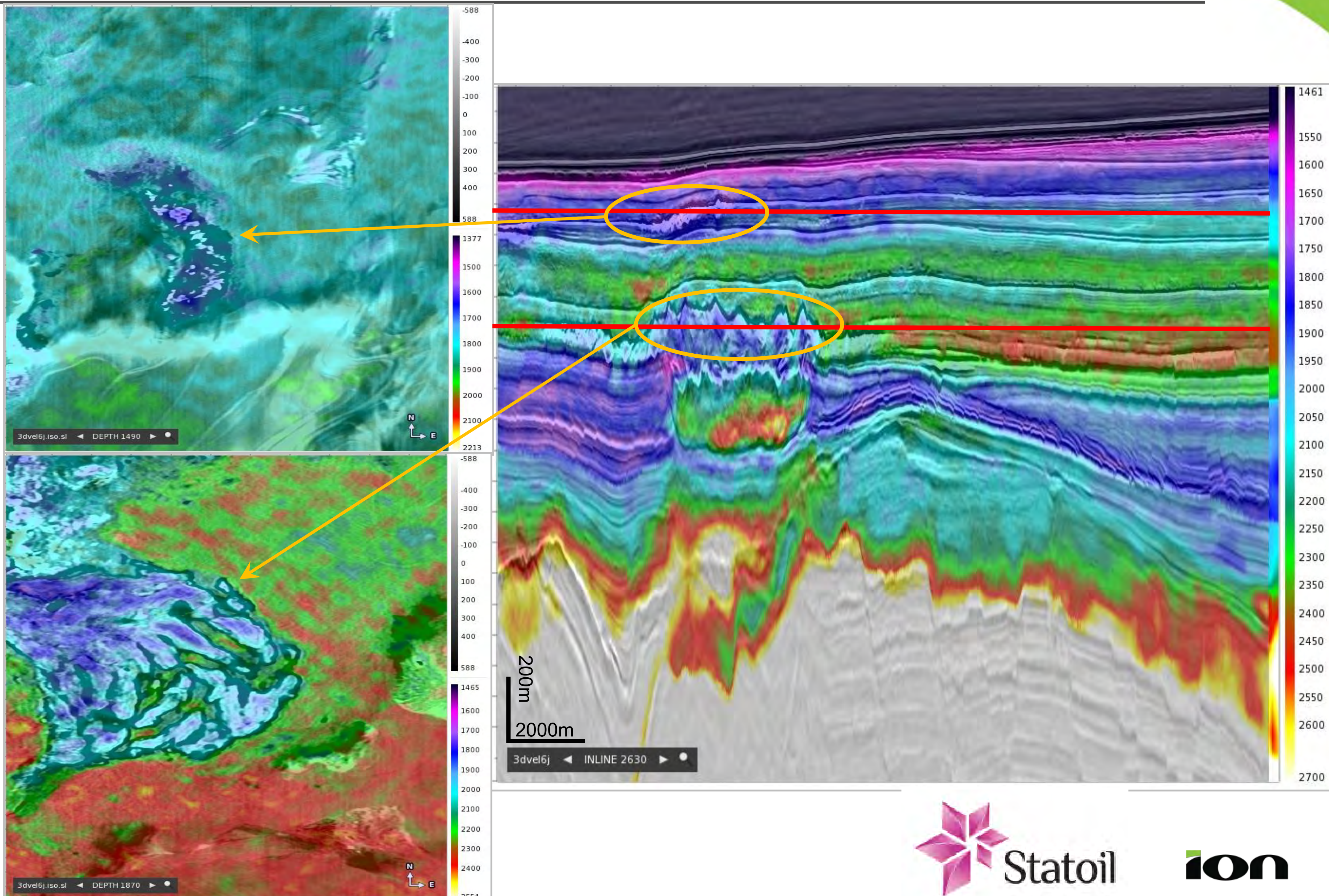


**[1]Statoil, [2]ION Geophysical**


Statoil

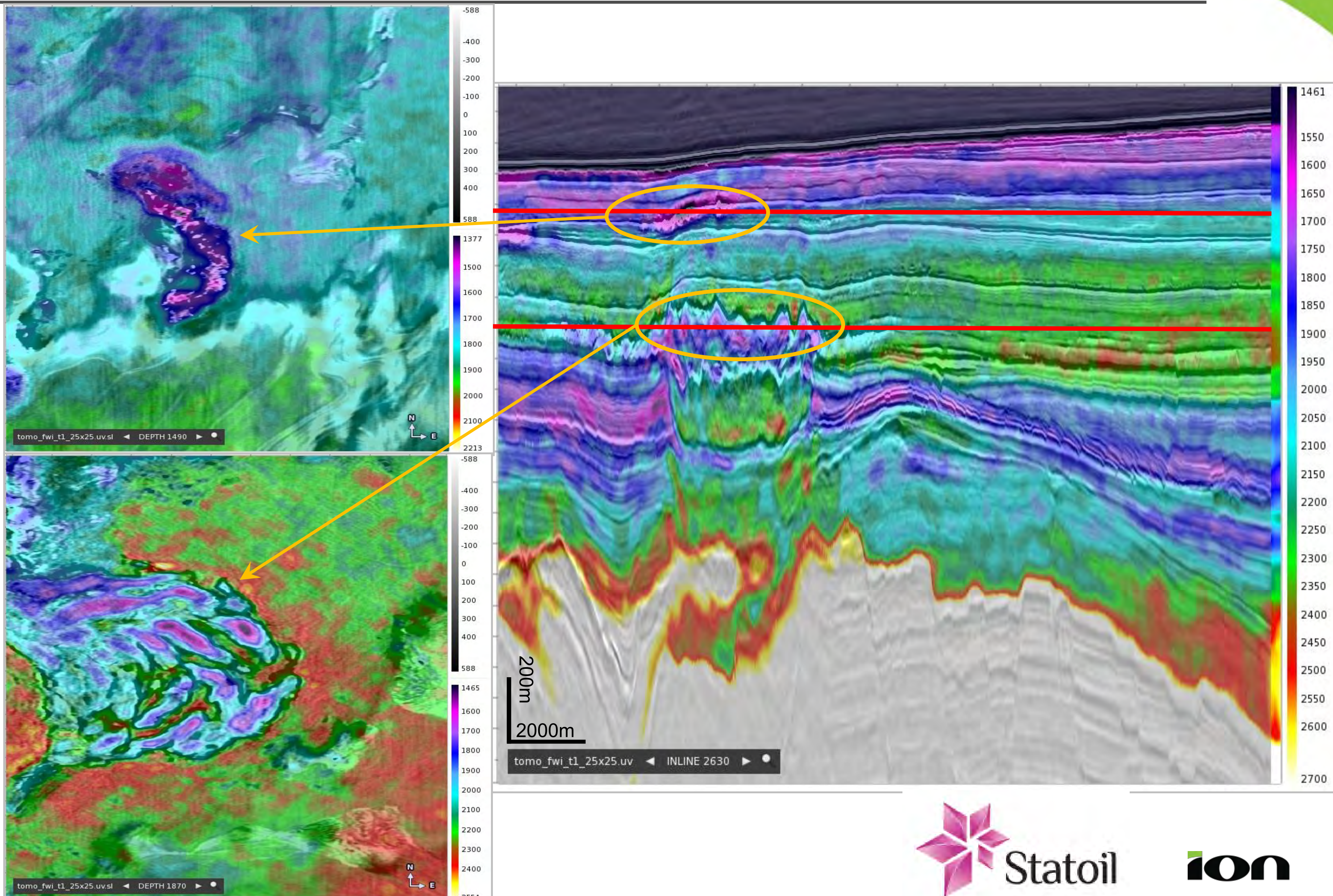
# Imaging highlights: Travel-time tomography

Depth slices at 1490m (top)  and 1870m (bottom)



# Imaging highlights: Acoustic FWI (to 12Hz)

Depth slices at 1490m (top) and 1870m (bottom)

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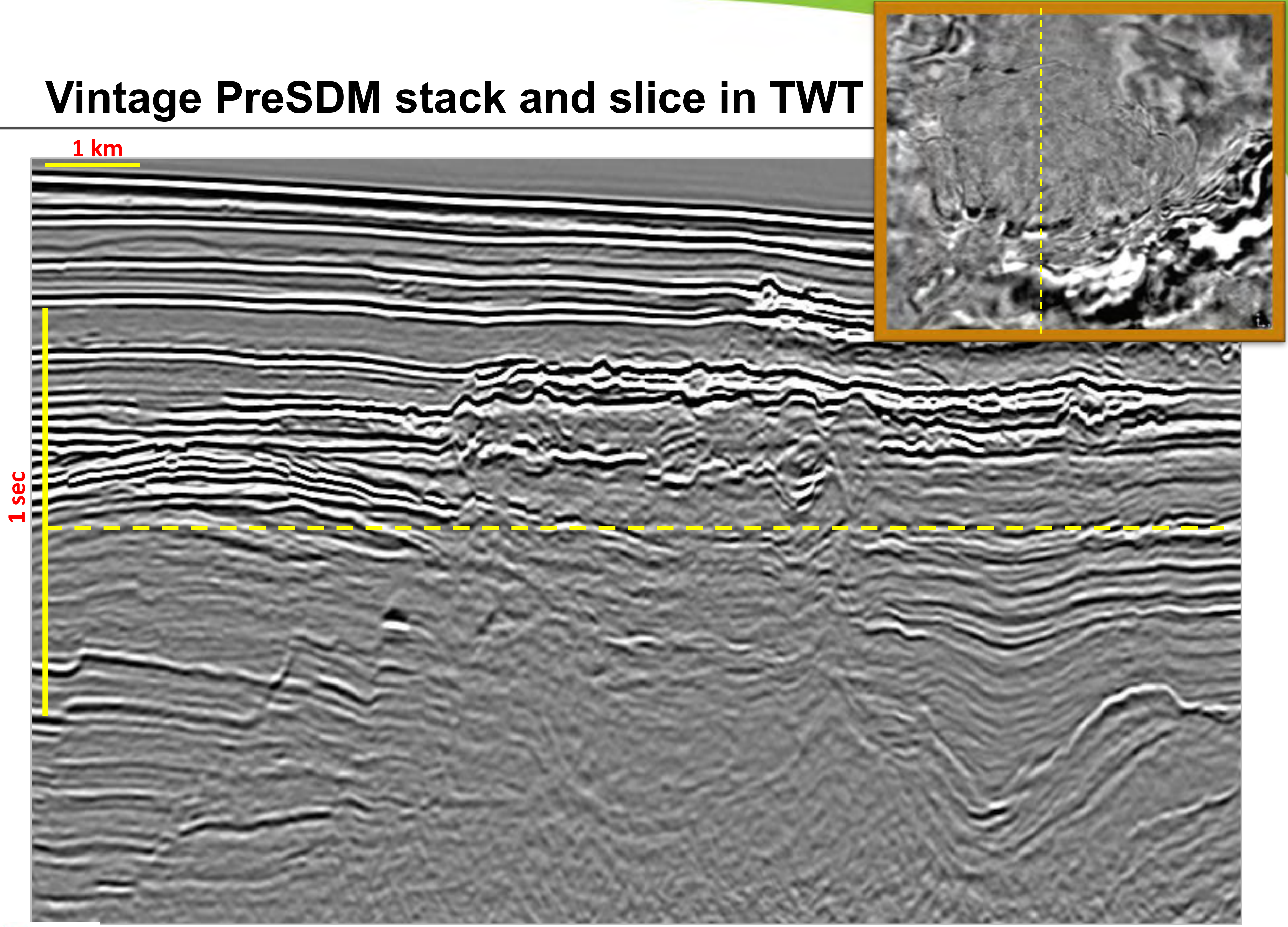
# Vintage PreSDM stack and slice in TWT

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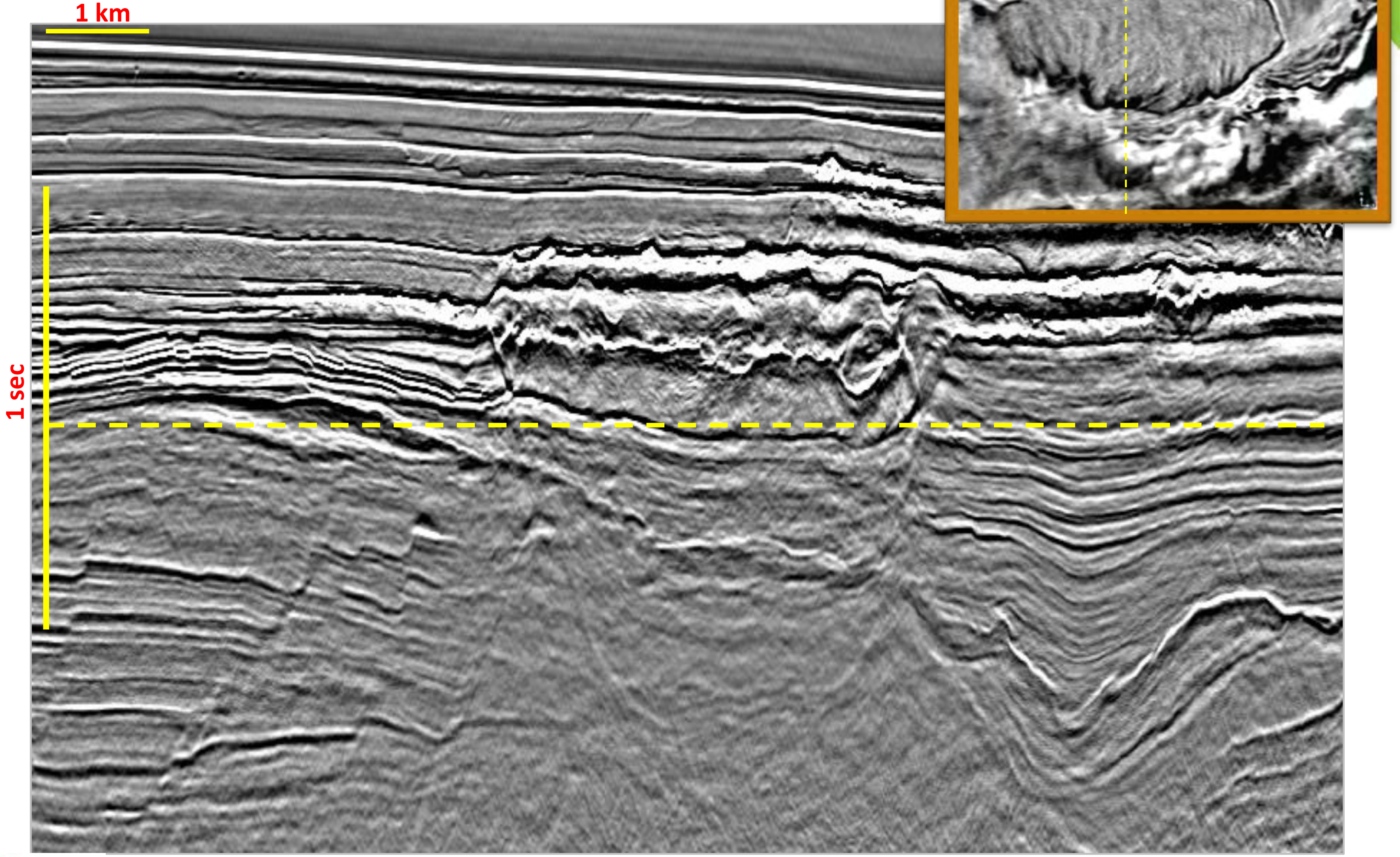
# Final PreSDM stack and slice in TWT

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# Full Waveform Inversion with a Reconstructed Wavefield (RFWI)

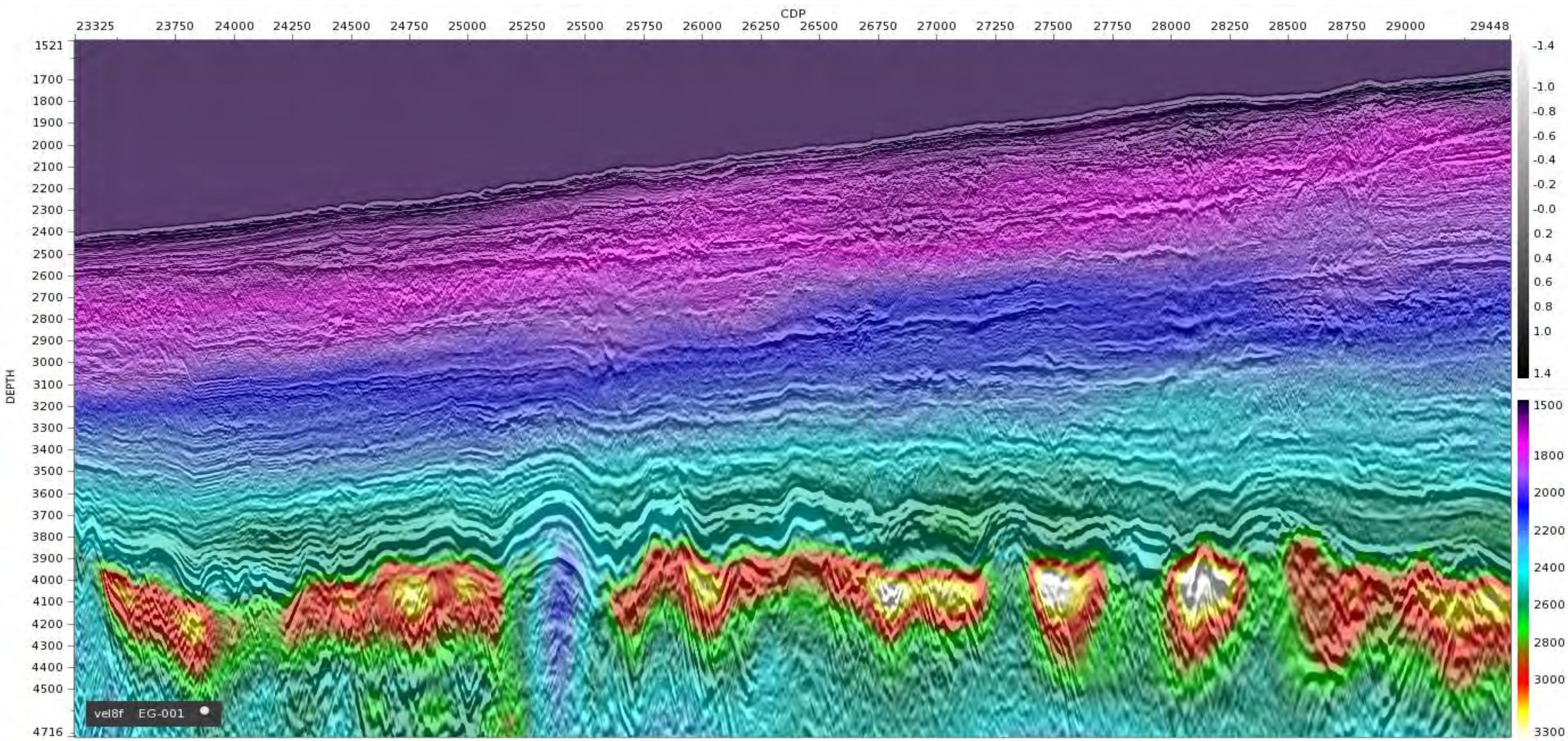
Nile Delta and another Deep Water Example

Chao Wang, Juergen Fruehn, Stuart Greenwood, Jeet Singh

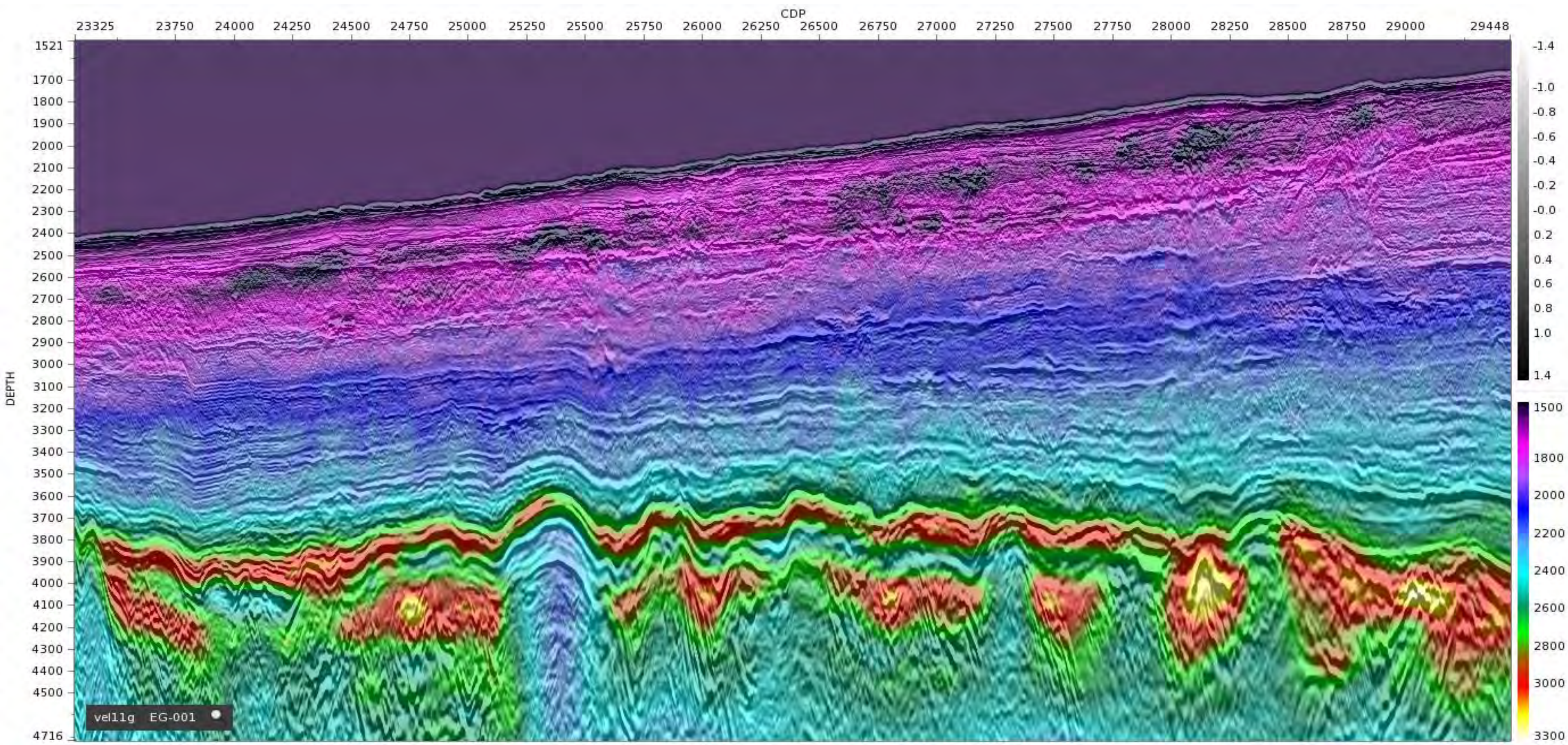
SEG 2017

Interpretational guidance courtesy of BP

# Nile Delta: Image with tomography model



# Nile Delta: Image with RFWI model



# Ray Based Tomography (zoom at well location)

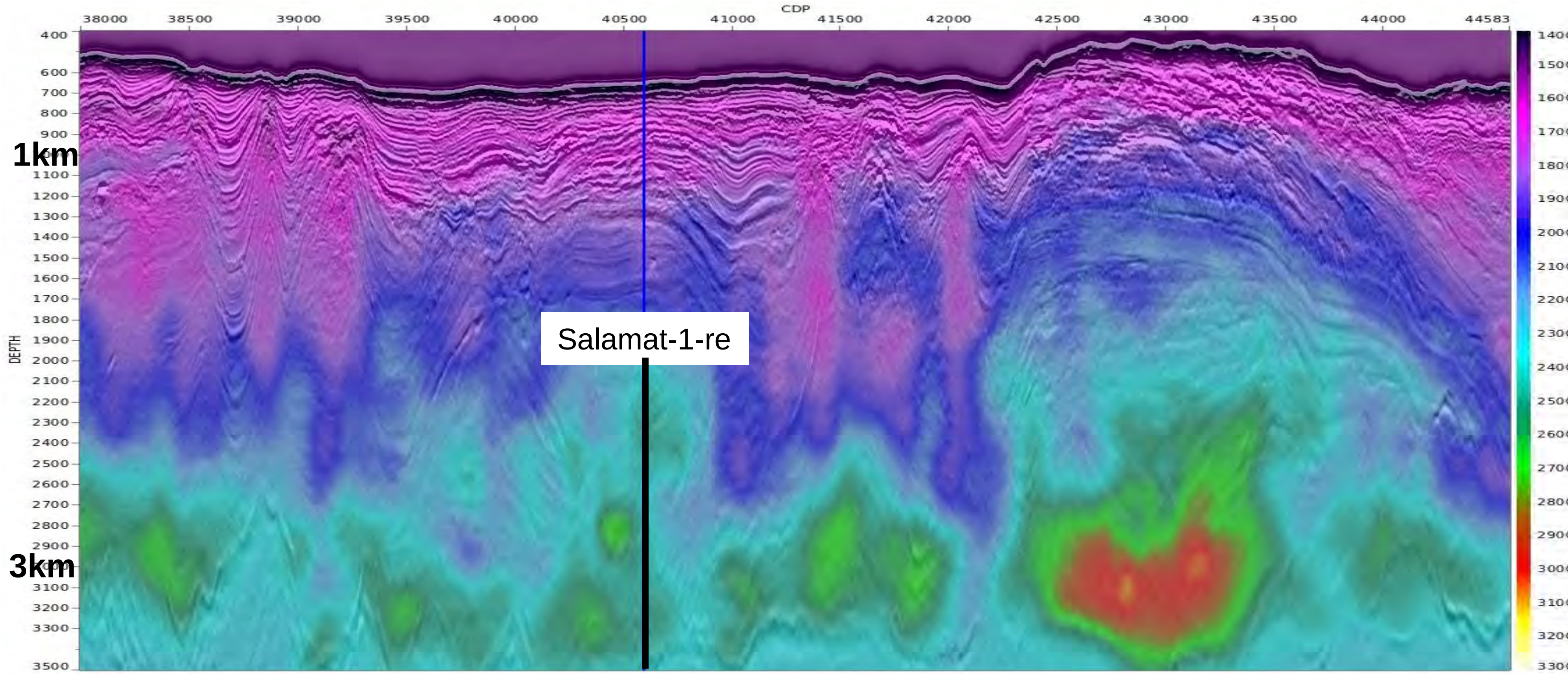



Image courtesy of Ed Brown, Univ. Leeds, MSc thesis

Tomo Cell Size: 150m x 15m
Autopicker: Every 4th CDP (50m)

10 km

# RFWI (zoom at well location)

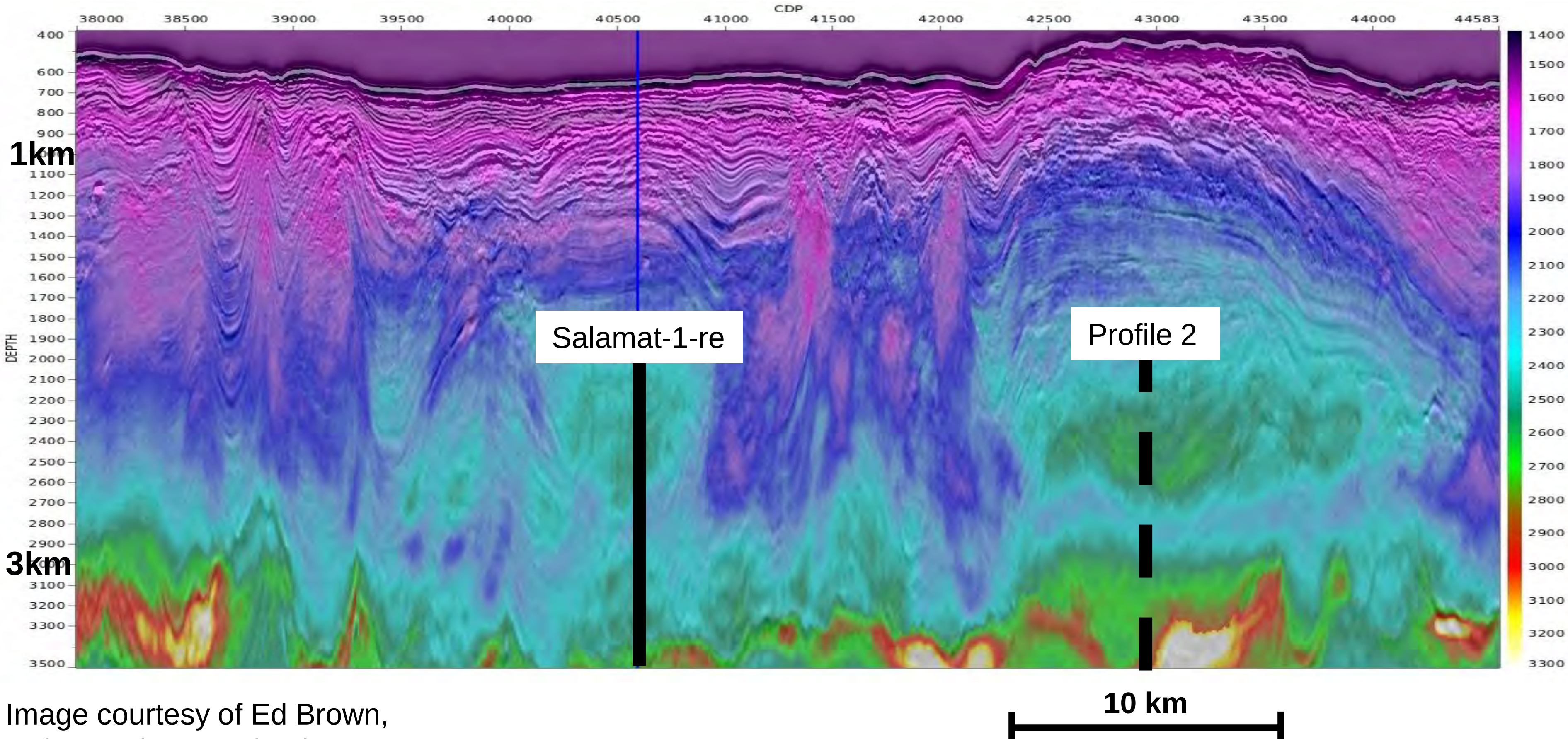



Image courtesy of Ed Brown,
Univ. Leeds, MSc thesis

# Velocity Profiles

**Salamat-1-re** **Profile 2**

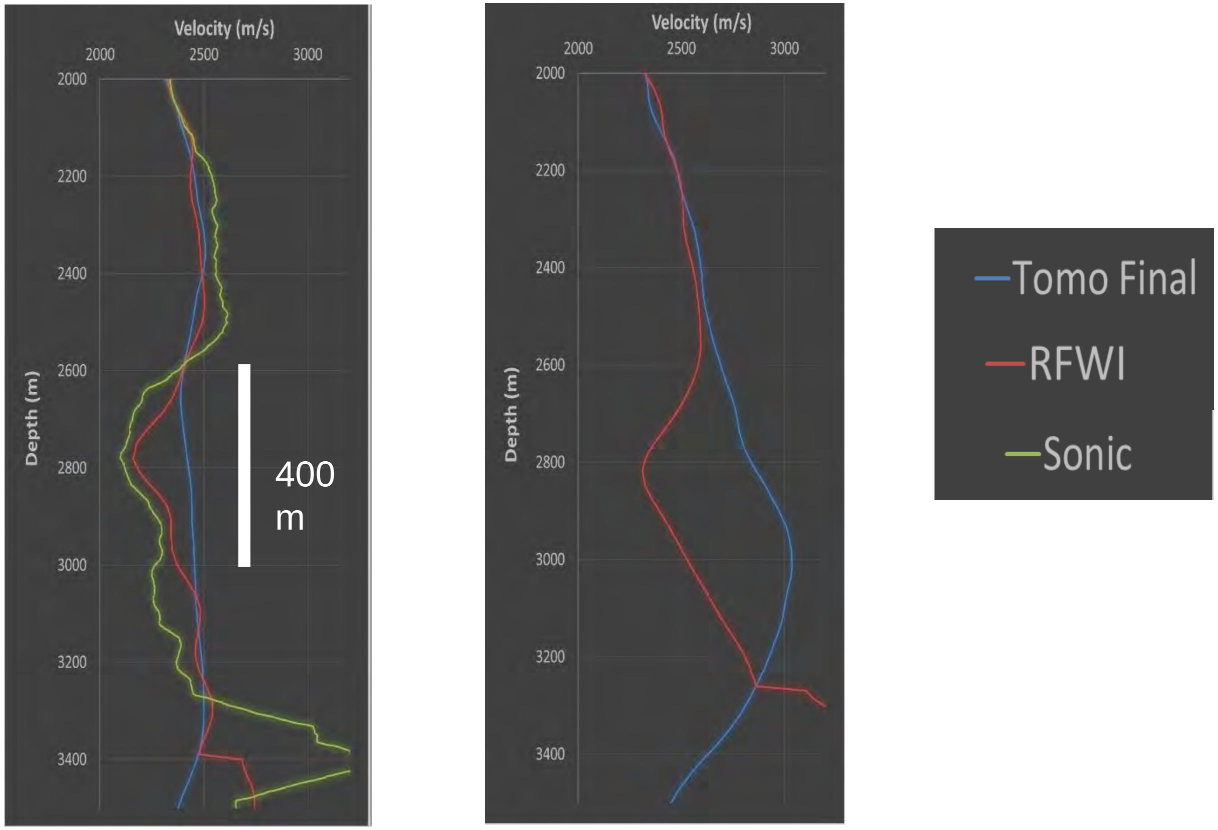



Image courtesy of Ed Brown, Univ. Leeds, MSc thesis

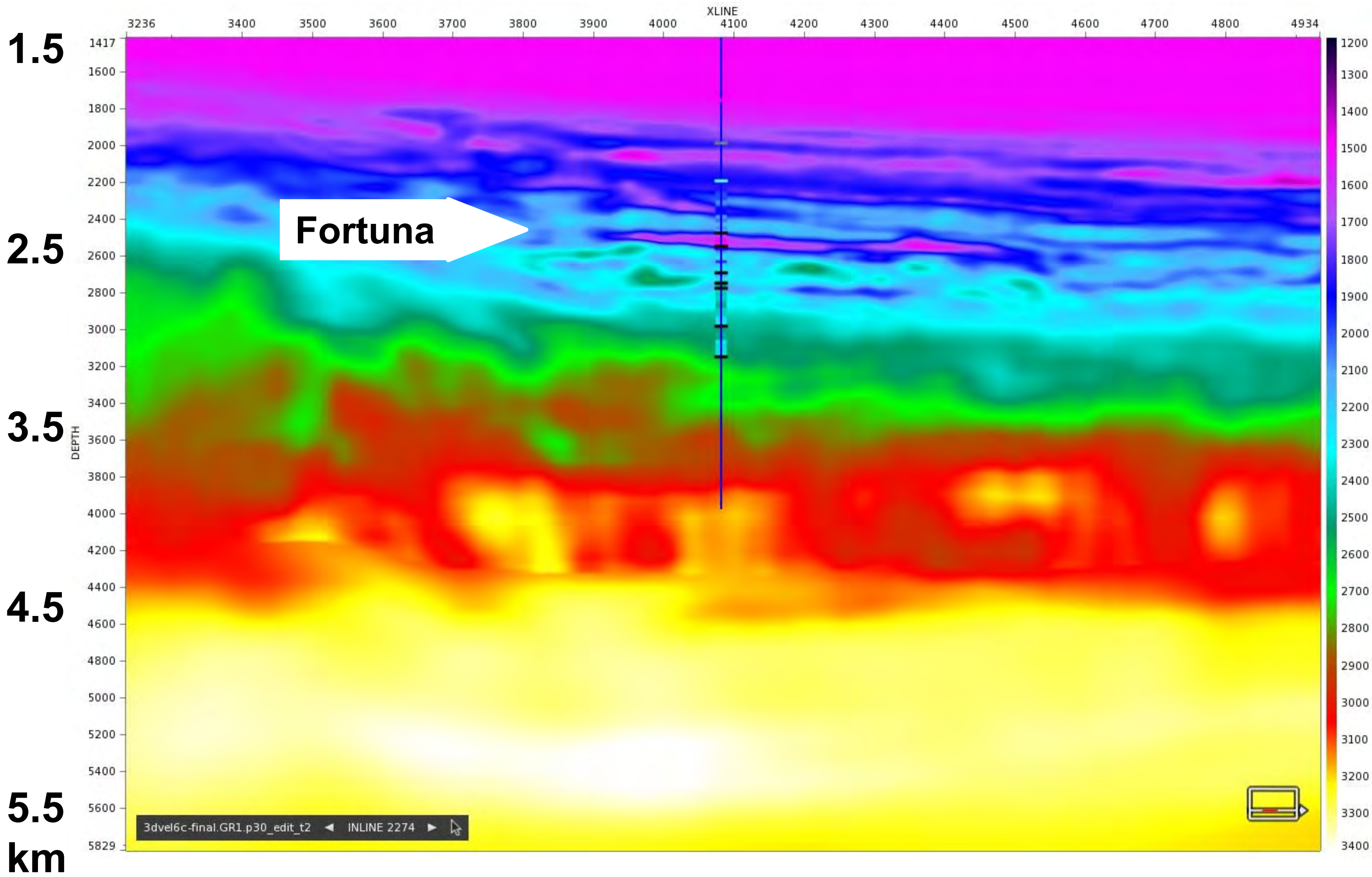
# The evolution of tomography and FWI: an example of high resolution velocity estimation using refraction and reflection FWI

presented at the:
EAGE-PESGB Velocity workshop 22/2/18

Ian F. Jones[1], Jeet Singh[1], Philip Cox[2], Matt Warner[2], Colin Hawke[2], Dale Harger[2], Stuart Greenwood[1]
1 ION Geophysical; 2 Ophir Energy UK

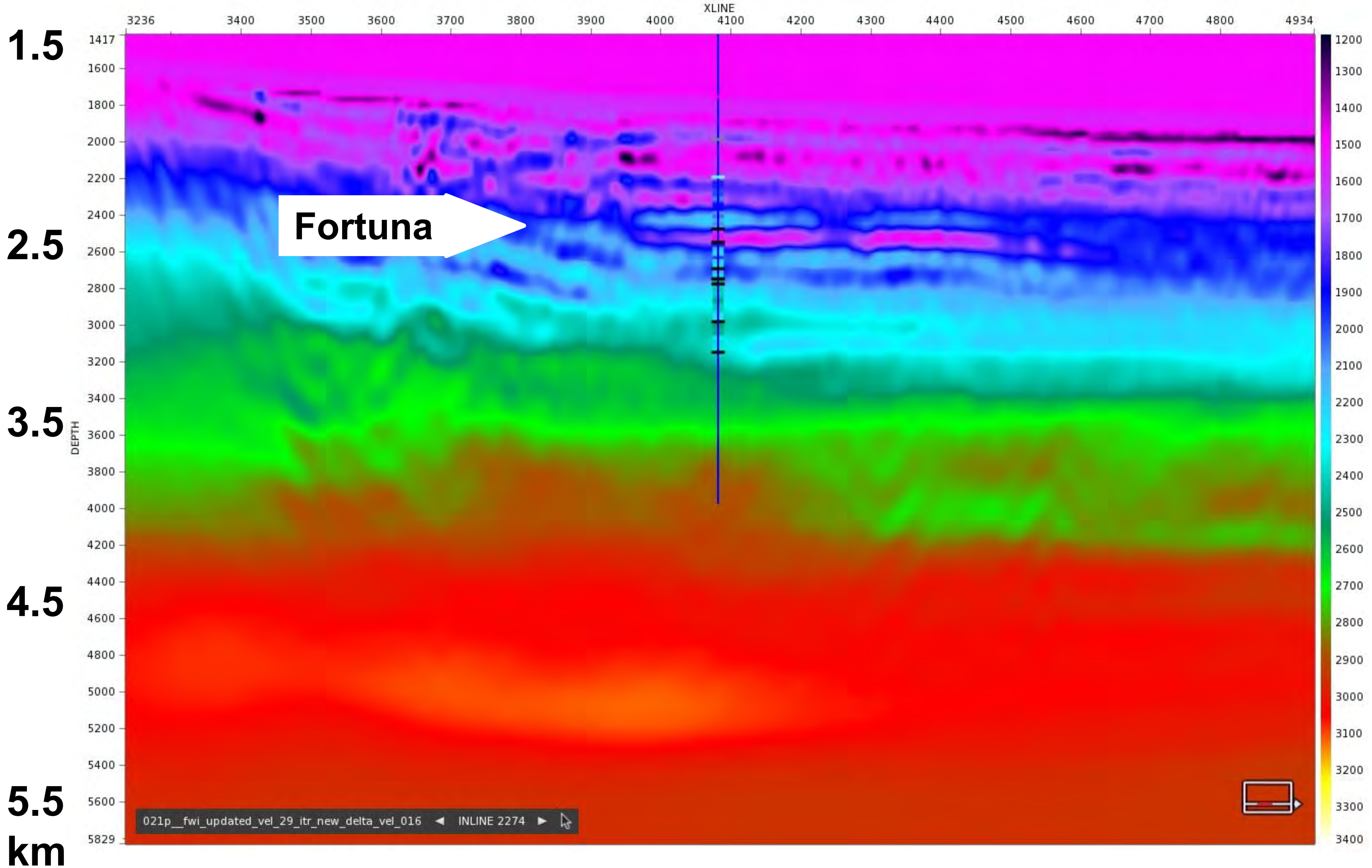
# Tomographic velocity

5 iterations



# FWI velocity (muted shot)

1-3-5-9 Hz, with 46 iterations

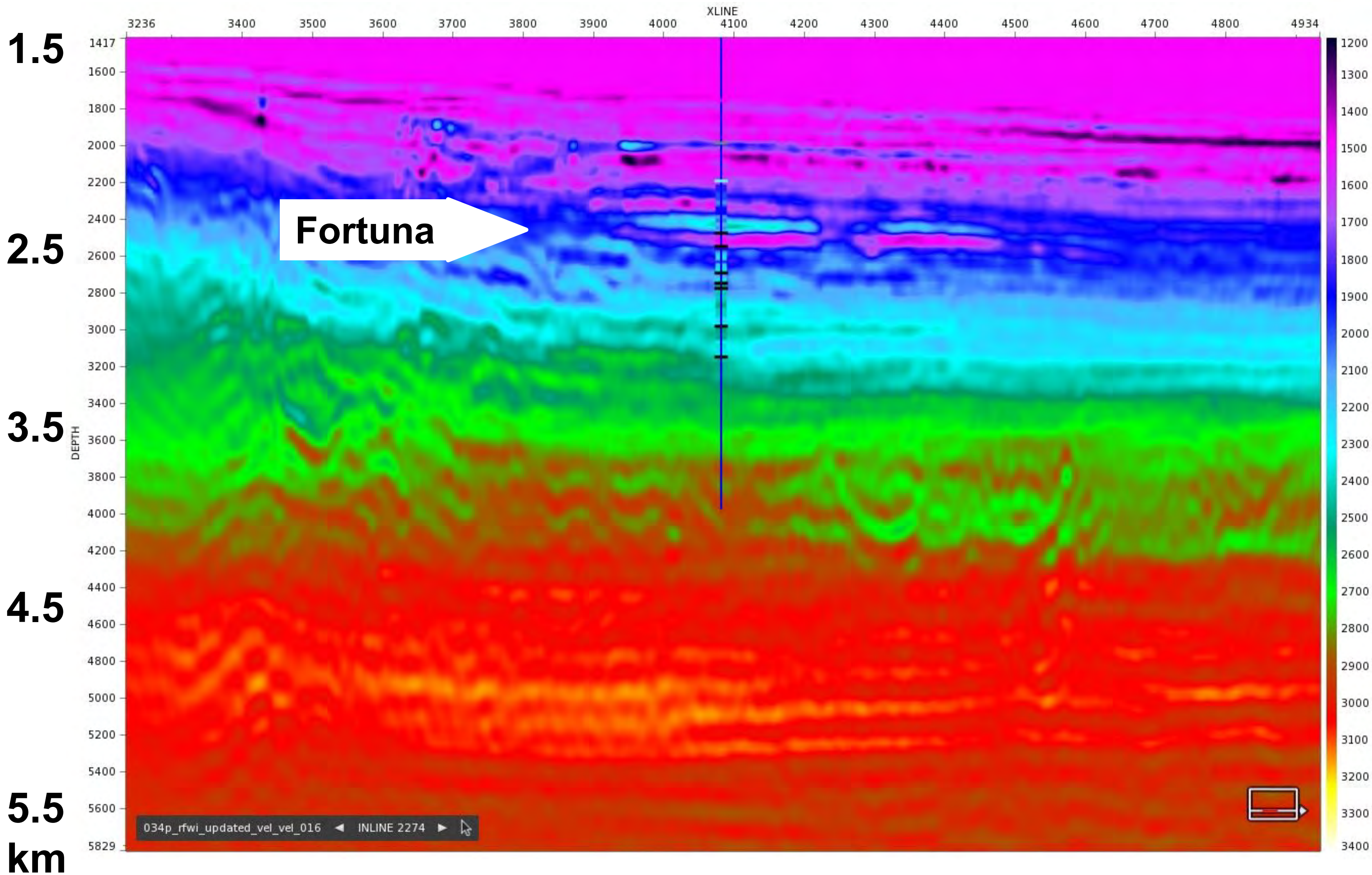



9Hz max

ion

# FWI velocity (full shot)

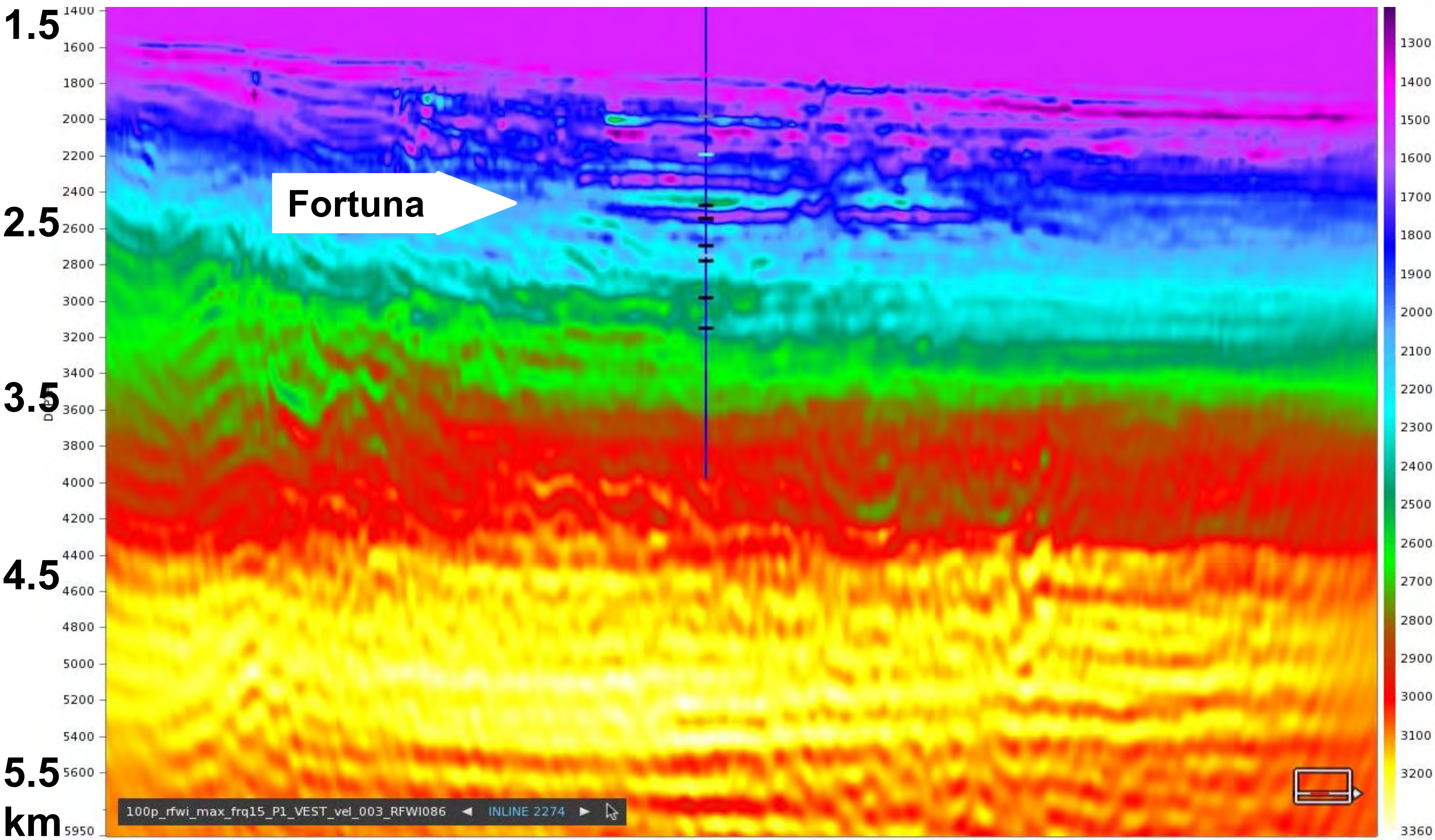
1-3-8-12 Hz, FWI updated velocity with FWI046+FWI016 (total=62)




12Hz max

# Reconstructed wavefield FWI (full shot)

Max, Frequency=15Hz,RFWI updated velocity with 1-3-12-15Hz, with FWI046+RFWI037+RFWI003( total=86) + delta




15Hz max

# Tomographic stack

5 iterations

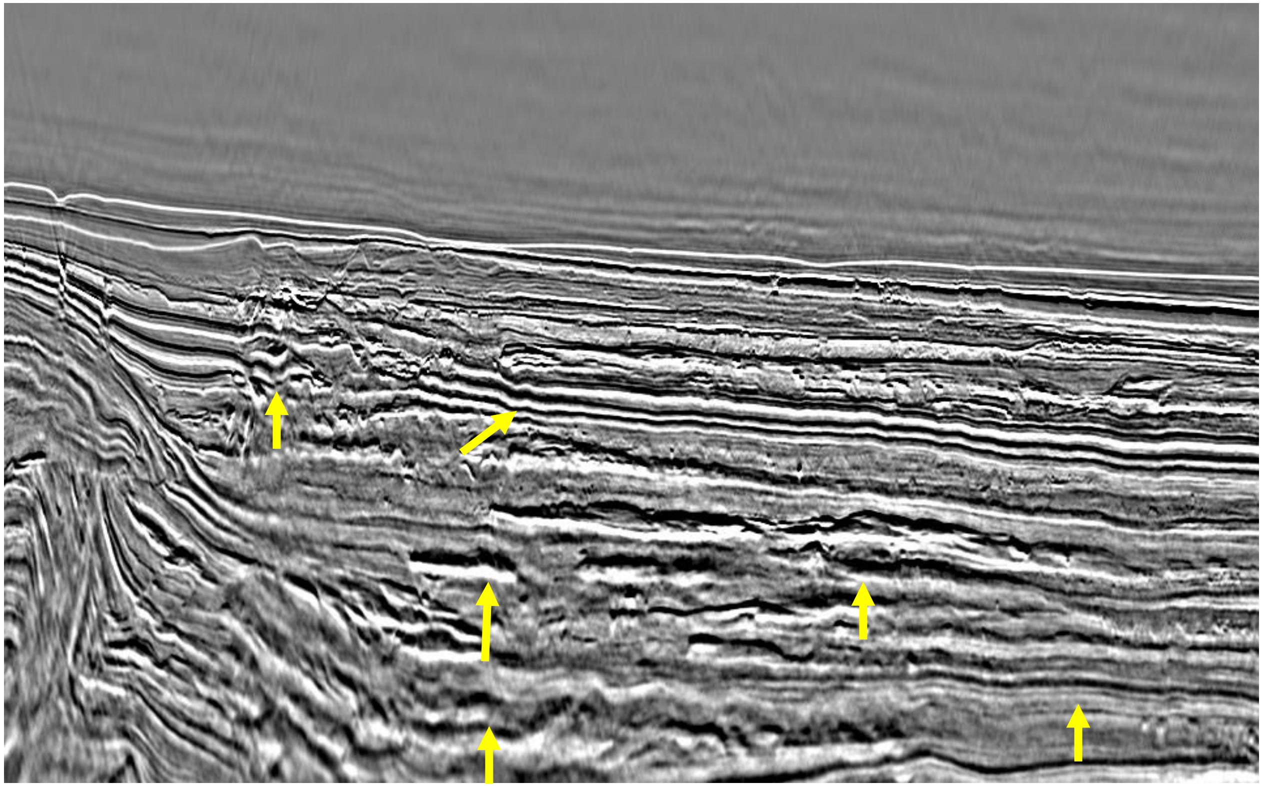


**Image differences are slight, but can be important for well-tie depths**

# RFWI updated stack

FWI056+RFWI038 iterations=94 iterations

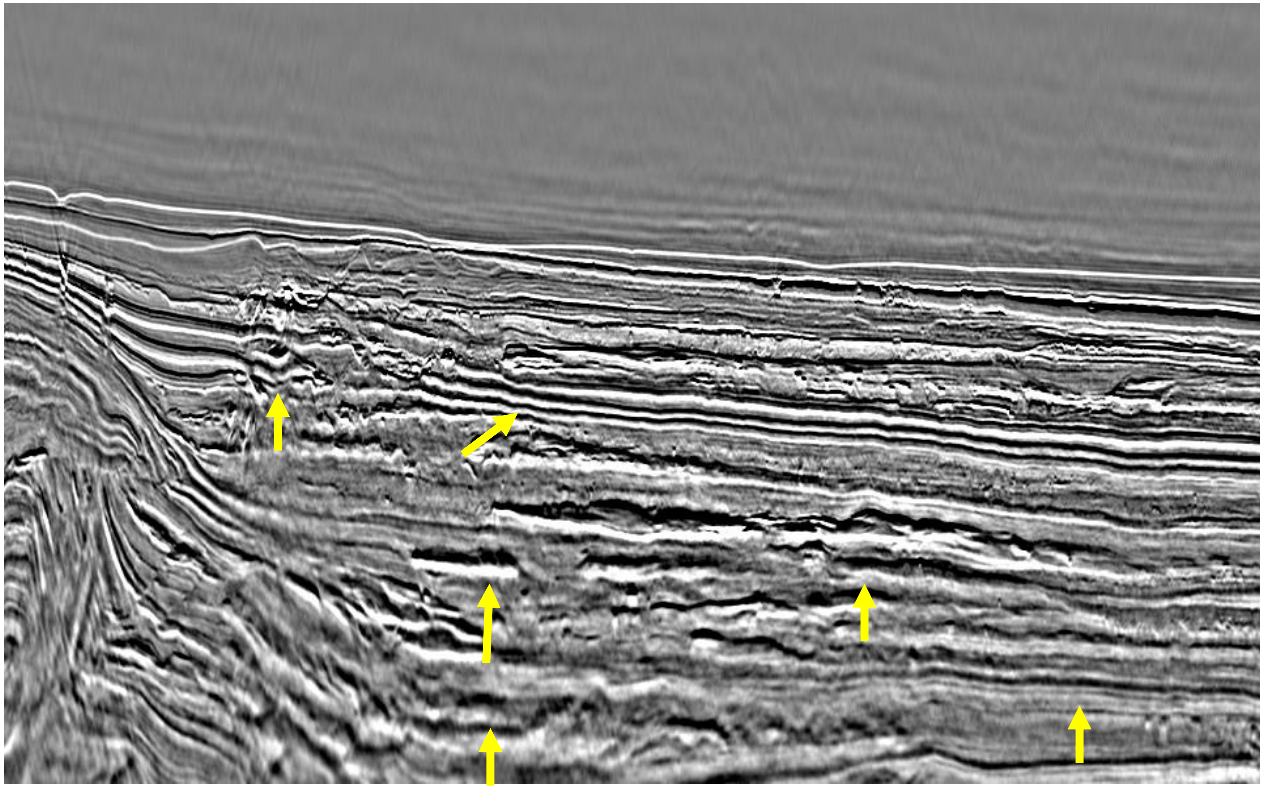
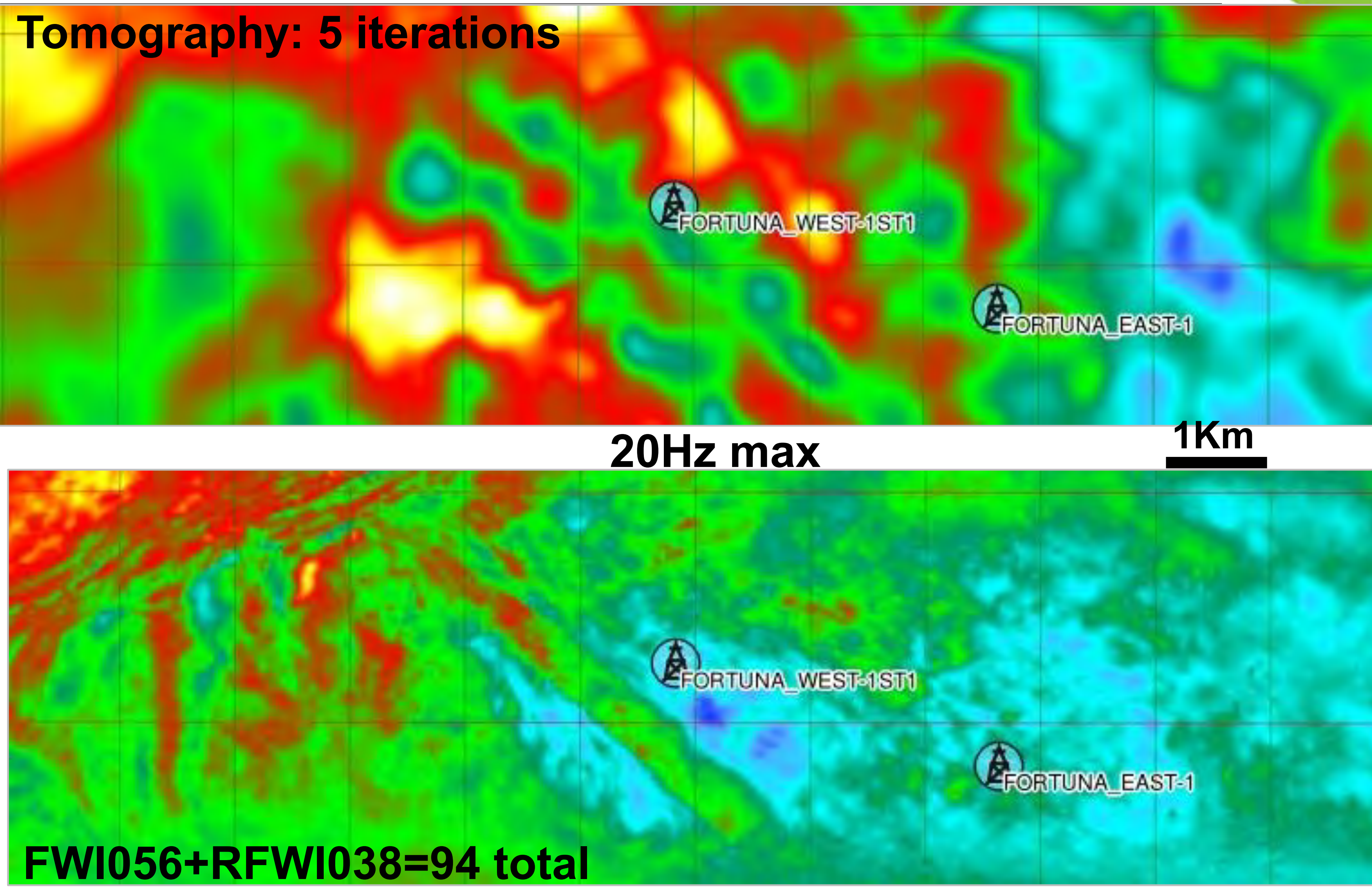


**Image differences are slight, but can be important for well-tie depths**

# Depth slice: Viscata reservoir level (2650m)



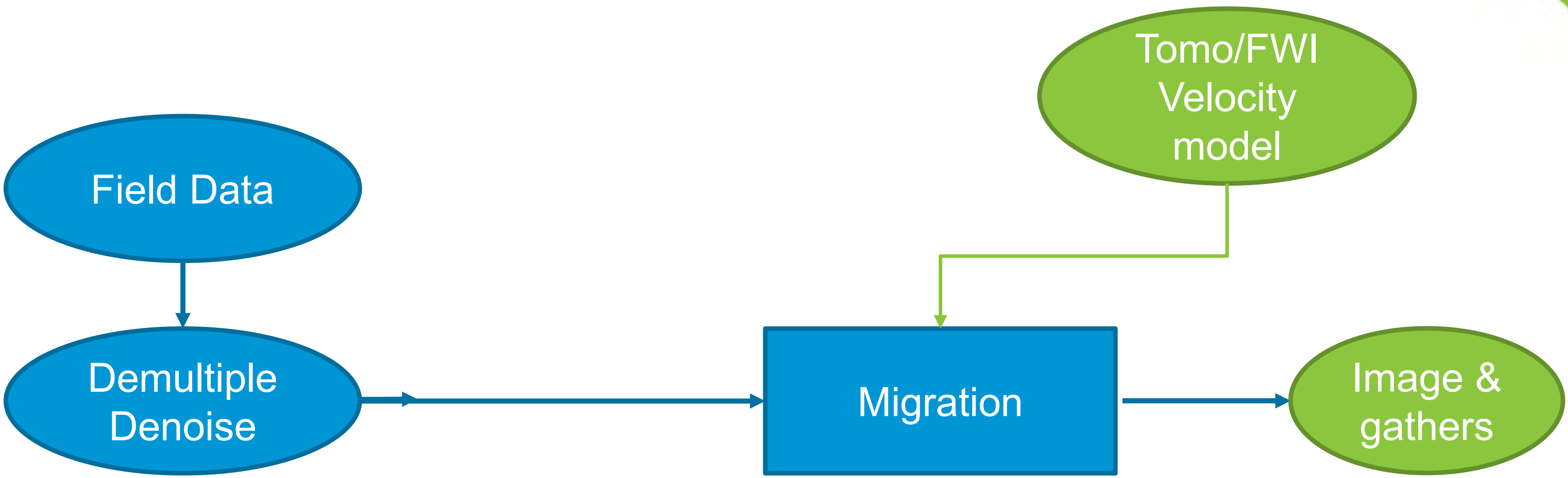
# Contemporary methodology …..

## In seismic data processing we aim to:

- Separate ‘signal’ from ‘noise’
- Build an anisotropic velocity model
- Migrate the data, producing ‘true amplitude’ angle classes

Whereas amplitudes in Kirchhoff migration are ‘correct’, wavefield extrapolation imaging conditions (as in RTM) are not. We need expensive (surface offset) gathers plus LS adaptation (or equivalent) to obtain good amplitudes … this may cost several times more than a basic RTM image

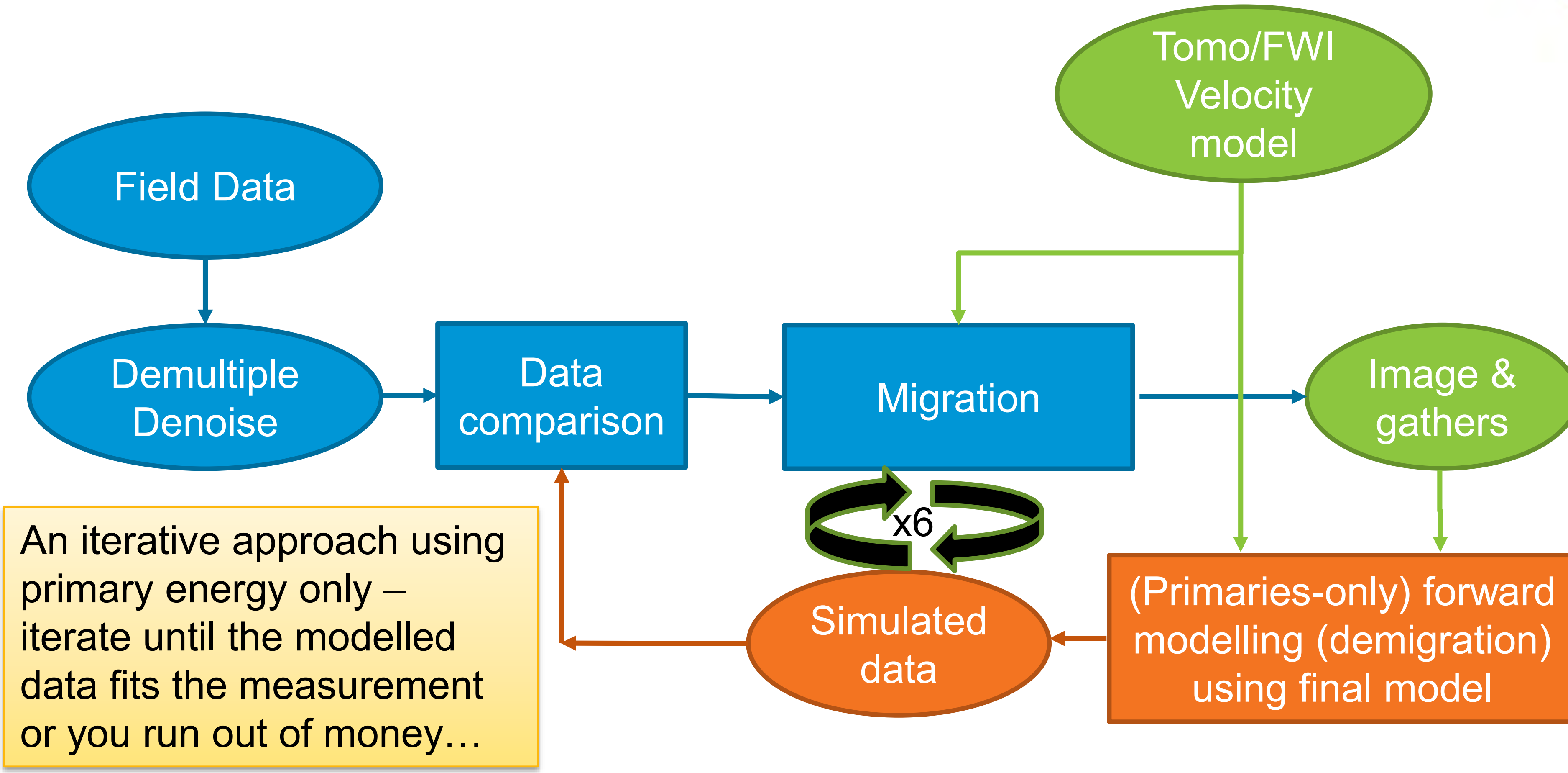
# Conventional Migration




A single pass estimate of reflectivity

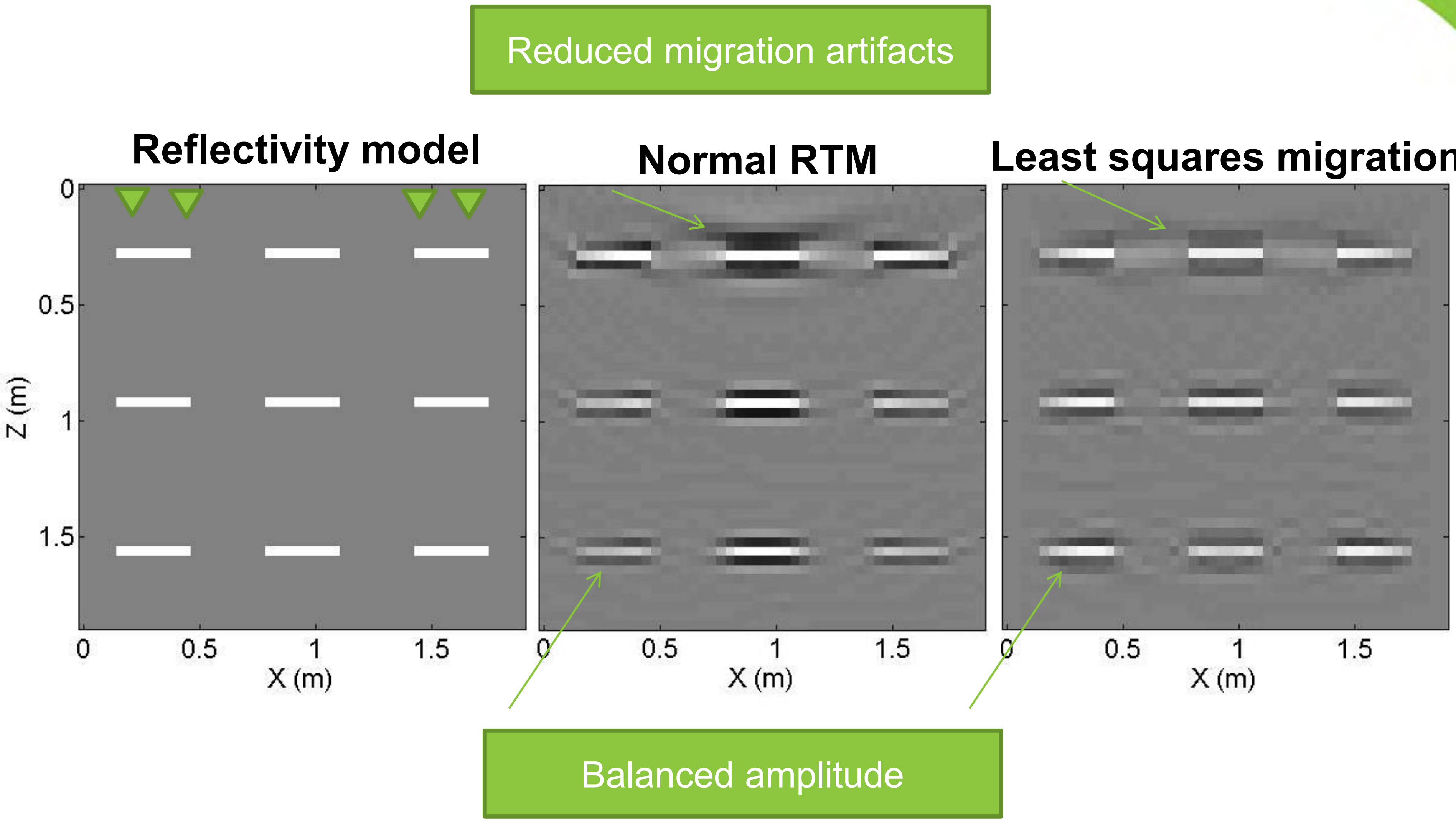
After Verschuur, 2015

# (Primaries only) Least-Squares Migration using final (tomo or FWI) model

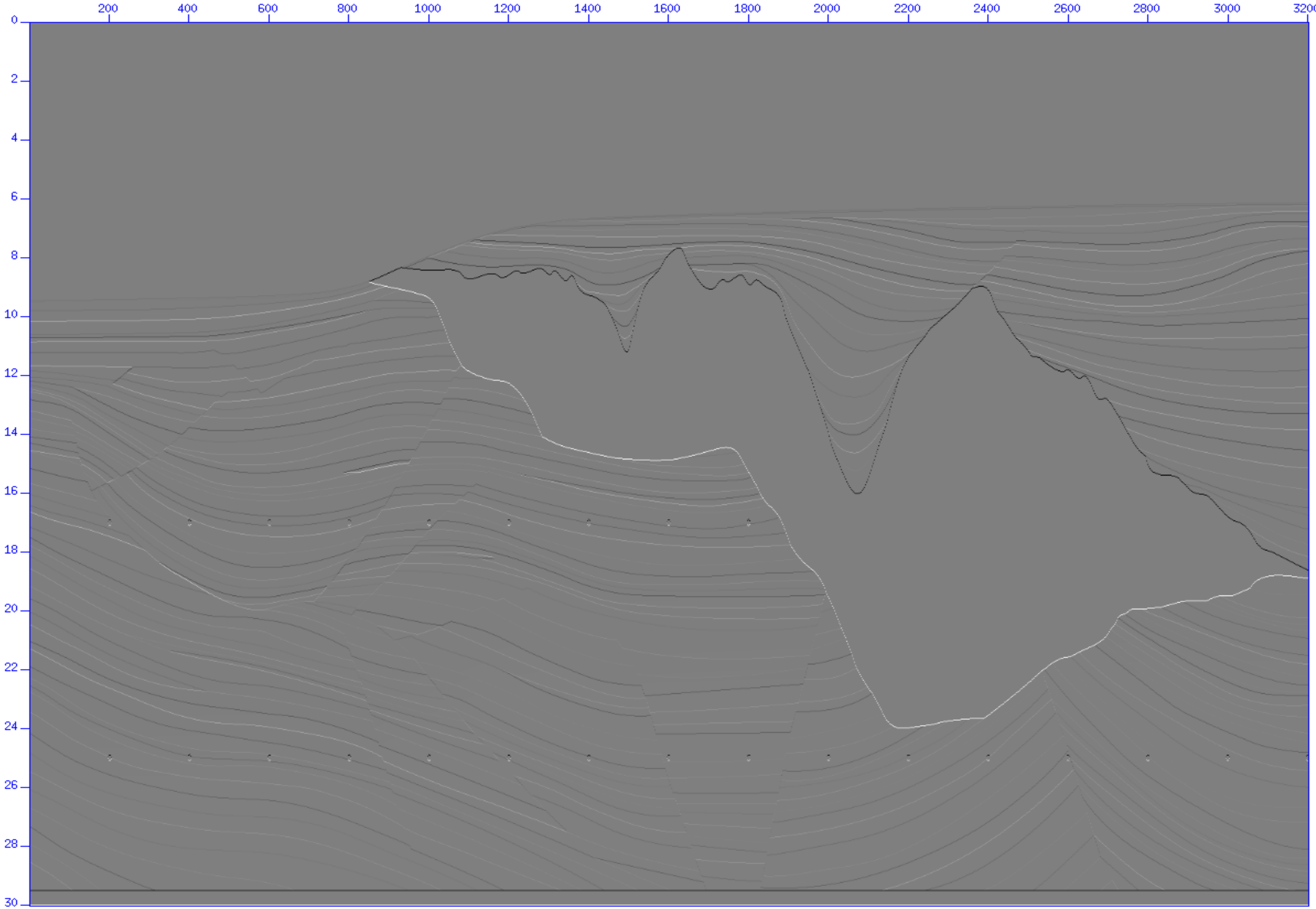



After Verschuur, 2015

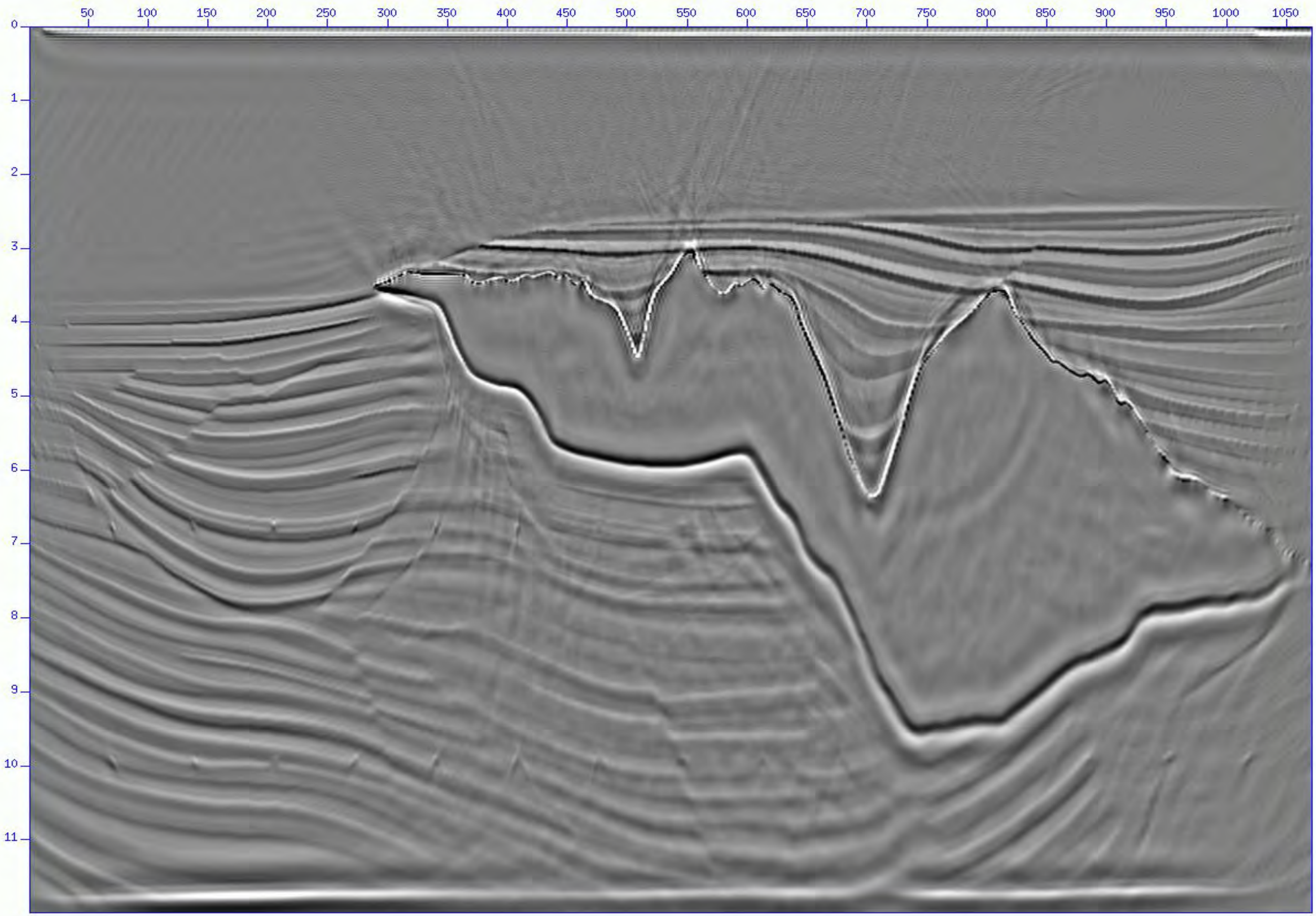
# Least Squares Migration



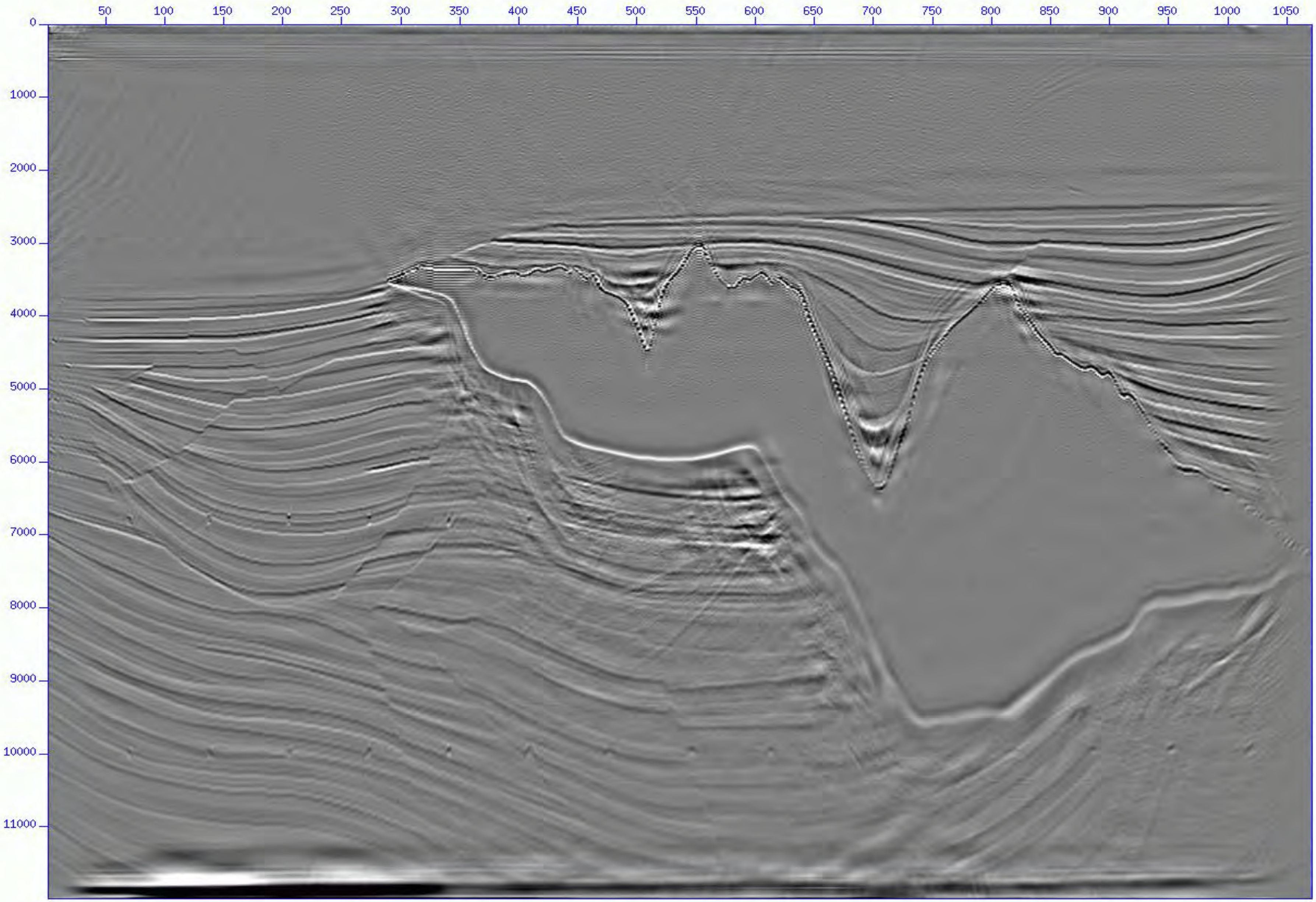
# Model Reflections



# Conventional RTM image



# Image after PSF deconvolution



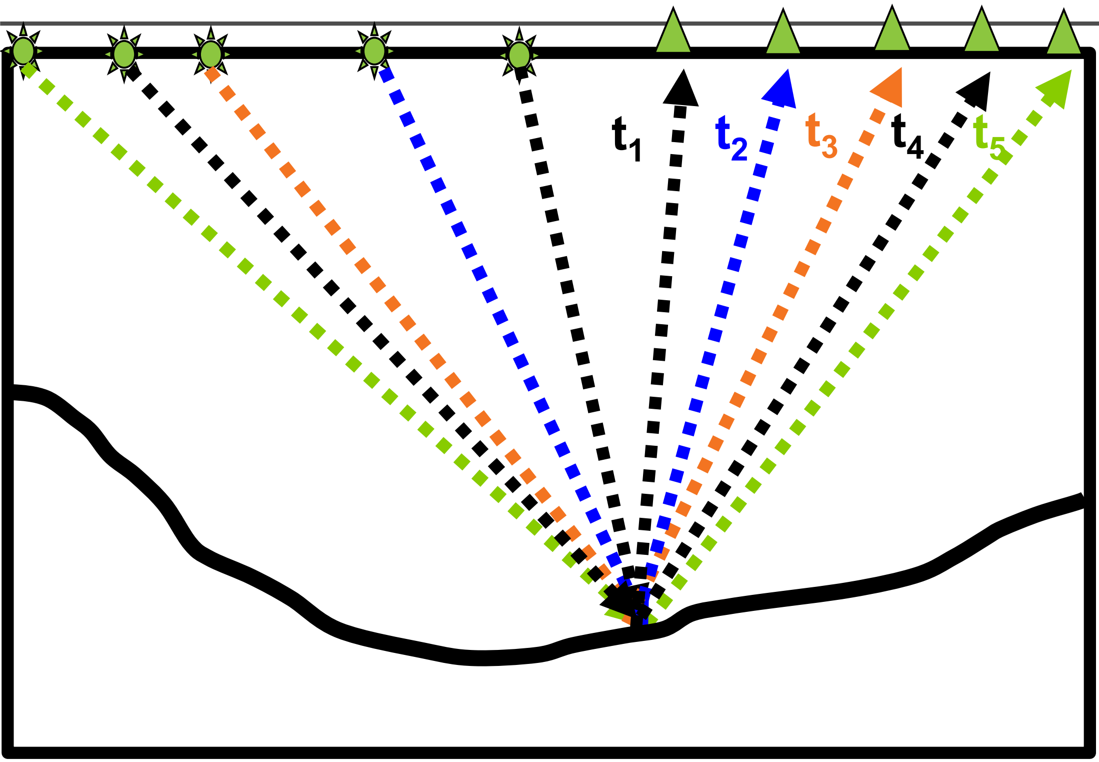
# Contemporary methodology …..

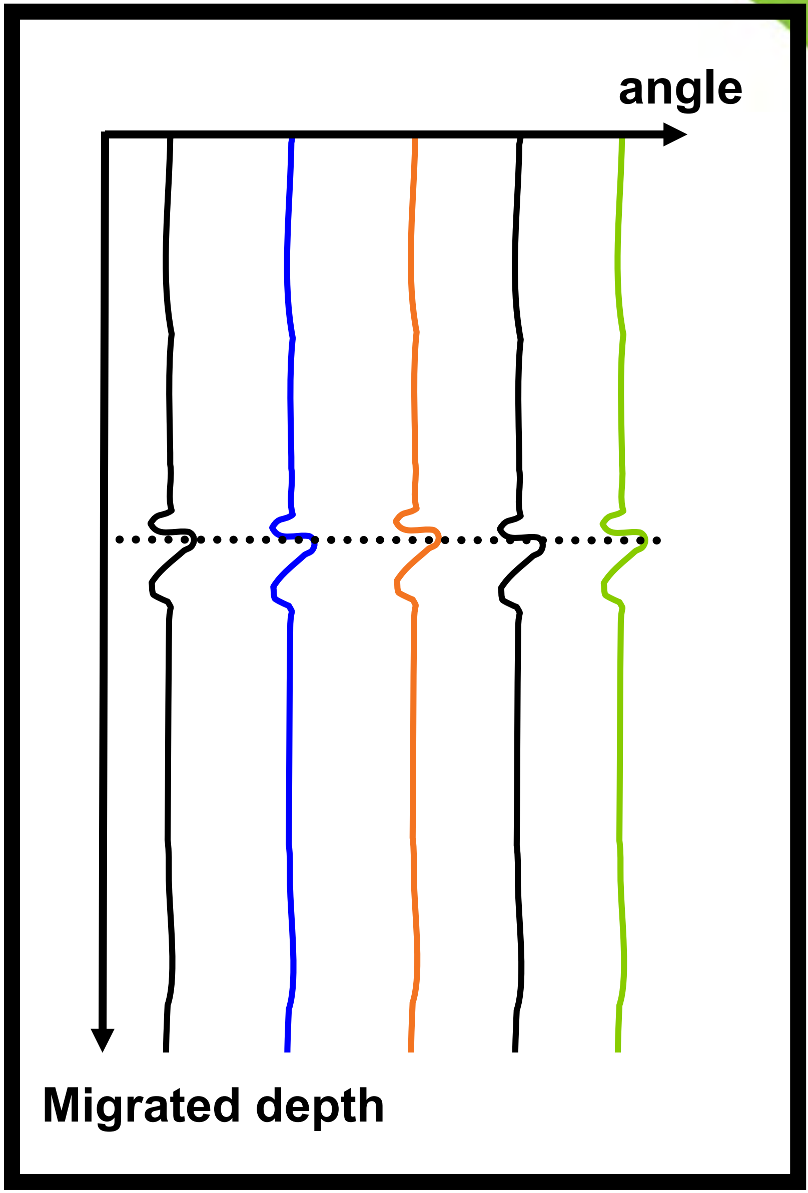
## In seismic data processing we aim to:

- Separate ‘signal’ from ‘noise’
- Build an anisotropic velocity model
- Migrate the data, producing ‘true amplitude’ angle classes
- Estimate elastic parameters via impedance inversion

Following migration, a separate group of geoscientists with different skill-sets, usually perform elastic impedance inversion of the trim-static flattened true amplitude angle gathers

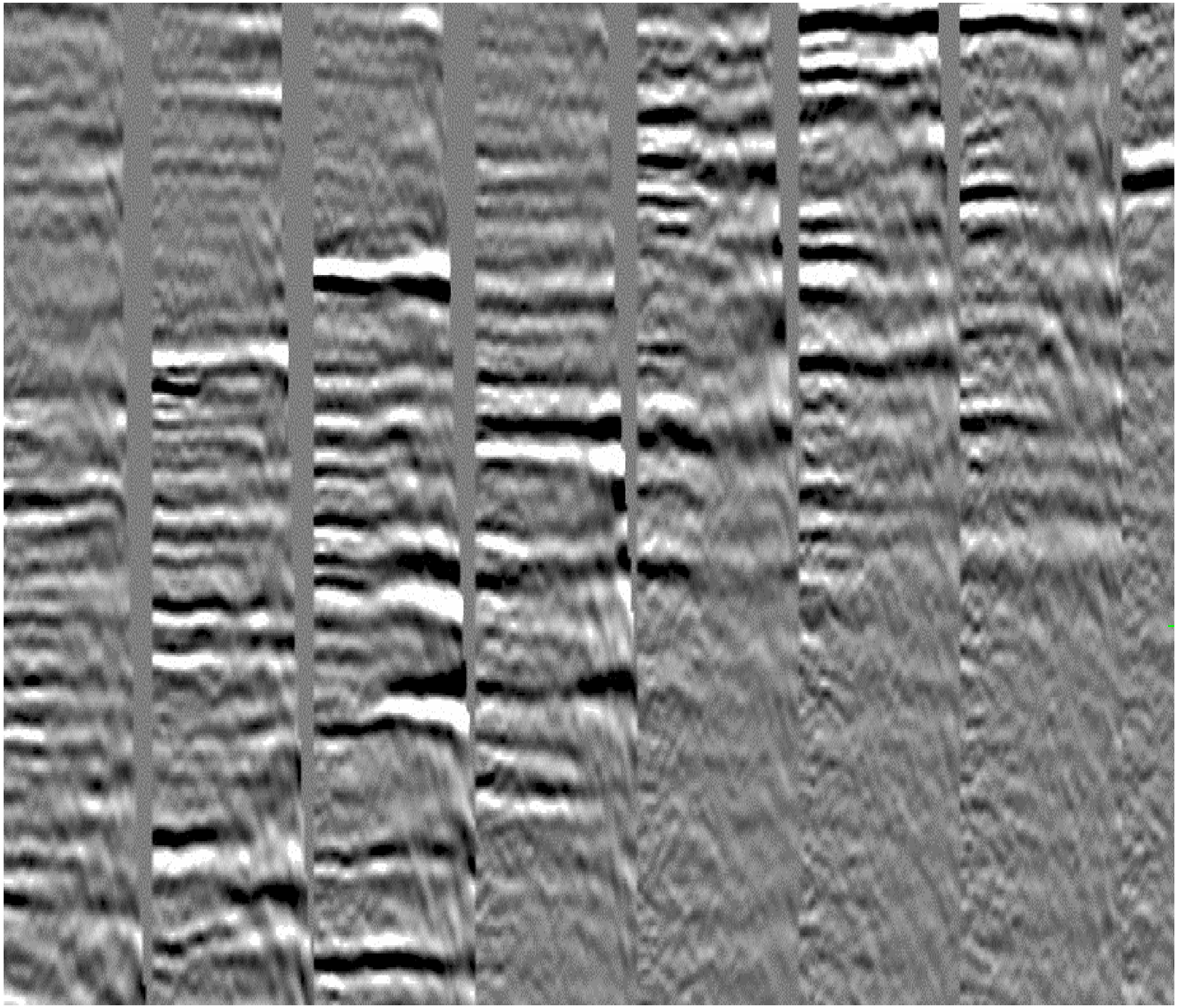
## Common image gather



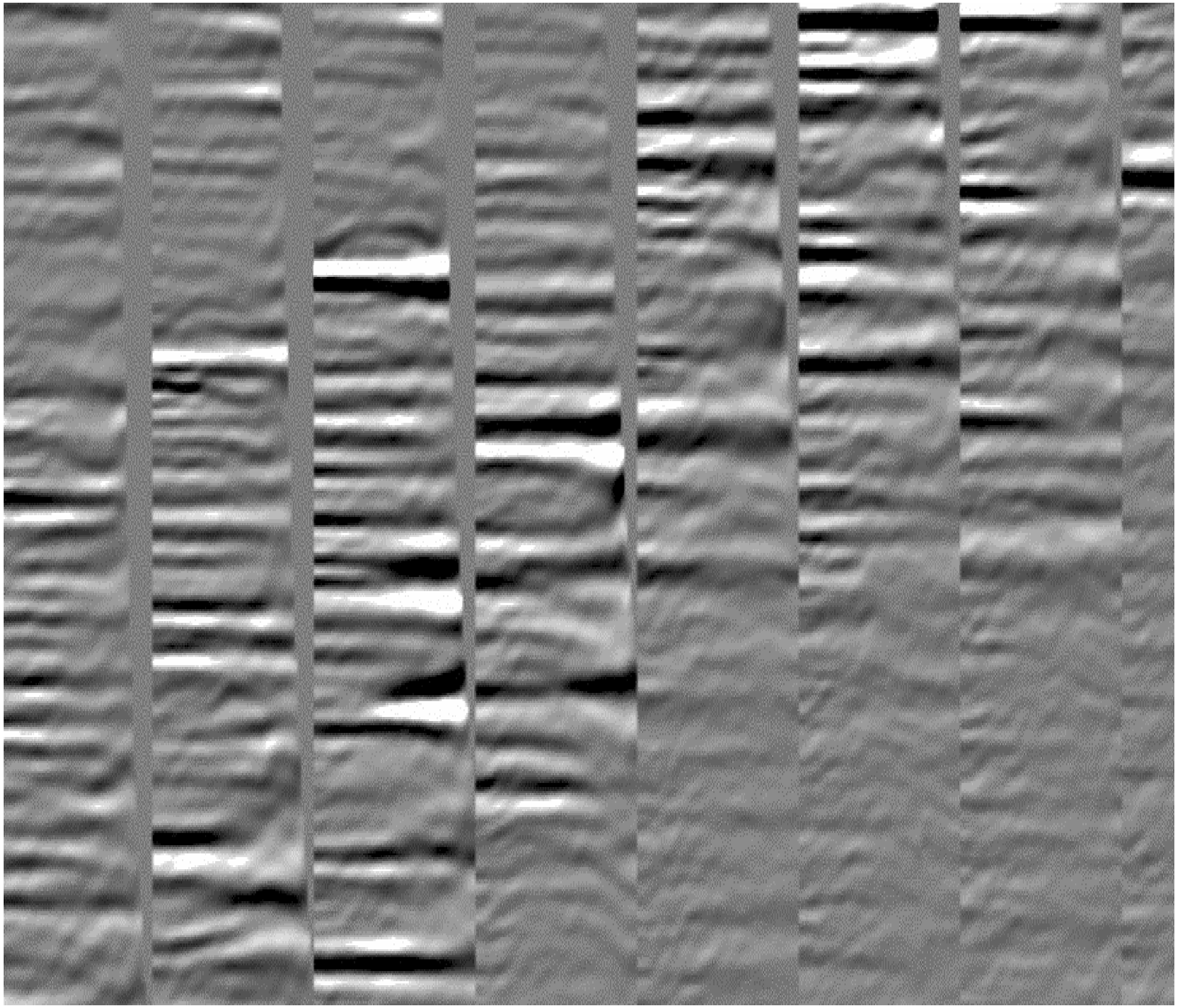




**After depth migration with an *acceptable velocity model*, all events in the gather should line-up ➔ 'flat gathers'**

# Gathers output from preSDM - not exactly flat

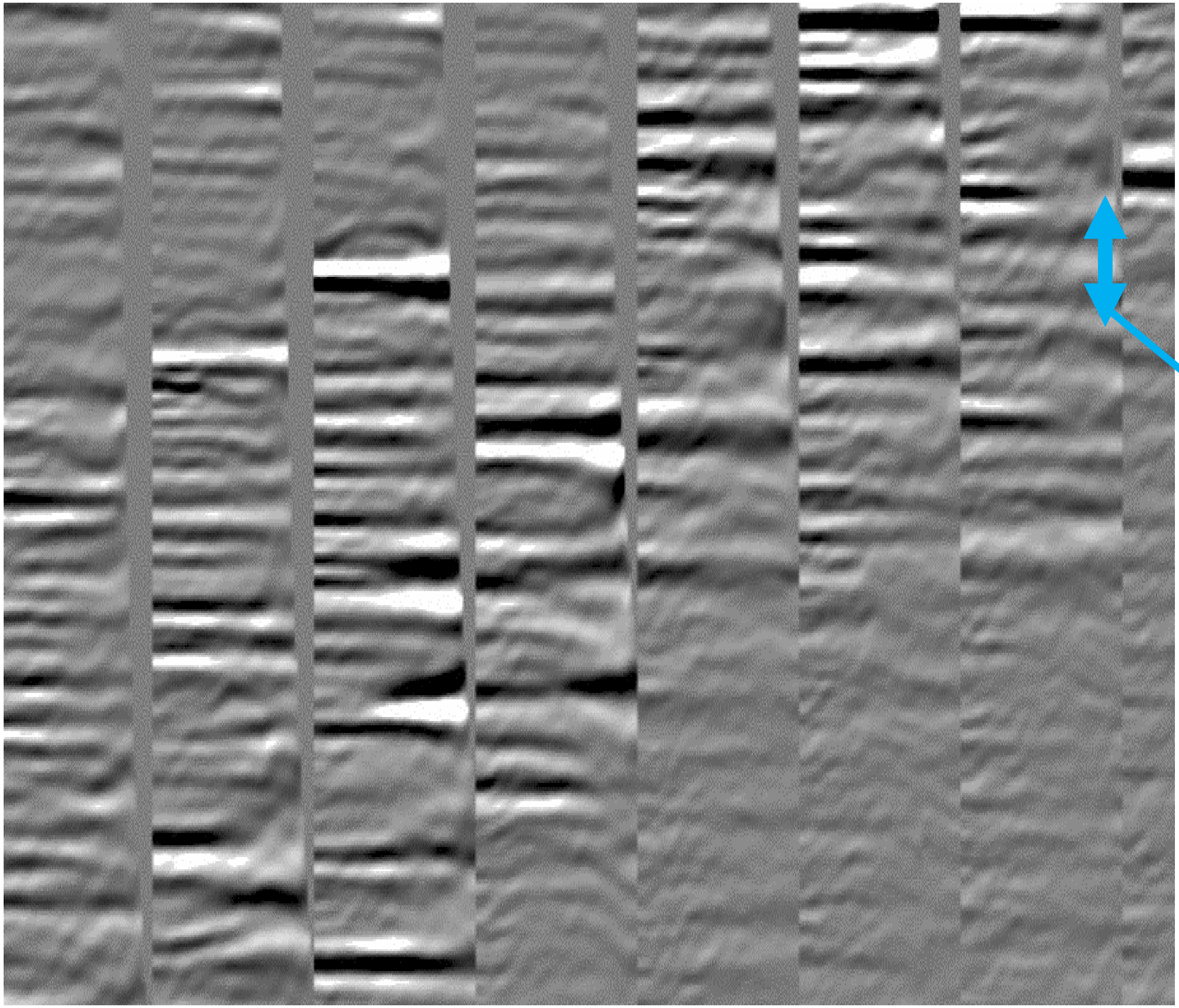


# After final residual event alignment and noise suppression



These data are now suitable for analyzing variations in amplitude:

# After final residual event alignment and noise suppression

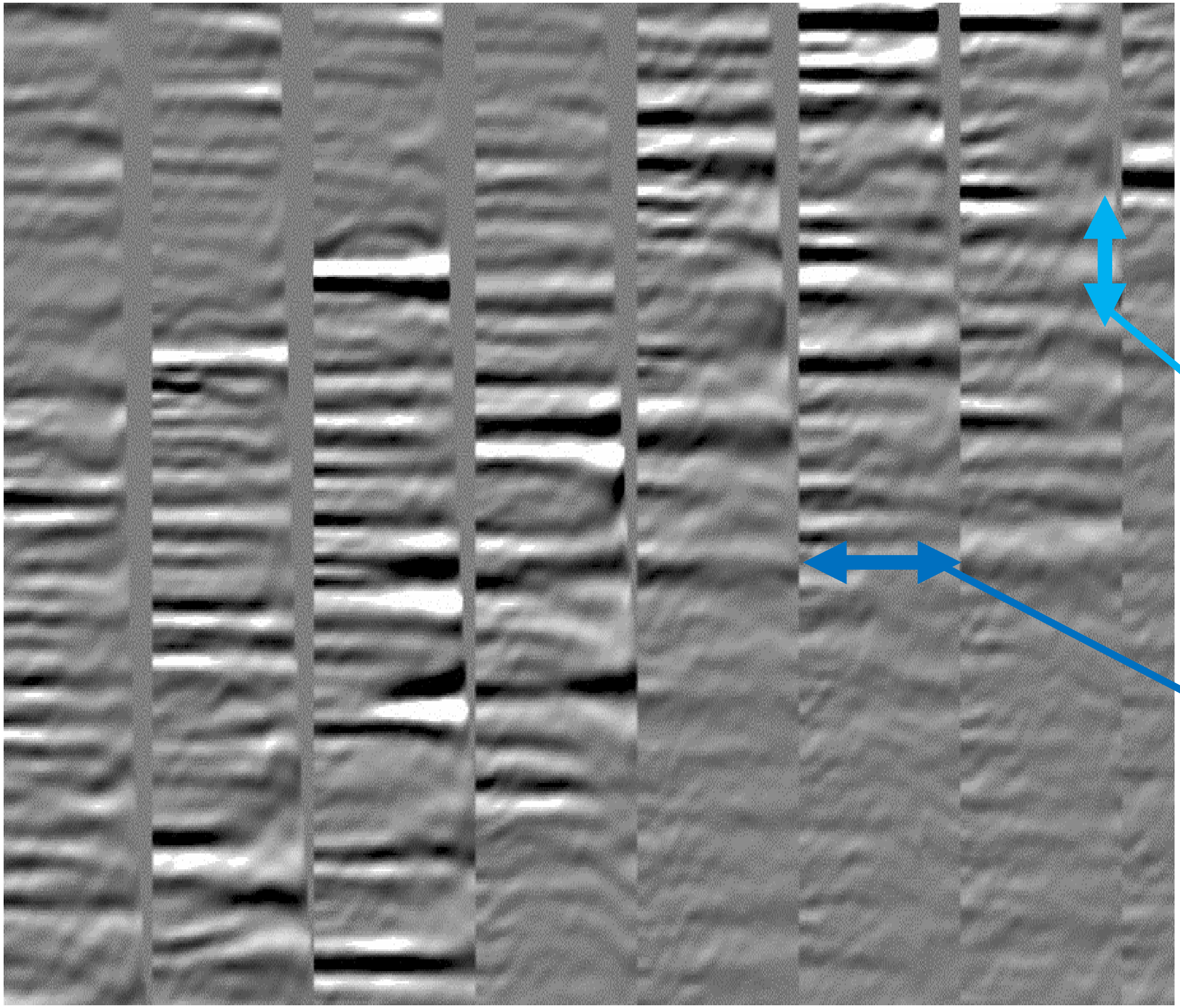


**These data are now suitable for analyzing variations in amplitude:**

**vertically from reflector-to-reflector:**

**$(\rho_2 v_2 - \rho_1 v_1)/(\rho_2 v_2 + \rho_1 v_1)$**

# After final residual event alignment and noise suppression



These data are now suitable for analyzing variations in amplitude:

vertically from reflector-to-reflector

and laterally versus incidence angle at the reflectors

# Rock physics basics:
## (for isotropic materials)

**The Knott-Zoeppritz equations (Mavko et al. approx):**

$$Rp_\theta \sim R_0 + B \sin^2(\theta) + C \{\tan^2(\theta) - \sin^2(\theta)\}$$

$$B = \delta V_p/2V_p - 2 (V_s/V_p)^2 (2\delta V_s/V_s + \delta\rho/\rho)$$

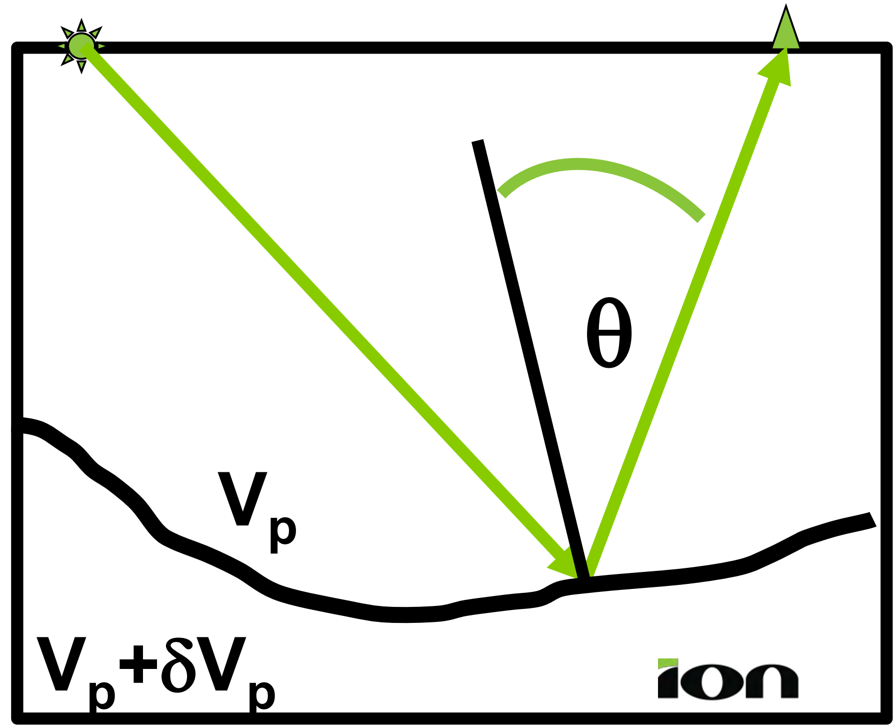
$$C = \delta V_p/2V_p$$

$$R_0 = \delta V_p/2V_p + \delta\rho/2\rho$$

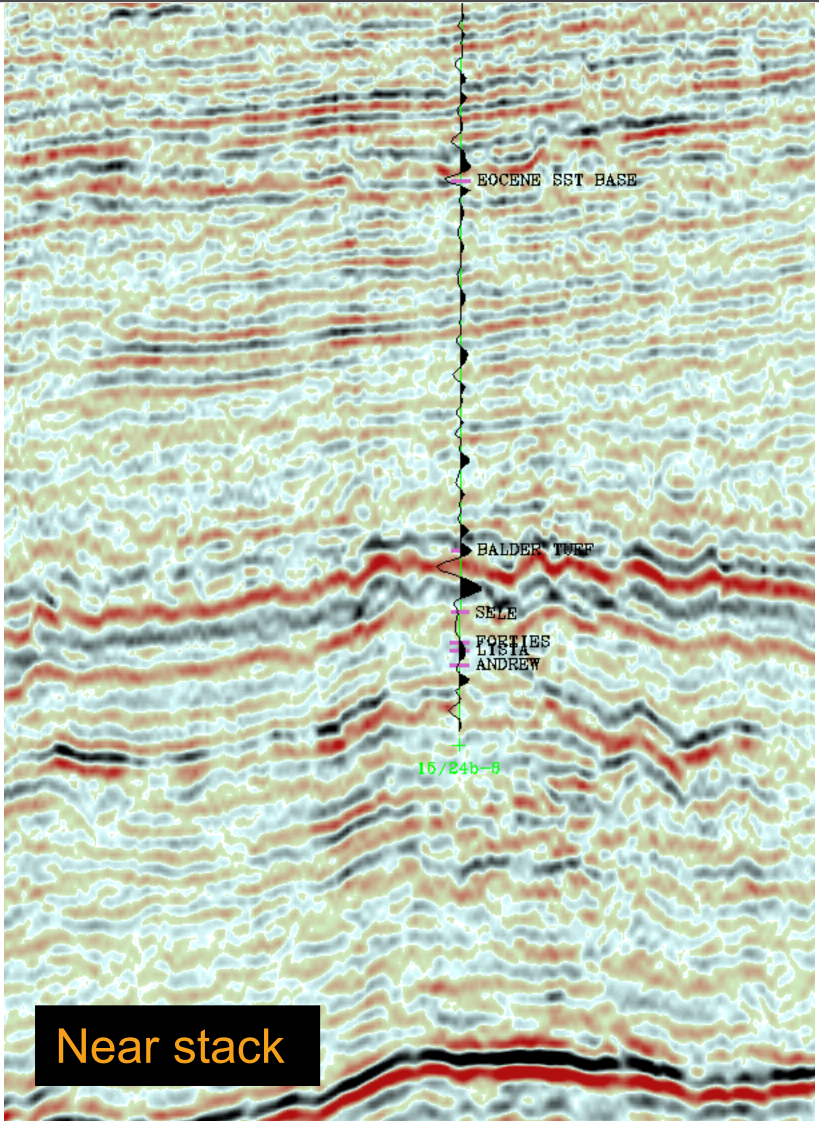
$$V_p = \sqrt{(\lambda + 2\mu)/\rho}$$

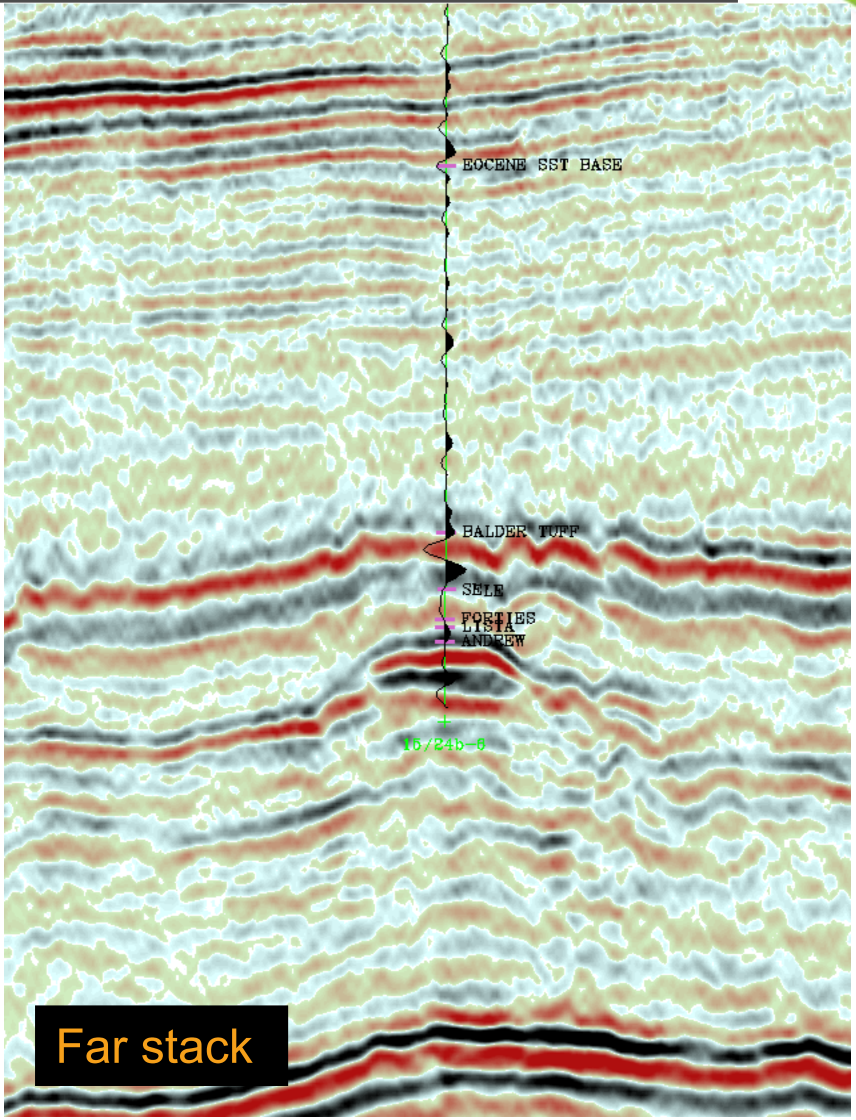
$$V_s = \sqrt{\mu/\rho}$$

cubical strain ($\lambda$) + shear stresses ($\mu$)

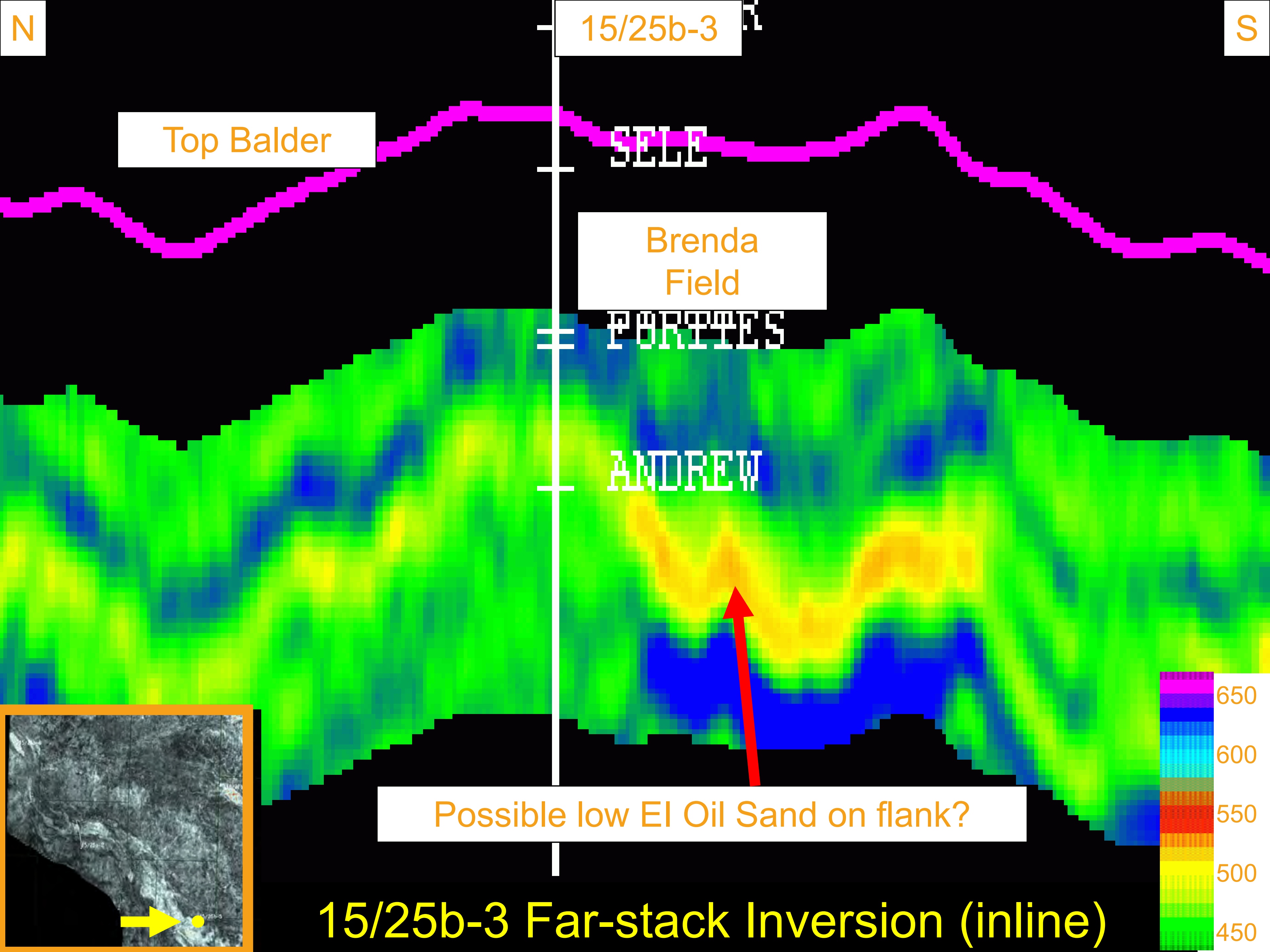


# 3D preSDM Showing AVO Anomalies Over Producing Fields




AVO angle stack synthetics



15/25b-3 Far-stack Inversion (inline)

# Contemporary methodology …..

Everything mentioned so far relates to technology within the ‘state of the art’.

And these techniques continue to be developed…

… e.g.  broadband signals processing, better demultiple, better VMB (FWI), migration amplitudes, ION’s RFWI, and ION’s RWI ….

However, all these isolated developments, including LSRTM, constitute ***INCREMENTAL*** improvements

# What comes next?

What are the main differences between ***incremental*** and ***transformational*** developments?

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Conventional methods, and their associated incremental developments, primarily are non-iterative over the whole workflow: some bits may be iterative (such as tomographic model update, or LS image enhancement), but the overall flow, from input data to final elastic parameters, is dealt with as a more or less a linear single pass approach

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Whereas the ***transformational*** routes offer adaptive iteration over a larger part of the entire workflow, with the possibility of exploiting the full wavefield (multiples, conversions, etc)

# What comes next?

Looking beyond ***incremental*** improvements to more ***transformational*** methodological changes, we have several avenues of development:

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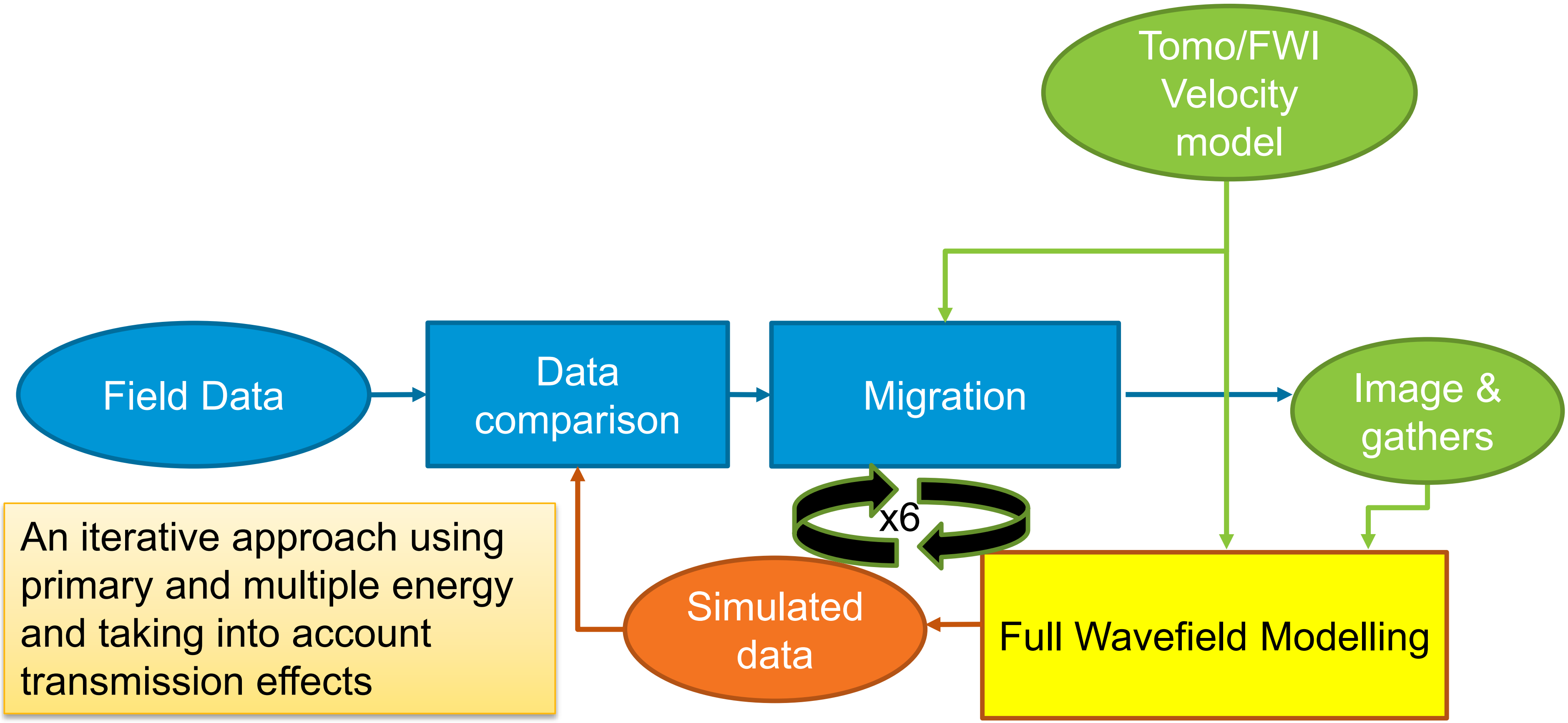
Looking beyond ***incremental*** improvements to more ***transformational*** methodological changes, we have several avenues of development:

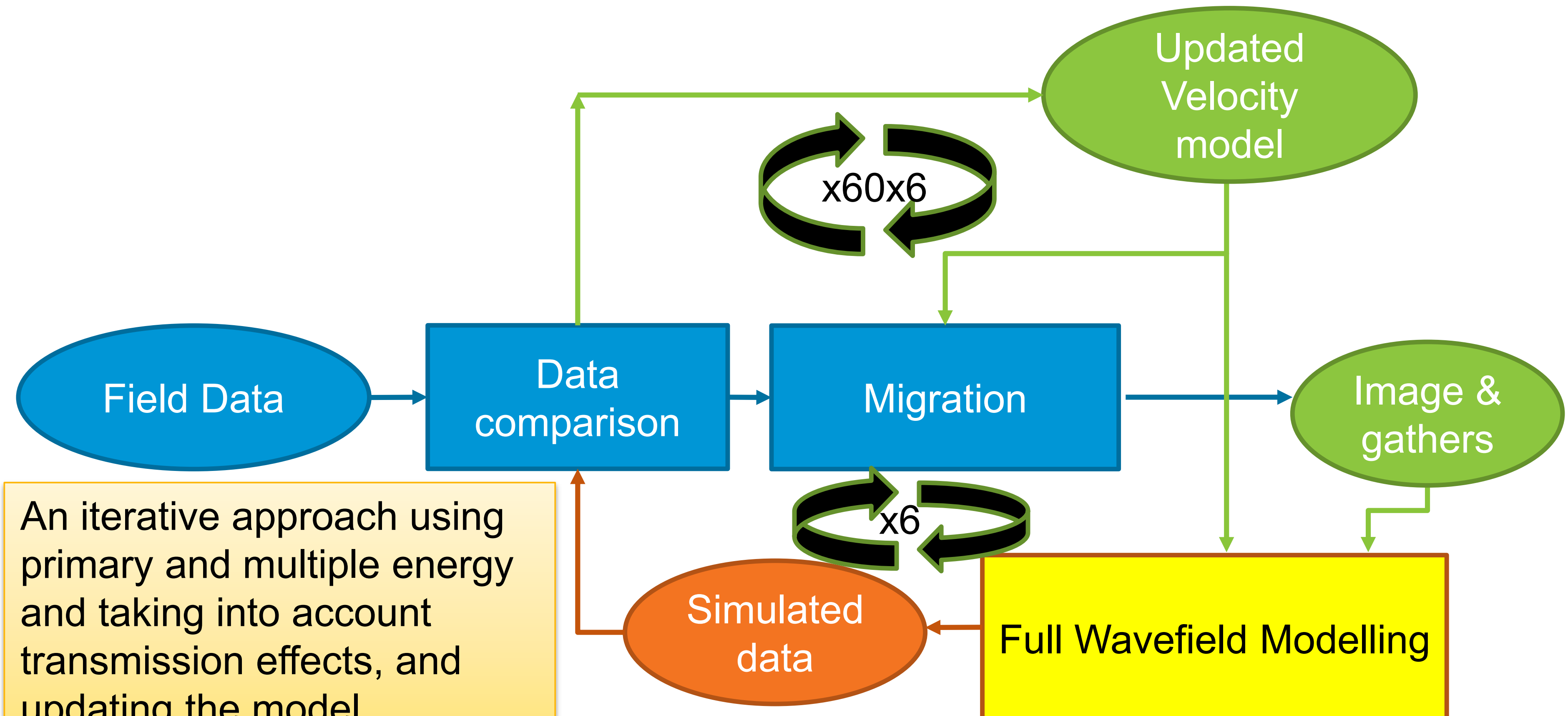
- **Imaging with multiples:**
  this is a step towards exploiting the full wavefield, but still leaves us with just reflectivity data in migrated space, rather than a suite of elastic parameters

# Full Wavefield Migration (FWM) using final (tomography or FWI) model




An iterative approach using primary and multiple energy and taking into account transmission effects

# Joint Migration Inversion (JMI)




An iterative approach using primary and multiple energy and taking into account transmission effects, and updating the model

# What comes next?

Looking beyond ***incremental*** improvements to more ***transformational*** methodological changes, we have several avenues of development:

- **Imaging with multiples:**
  this is a step towards exploiting the full wavefield, but still leaves us with just reflectivity data in migrated space, rather than a suite of elastic parameters

- **Full elastic parameter estimation (elastic FWI):**
  the promise of this approach is to sidestep the intermediate output of angle gathers in migrated space, and instead to invert for the parameter fields that best explain the observed data

# What comes next?

- What is the motivation for moving beyond current ‘best-practice’?

- What technologies are required to fulfil these ambitions?

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  - Increase resolution in reservoir attributes to the extent that they can directly influence drilling decisions and further reduce risk
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# What comes next?

- What is the motivation for moving beyond current ‘best-practice’?
  - Increase resolution in reservoir attributes to the extent that they can directly influence drilling decisions and further reduce risk
  - And, to exploit the full wavefield to the maximum extent possible (exploit multiples, elastic effects, etc)

- What technologies are required to fulfil these ambitions?
  - Low frequency sources
  - Sparse acquisition (?)
  - Two-way propagation wave inversion (to use multiples)
  - Elastic inversion
  - Full vector inversion (multicomponent recorded wavefields)

# The ultimate goal of full waveform inversion….

At present, the limiting assumptions we make in waveform inversion limit what we can achieve:

we can currently forward model with a priori parameters for:

*anisotropic Vp, density, attenuation, (and perhaps Vs)*

but generally we *invert only for P-wave anisotropic velocity*

# The ultimate goal of full waveform inversion….

However, if we can push the frequency range of the inversion, and invert for: *anisotropic Vp, density, attenuation, (and perhaps Vs)*

Then we can directly output the desired elastic parameter volumes, rather than resorting to the intermediate step of migrated gathers ….

# High-resolution attribute example

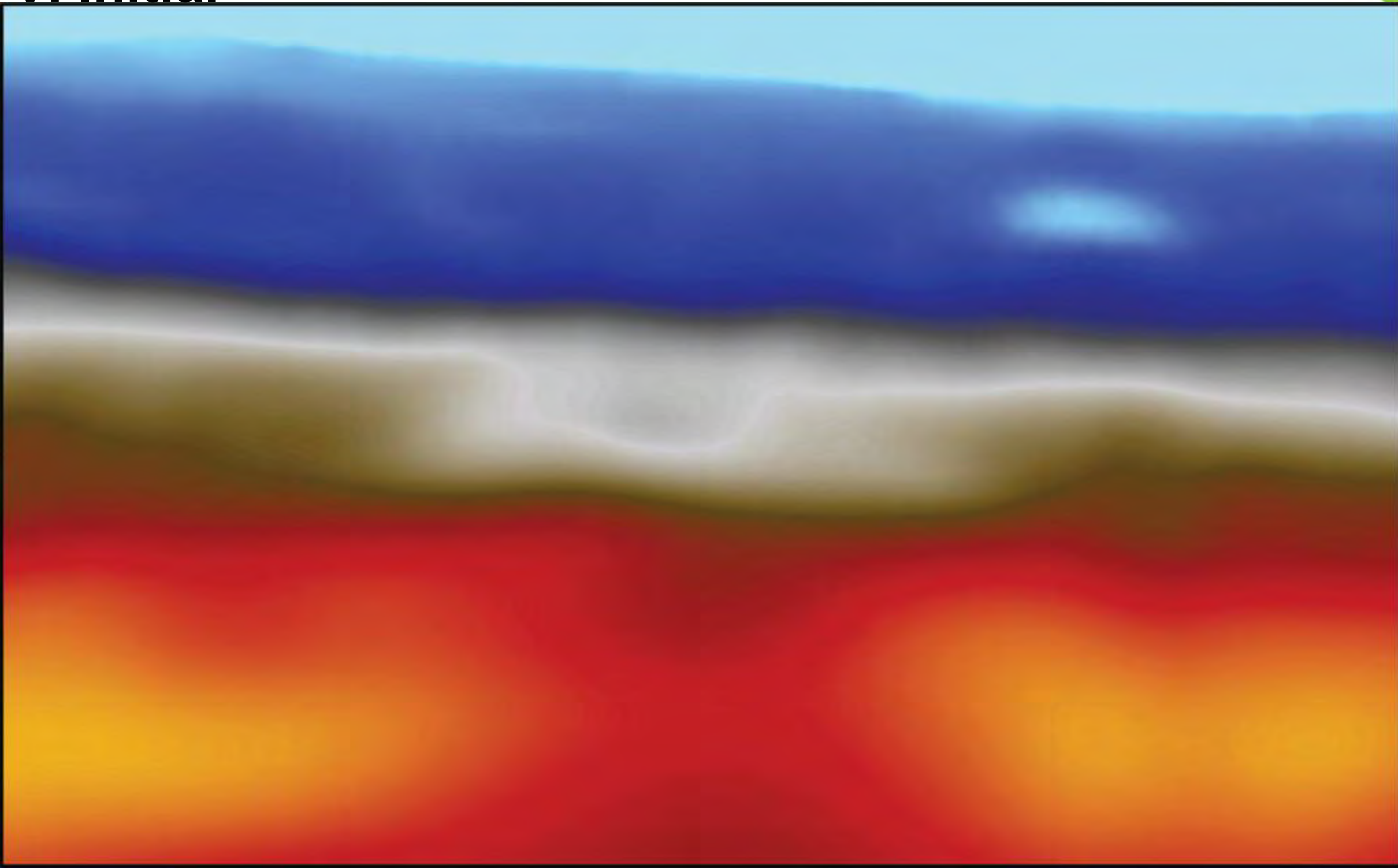
**Courtesy of Steve Hughes, XoM**

Partha Routh, et al., TLE Jan. 2017

Direct inversion of attributes using 40Hz FWI

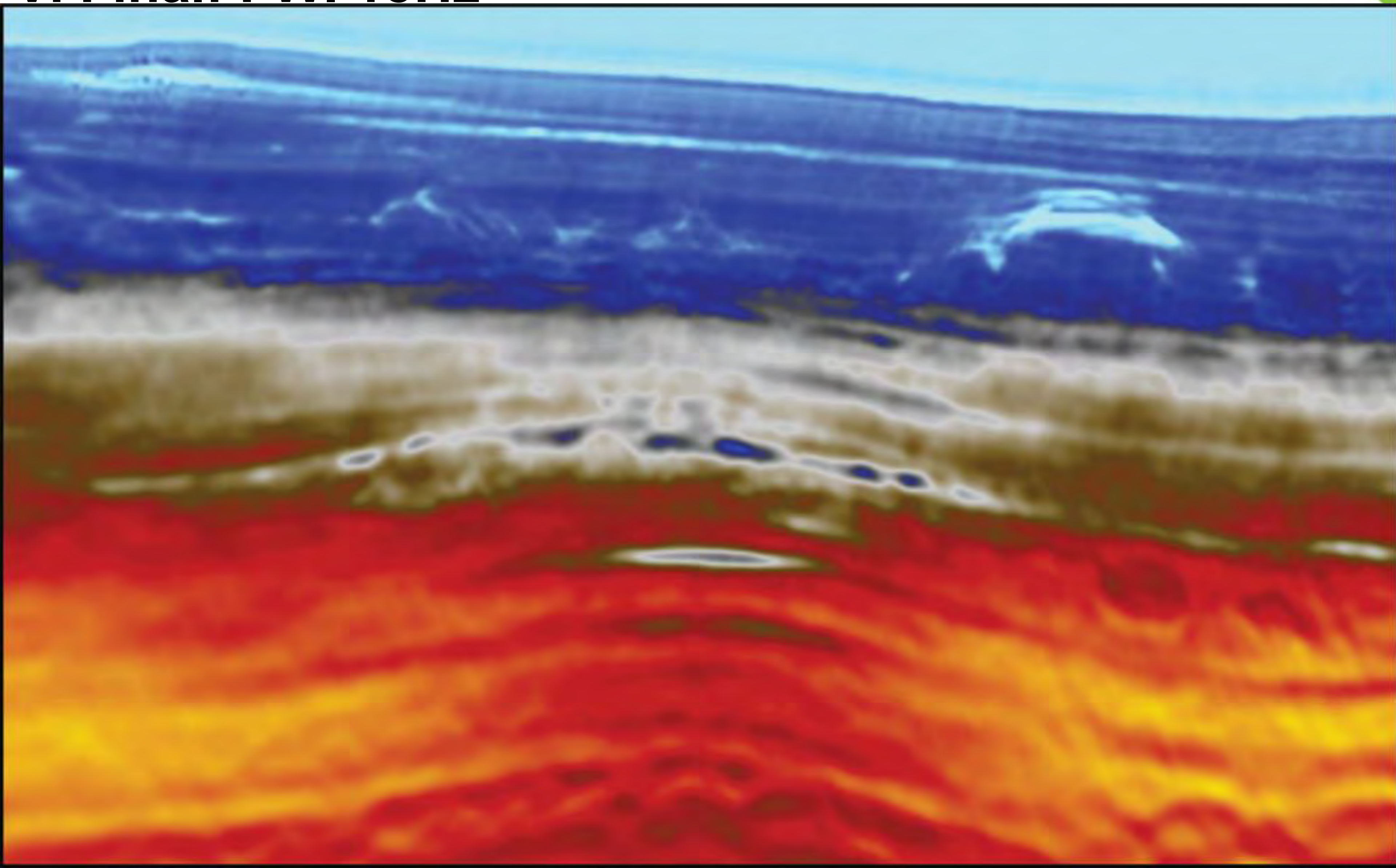
# Tomo velocity model suitable for Kirchhoff migration

## Vi Initial



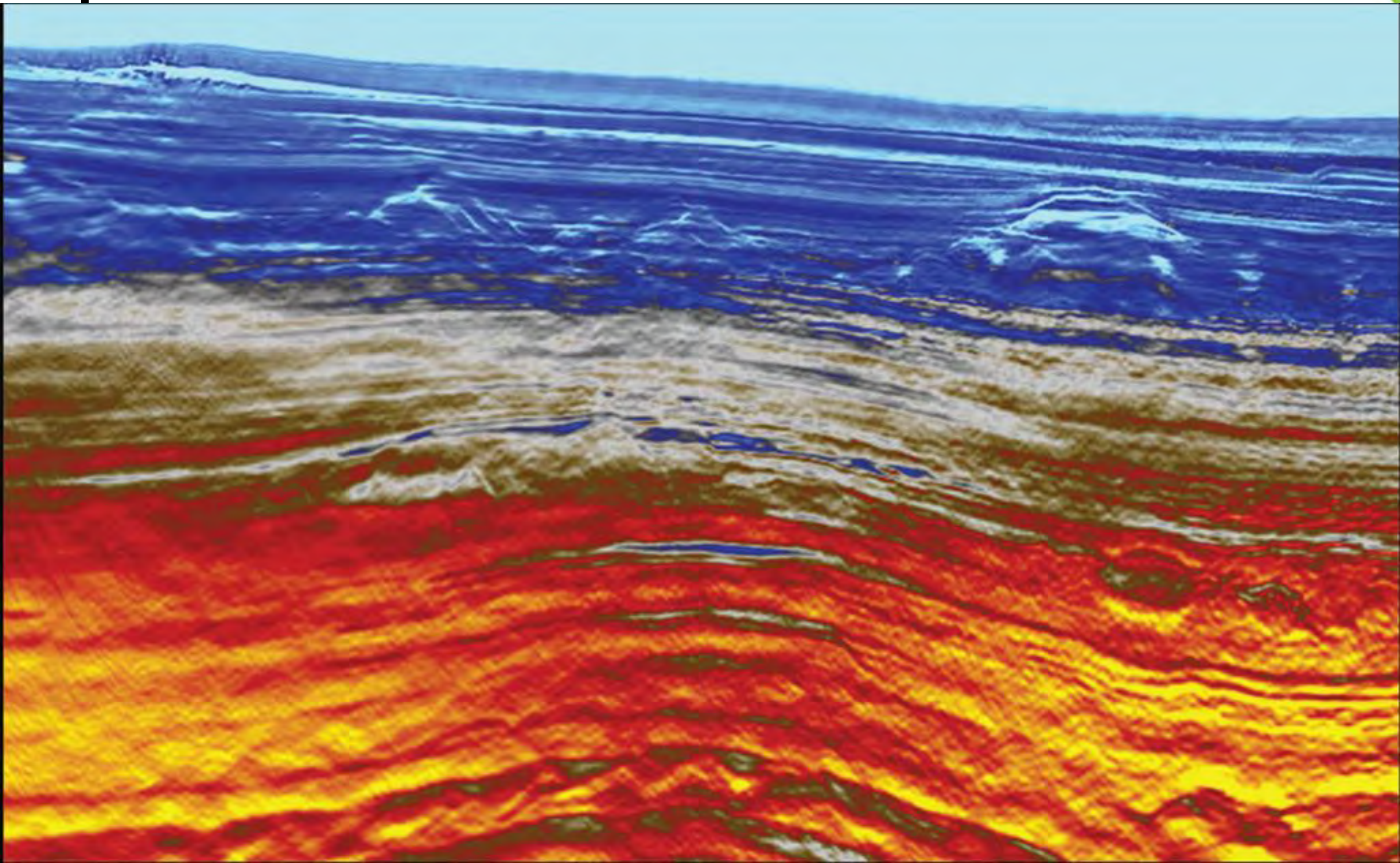
# FWI Velocity model suitable for RTM

## Vi Final: FWI 15Hz



# Impedance model suitable for interpretation

## Impedance: FWI 40Hz

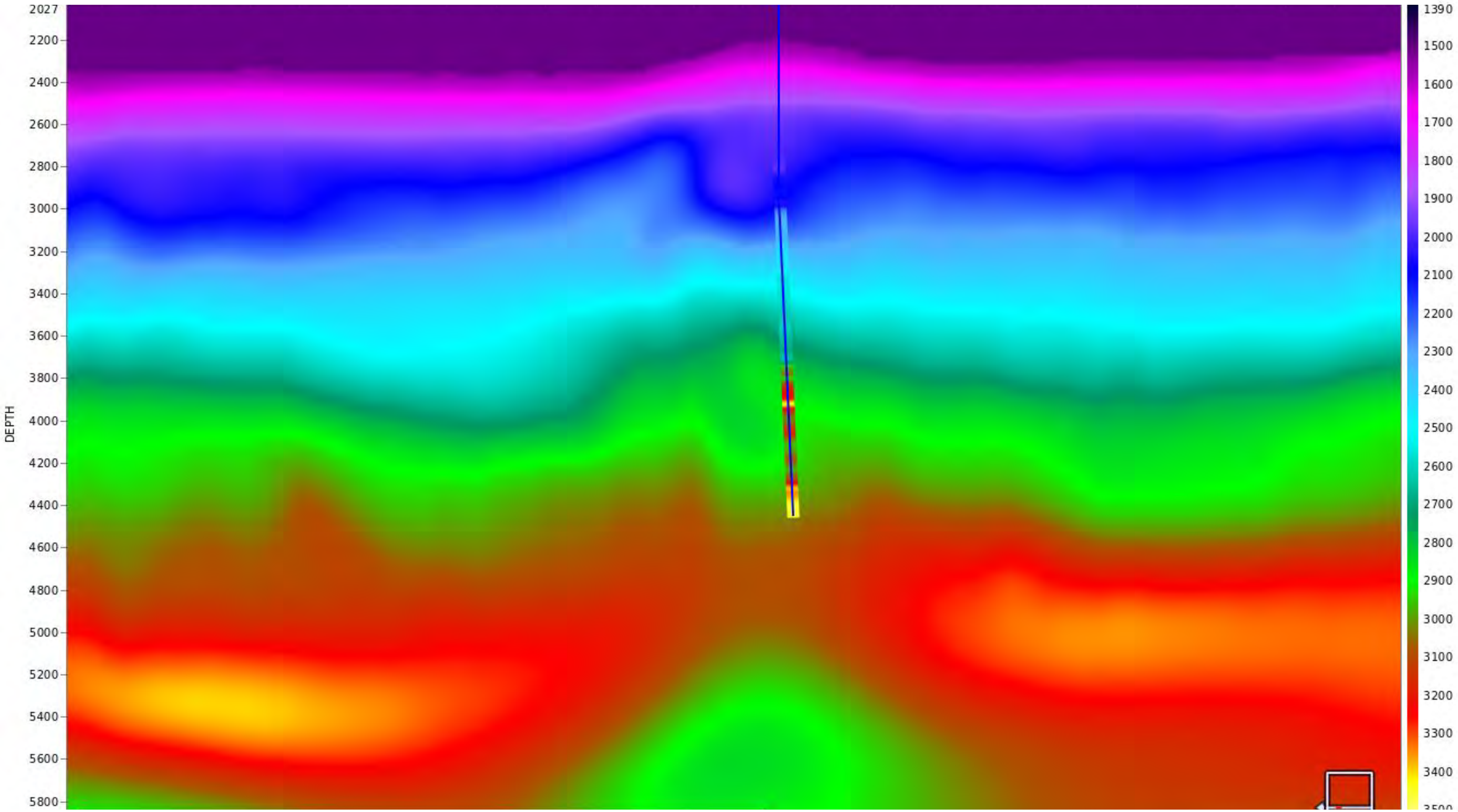


## High-resolution attribute example

**Courtesy of Yannick Cobo, ION**

**Intermediate solution using 12Hz FWI to constrain subsequent impedance inversion**

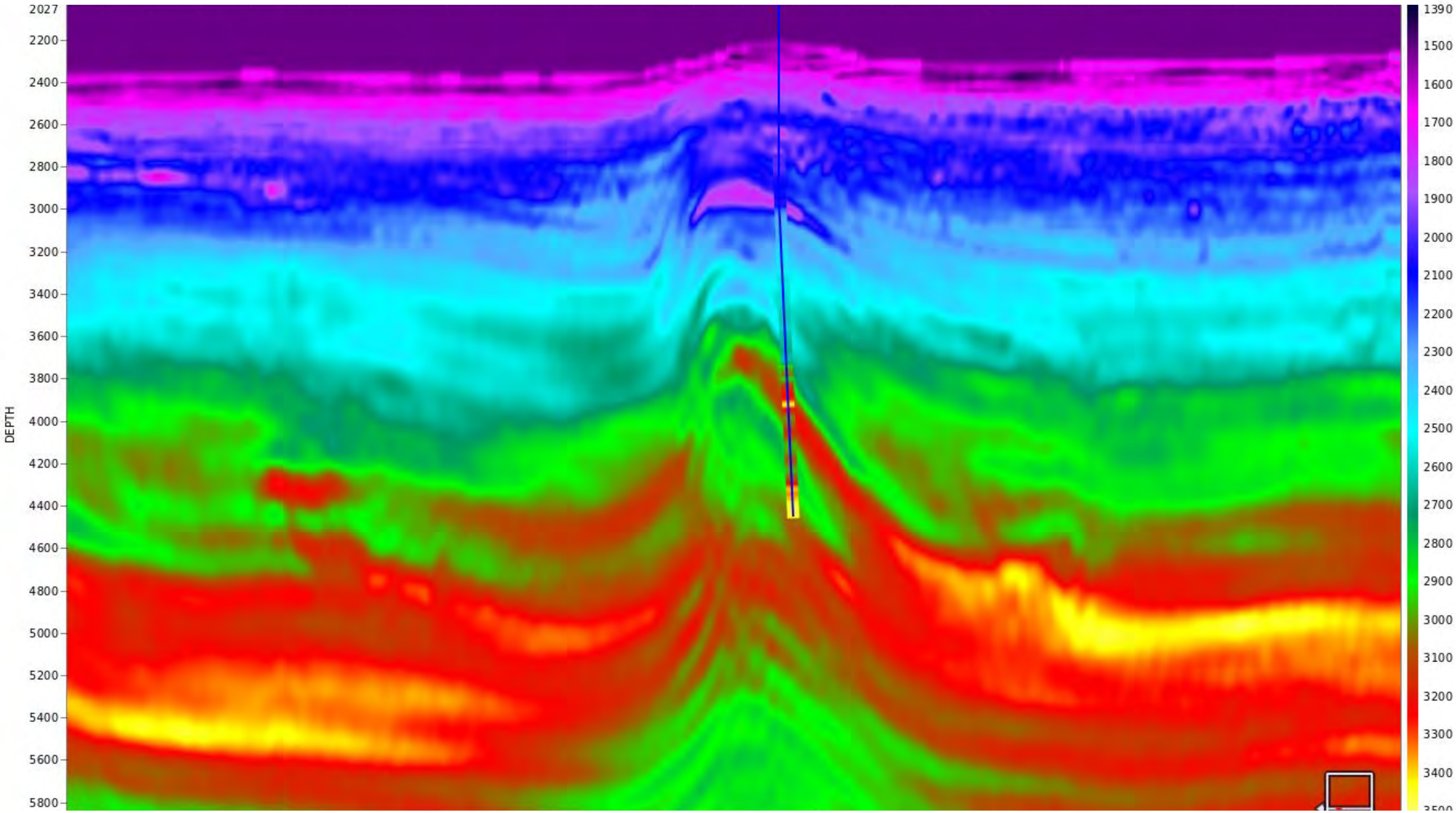
# Tomography Velocity




*Data processed by ION Geophysical in Partnership with Schlumberger, who holds data licensing rights*

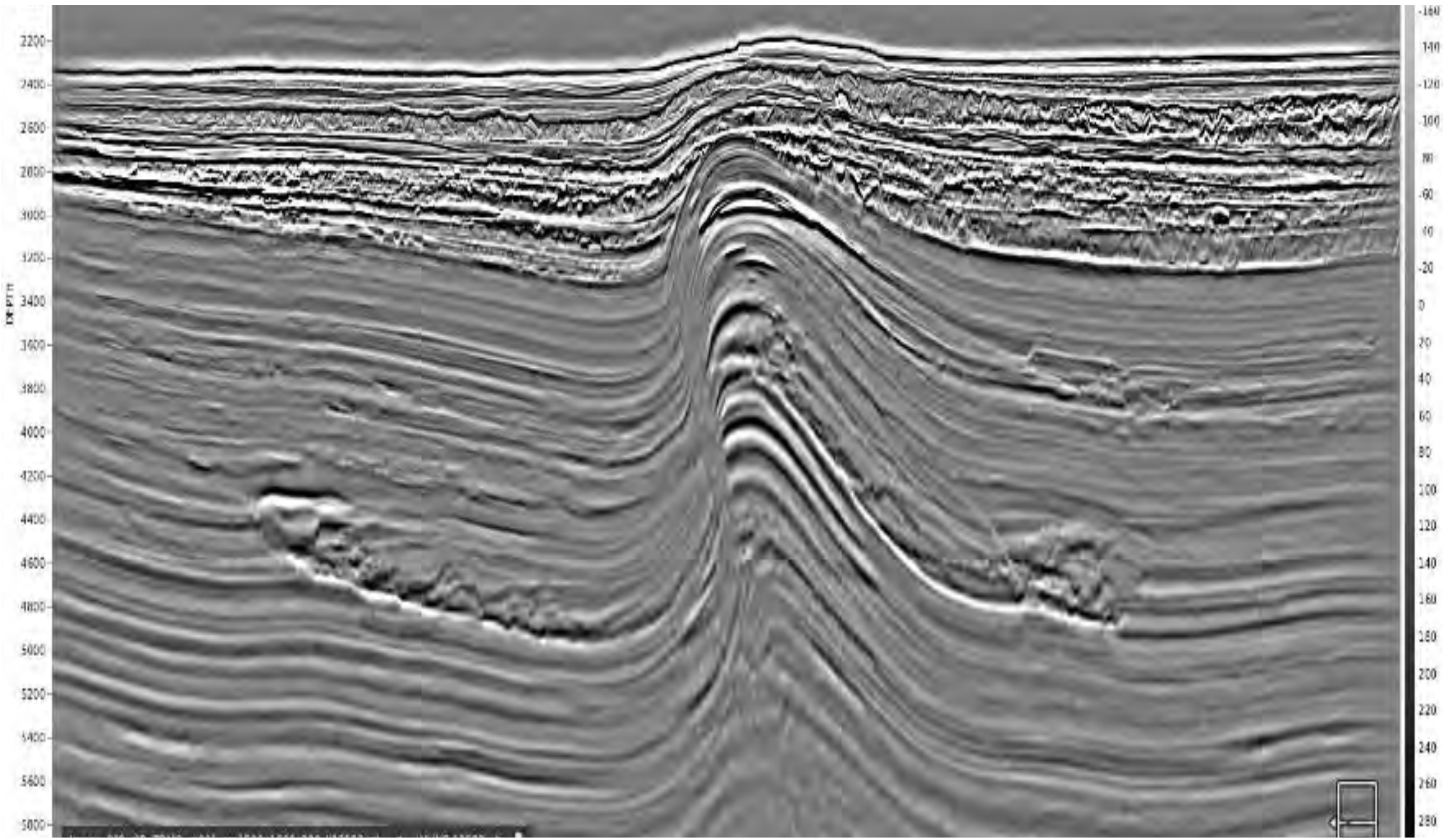
ION

# Reconstructed-wavefield 12Hz FWI velocity




*Data processed by ION Geophysical in Partnership with Schlumberger, who holds data licensing rights*

# 3D TTI preSDM using tomography model




*Data processed by ION Geophysical in Partnership with Schlumberger, who holds data licensing rights*

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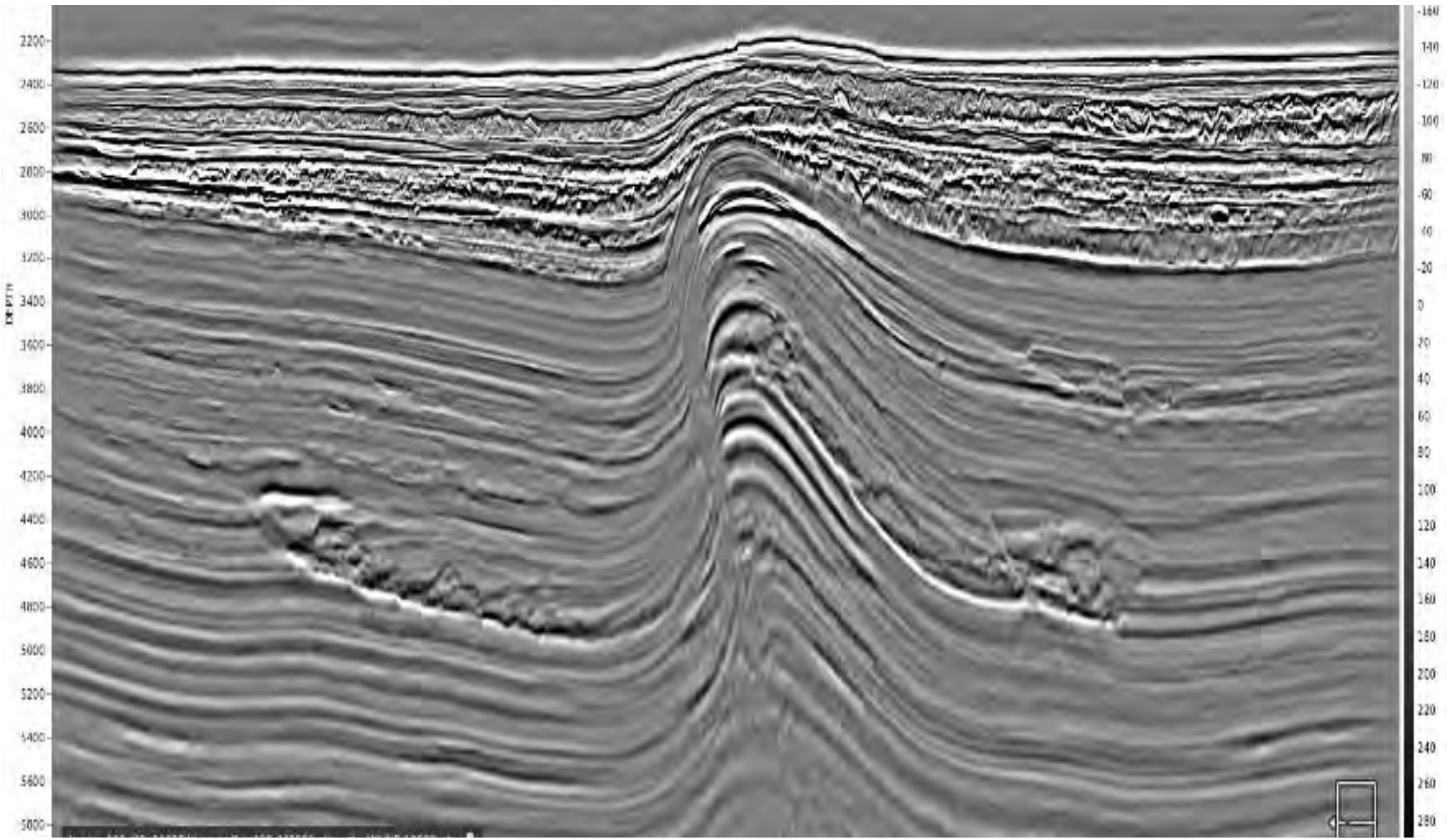
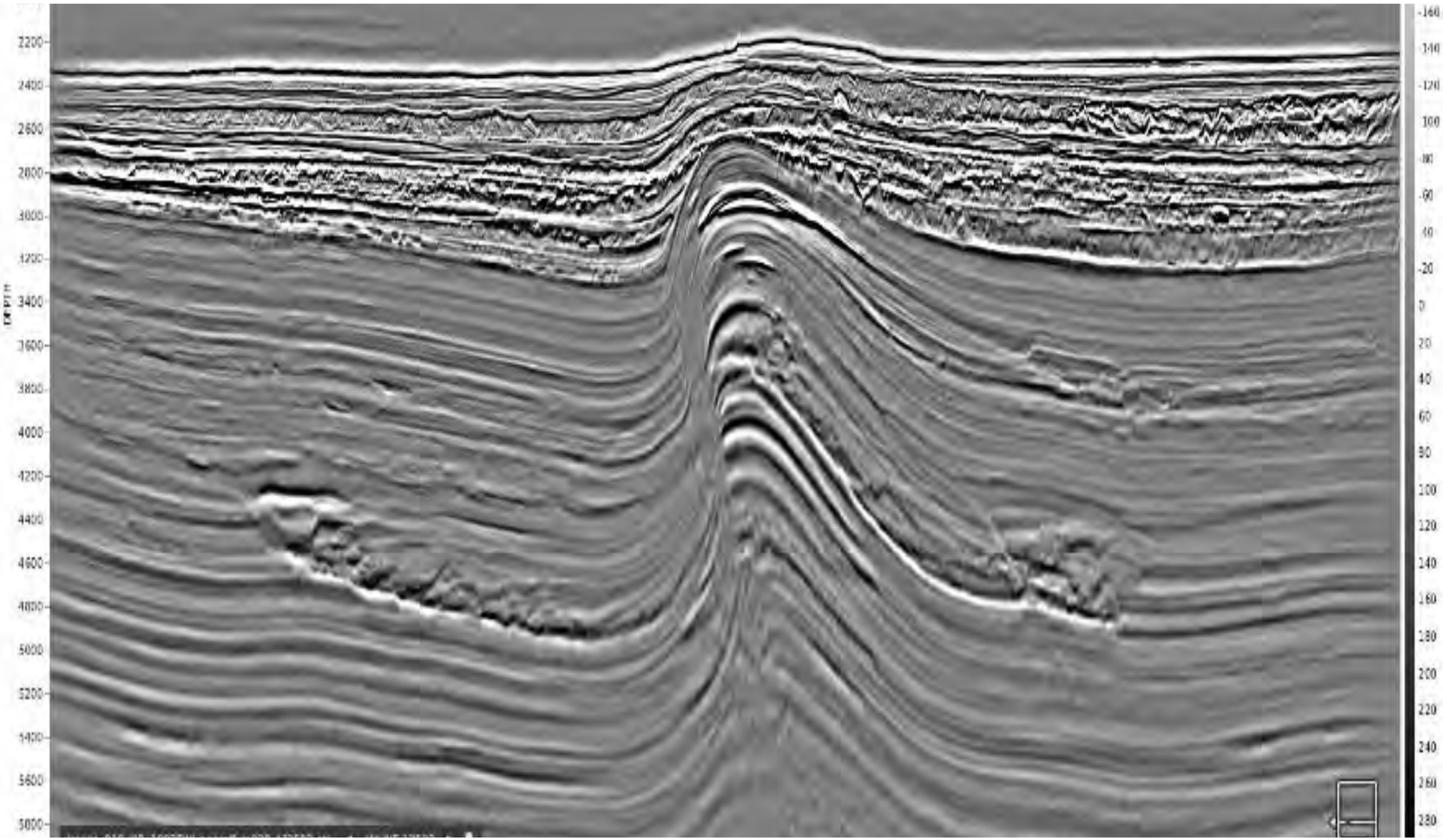
# 3D TTI preSDM using FWI velocity update



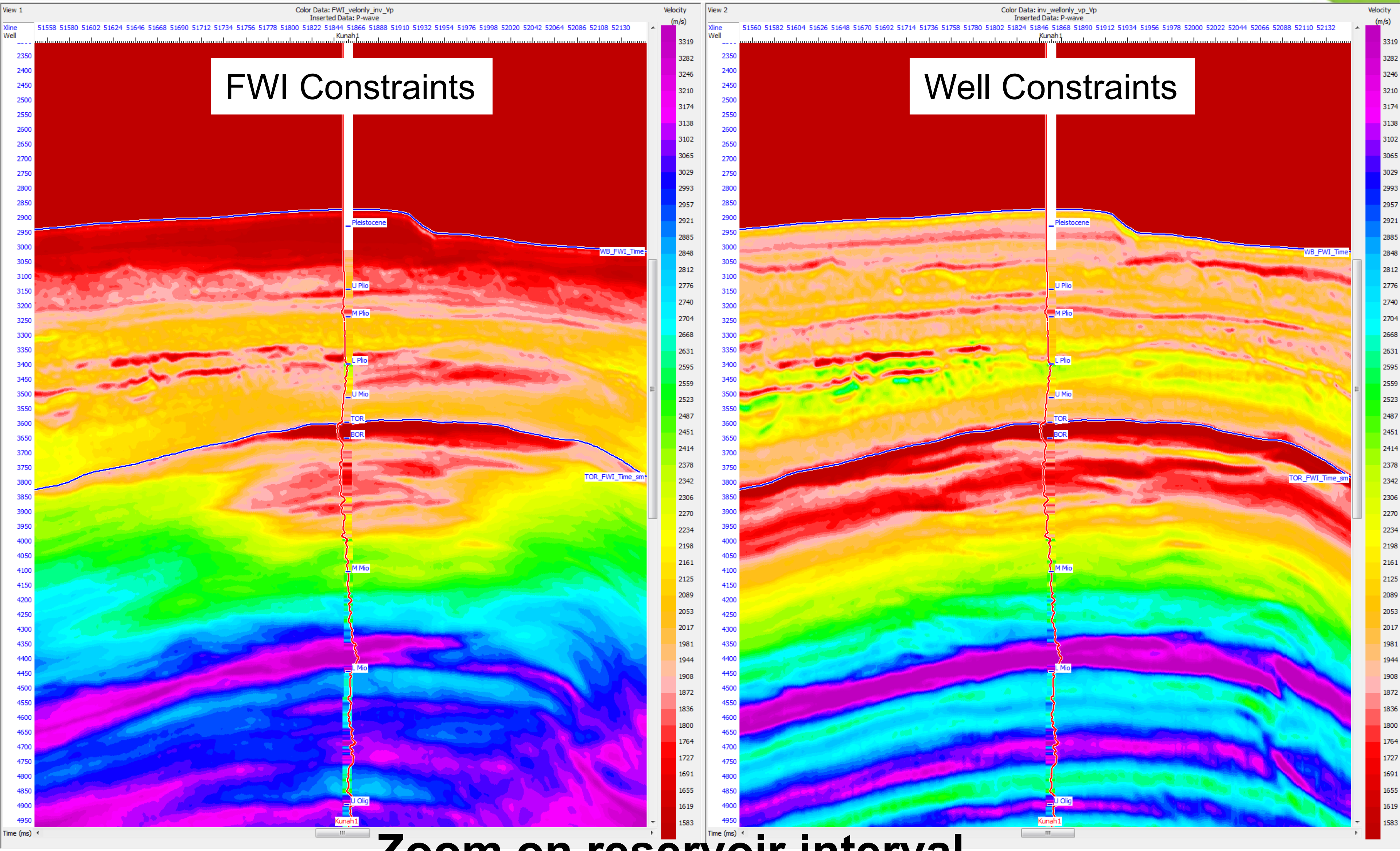

*Data processed by ION Geophysical in Partnership with Schlumberger, who holds data licensing rights*

# 3D TTI preSDM using FWI velocity & epsilon update



*Data processed by ION Geophysical in Partnership with Schlumberger, who holds data licensing rights*

# Impedance inversion using FWI vs Well low-freq trend




**Zoom on reservoir interval**

*Data processed by ION Geophysical in Partnership with Schlumberger, who holds data licensing rights*

# Conclusion

**The seismic method has not yet achieved its full potential:**

**- the increased cost-effectiveness of compute infrastructure facilitates enhanced exploitation of the recorded data, so as to better image and understand our reservoirs, with an associated reduction in risk.**

# Thank you for your attention!

Powering data-driven decisions