

# Sensitivity Analysis of 4D Full Waveform Inversion

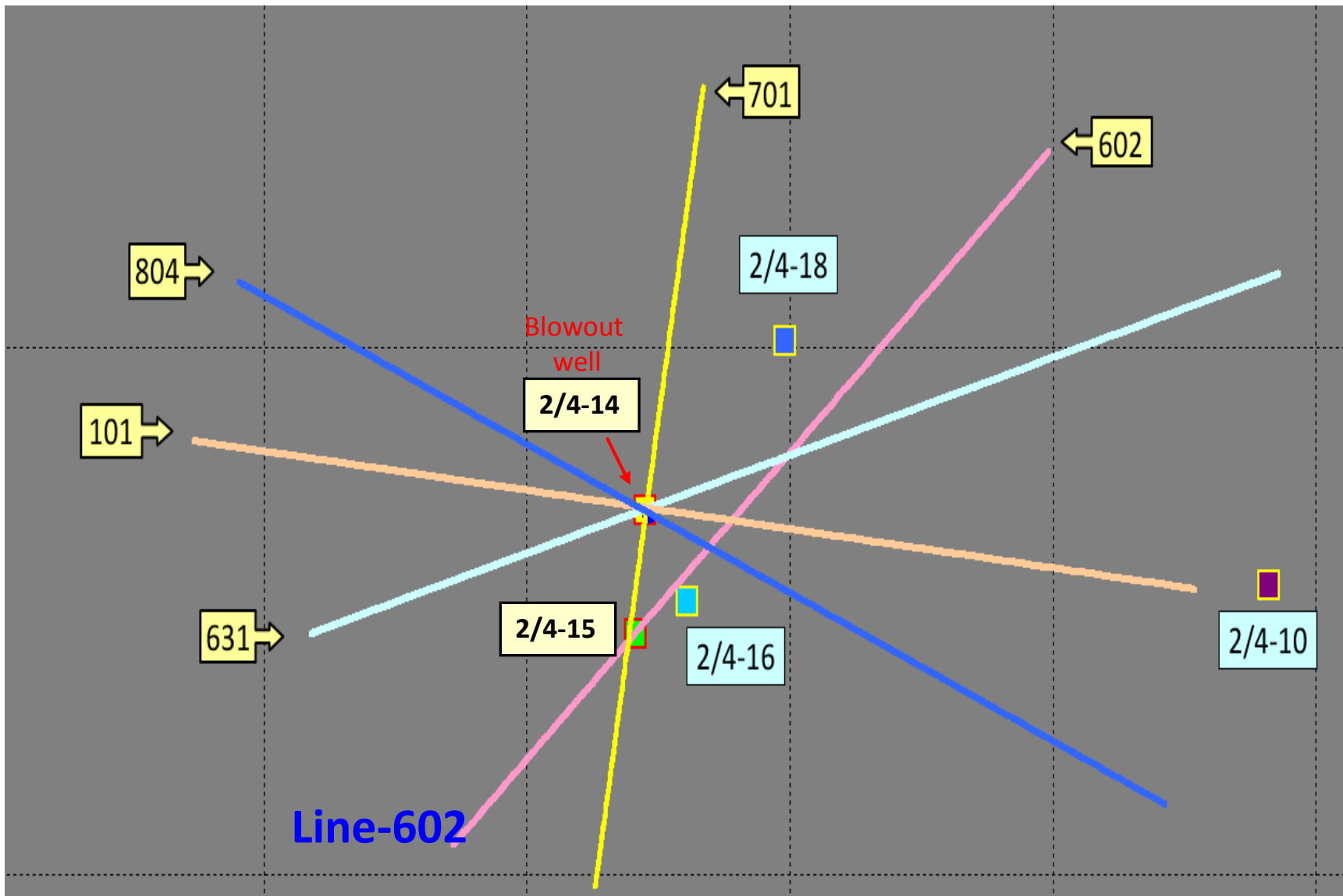
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Martin Landrø

ROSE Meeting (23 April, 2013)

# Objectives

- Determine the feasibility of using 4D FWI on the LOSEM field data (Monitoring Shallow-Gas Migration After a Subsurface blowout)
- Suggest proper practices for performing successful 4D FWI

# Study Area

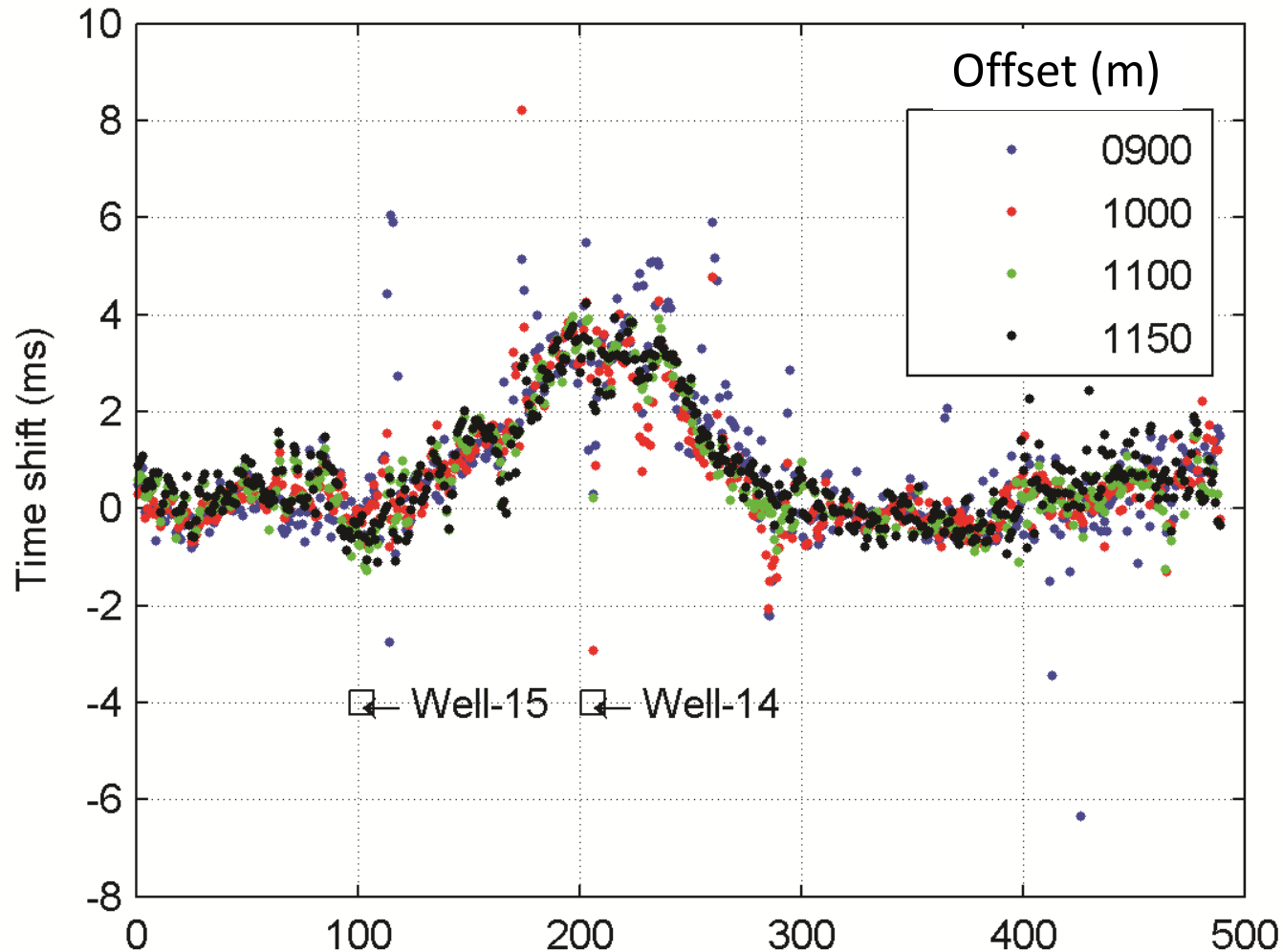


Records Max offset = 1200 m

(Martin Landrø, et. al, 2010)

# Motivation:

## HeadWave time-shift ( $\Delta T$ ) relative to well location

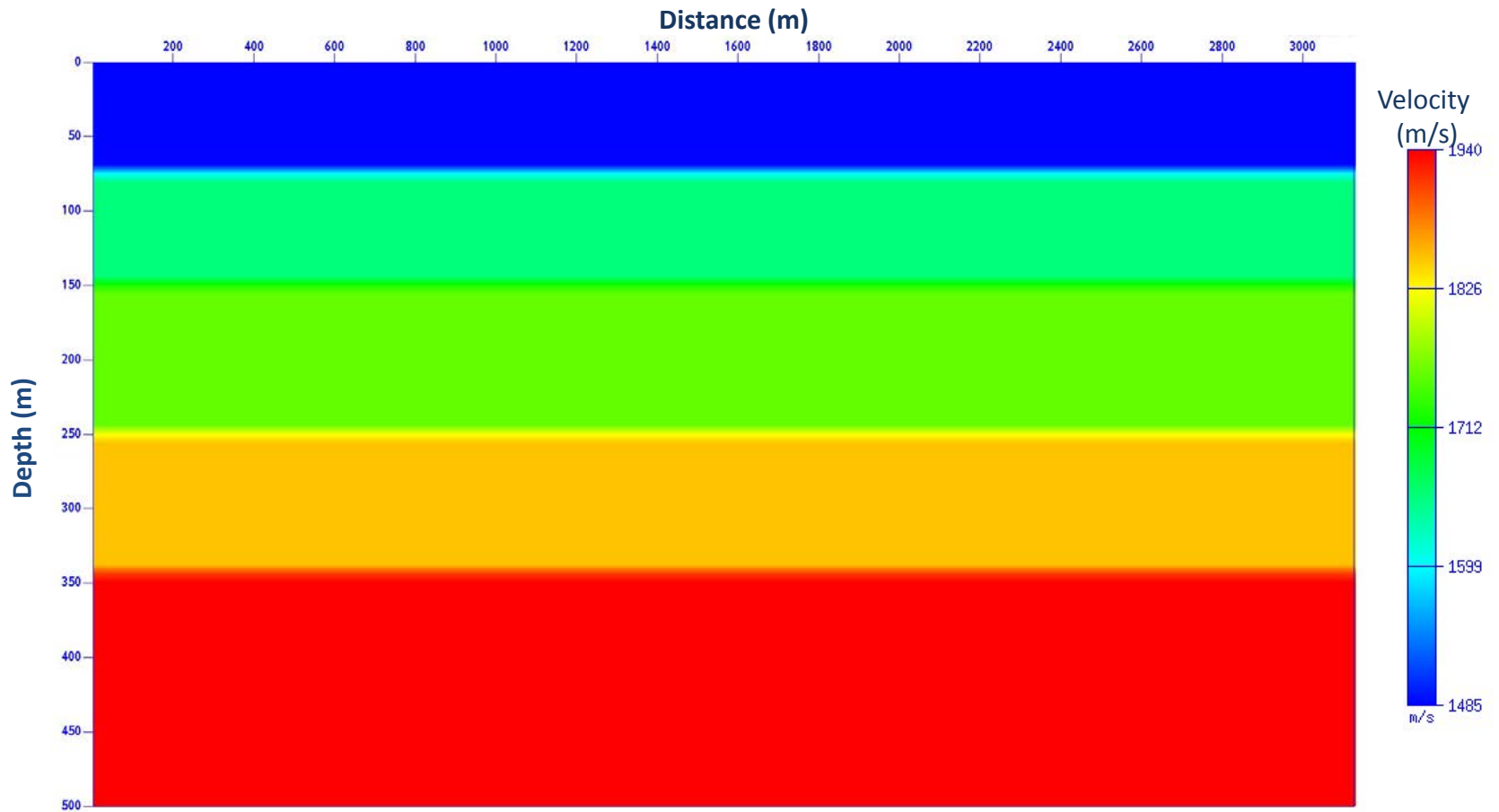


Timeshifts are observed around the blow out well

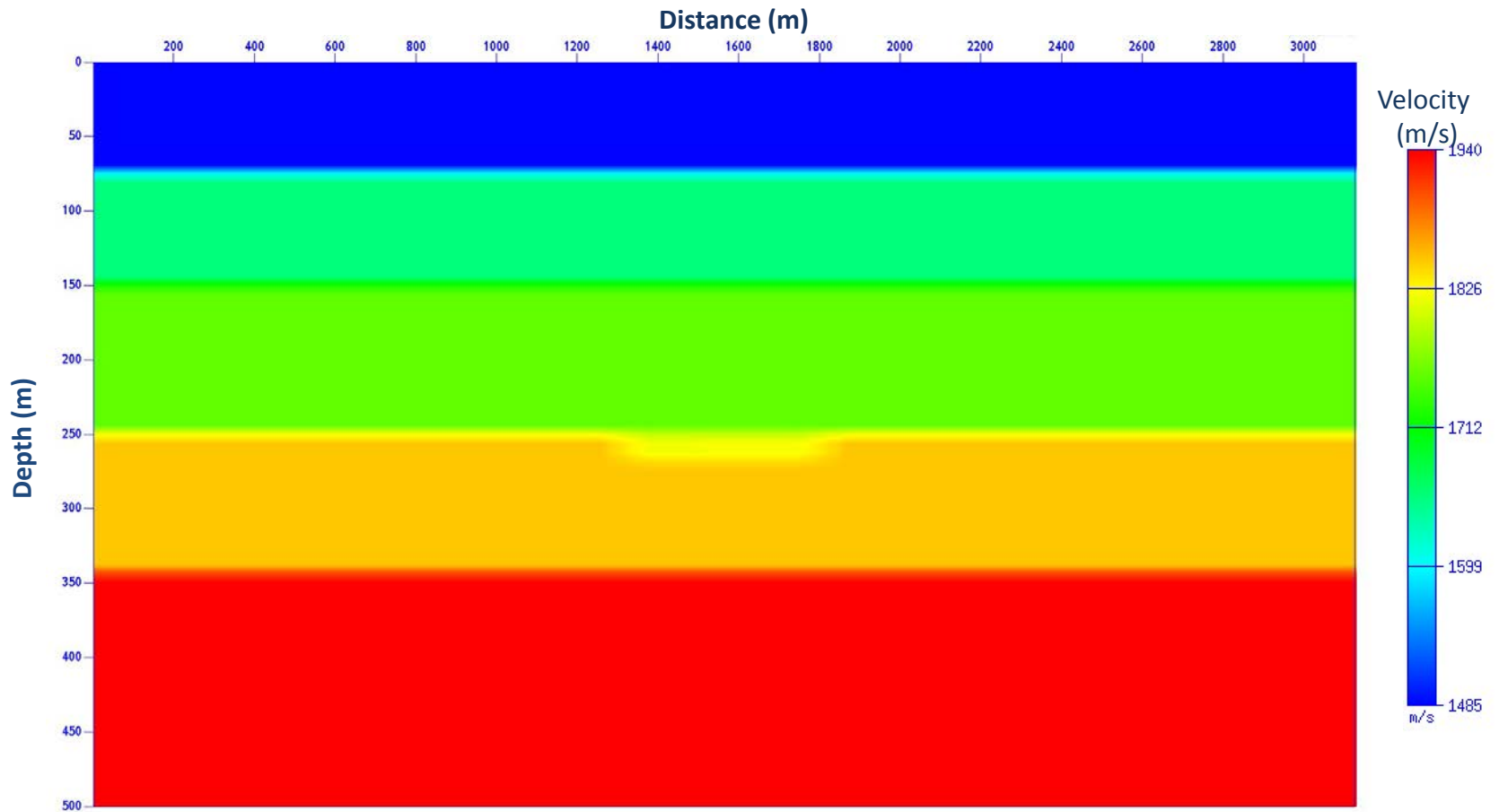
# Outline

- **Introduction**
- **Test 1:** 4D anomaly (magnitude & lateral extent)
- **Test 2:** Inversion Frequency Range
- **Test 3:** Modeling Free Surface Multiples
- **Test 4:** Offset range in presence of noise
- **Test 5:** Effect of Smoothing Initial Velocity Model
- **Field Data Example**
- **Conclusions**

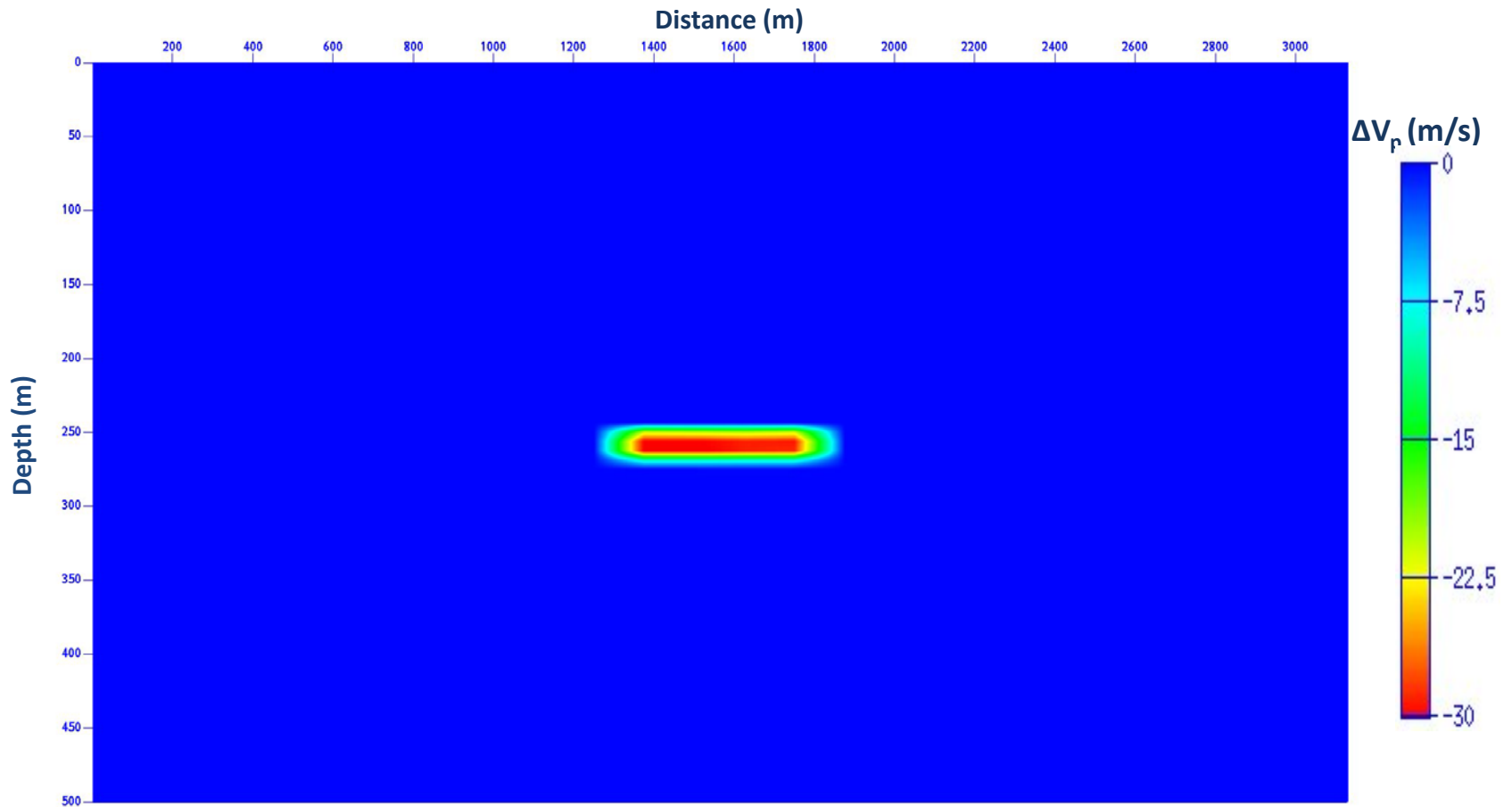
# Base model (Vp)



# Monitor Model (Vp)



$$\Delta V_p \text{ (m/s)} = V_{p_{\text{Monitor}}} - V_{p_{\text{Base}}}$$





# FWI Method

Least squares difference minimization [Tarantola, 1984]

$$\mathcal{J} = \frac{1}{2} \|u(r, t, s) - d(r, t, s)\|^2$$

The data  $d$  satisfies the acoustic wave equation

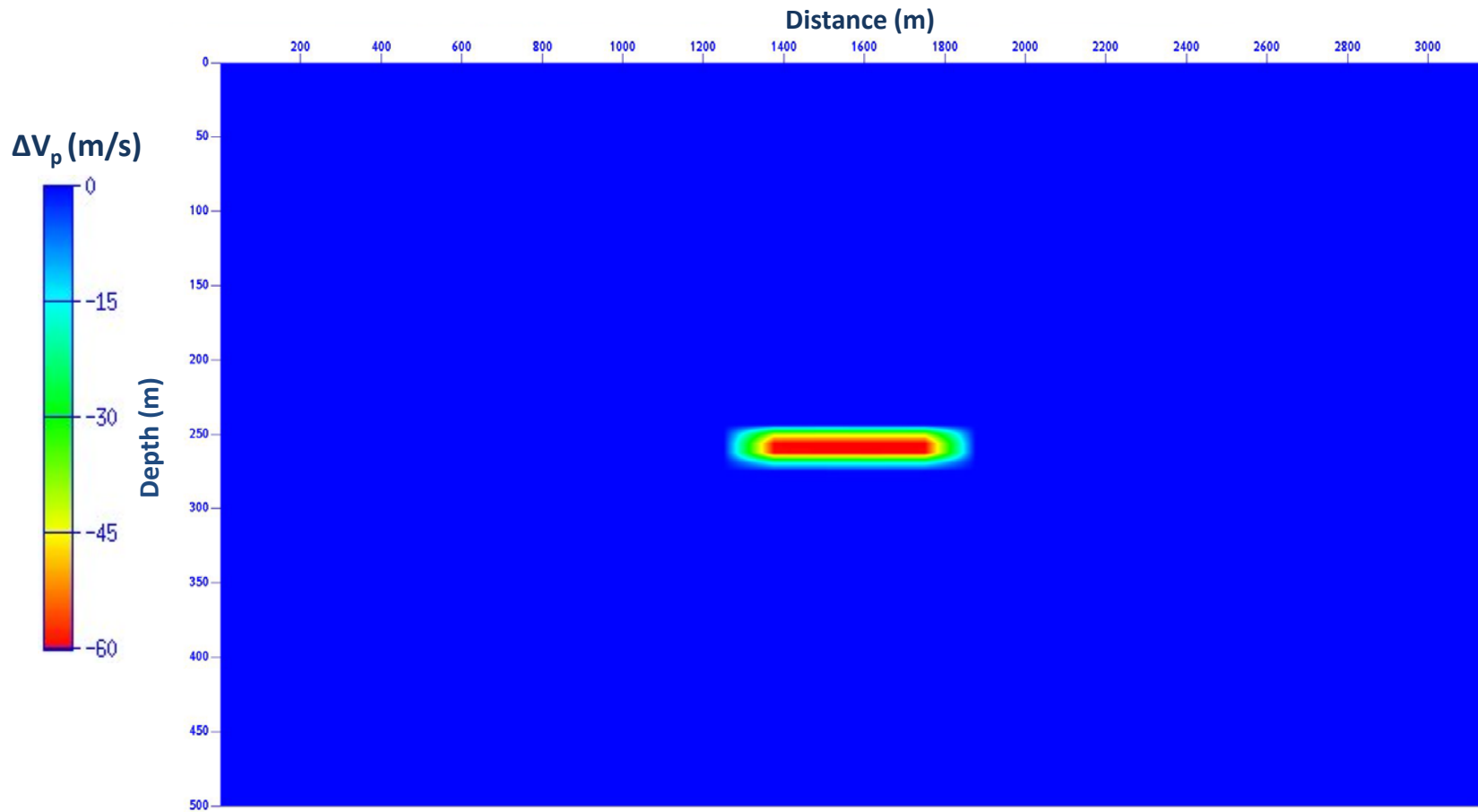
$$\left[ \frac{1}{\rho(x)v(x)^2} \frac{\partial^2}{\partial t^2} - \nabla \cdot \left( \frac{1}{\rho(x)} \nabla \right) \right] d(r, t, s) = S(x, t)$$

# Test 1: 4D Anomaly (Magnitude & size)

- **Part1:** The expected Vp difference ( $\Delta V_p$ ) due to gas migration is between 30-60 m/s (2-4%)
- **Part2:** Run tests with different lateral extents of the gas anomaly (100-200-500-1000 meters)

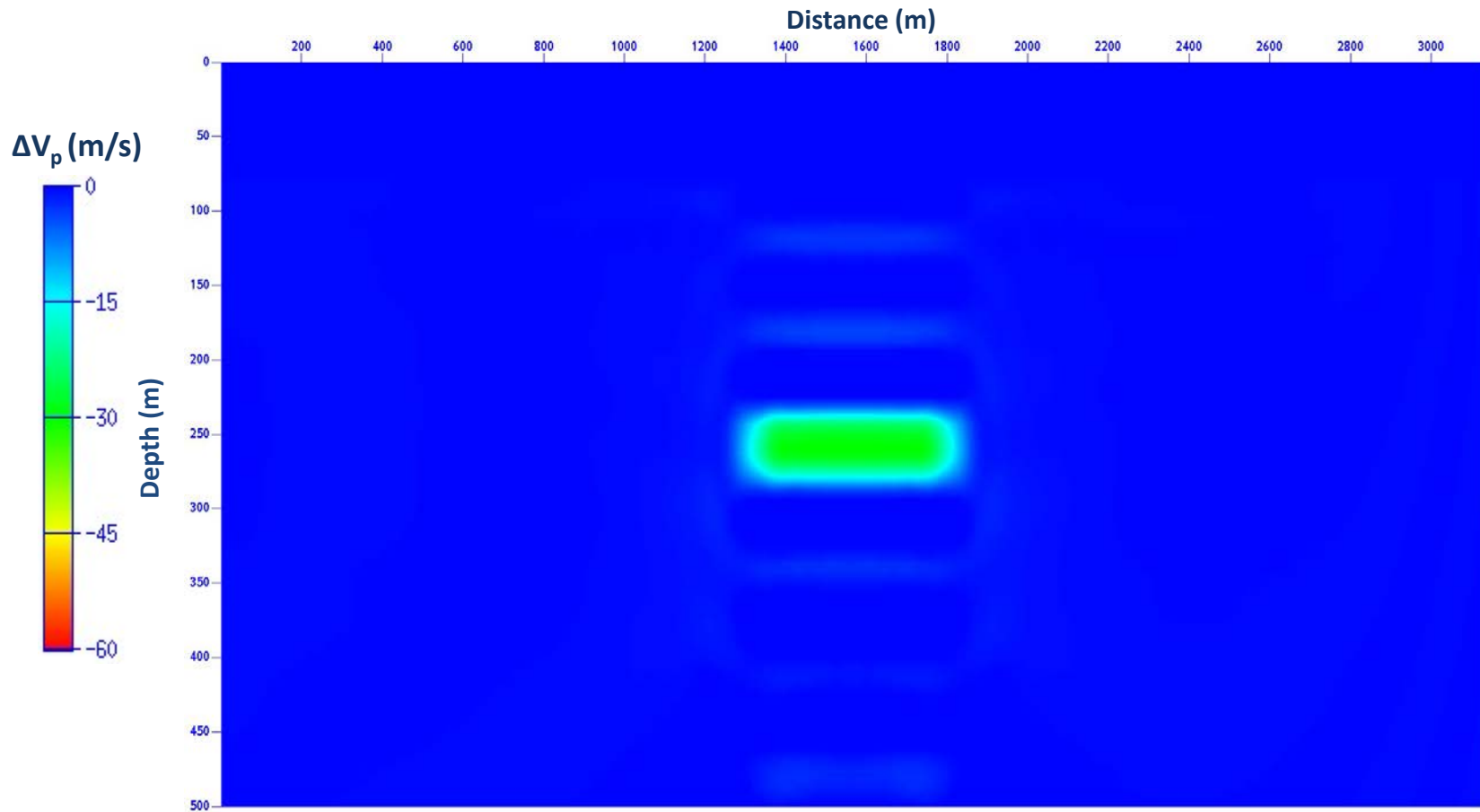
# 4D Anomaly1:

$\Delta V_p$  (m/s) = 60 m/s (4%)



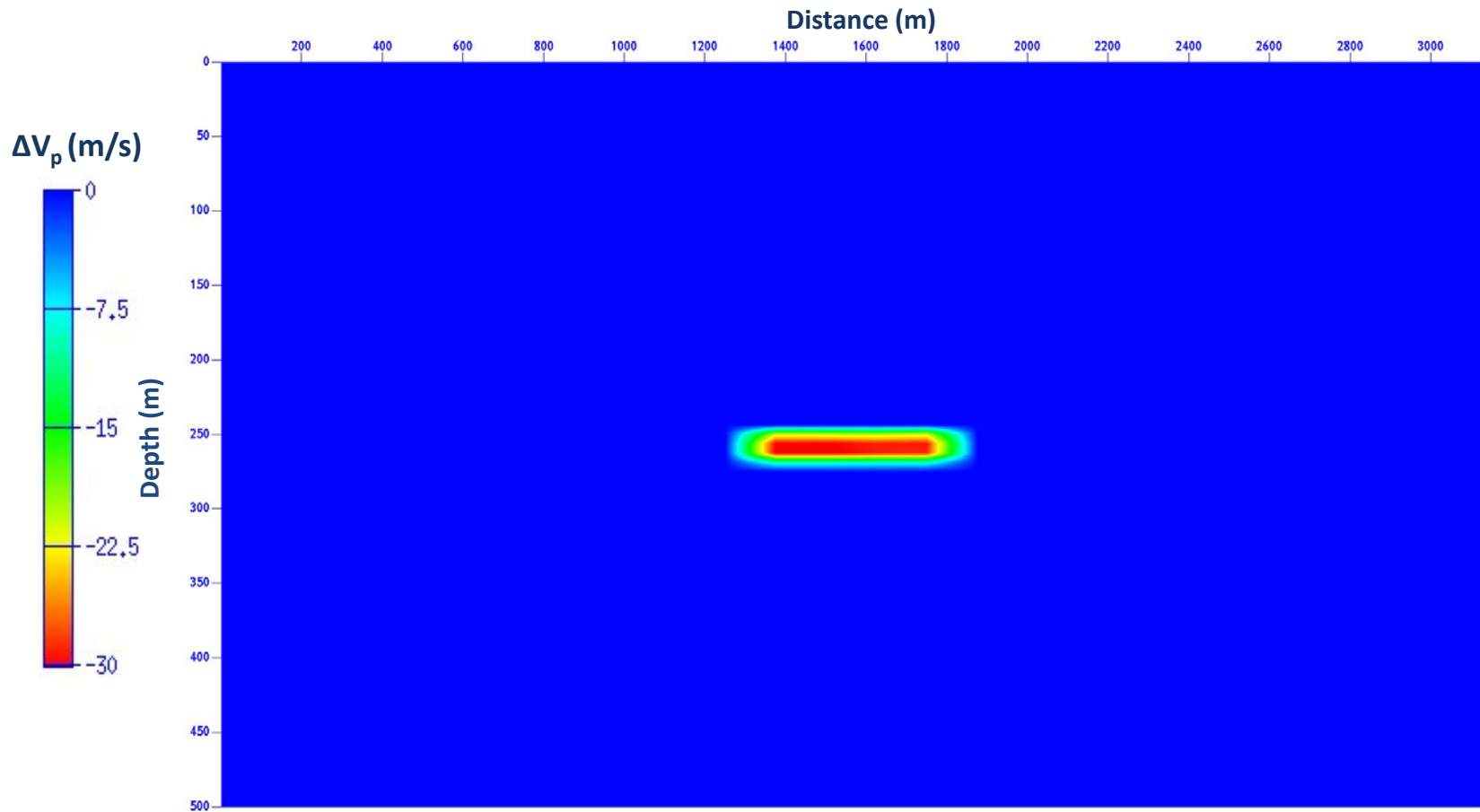
# 4D Anomaly2 (Inverted):

*Detected* ( $V_p$ ) Difference=30 m/s ( $\sim 2\%$ )



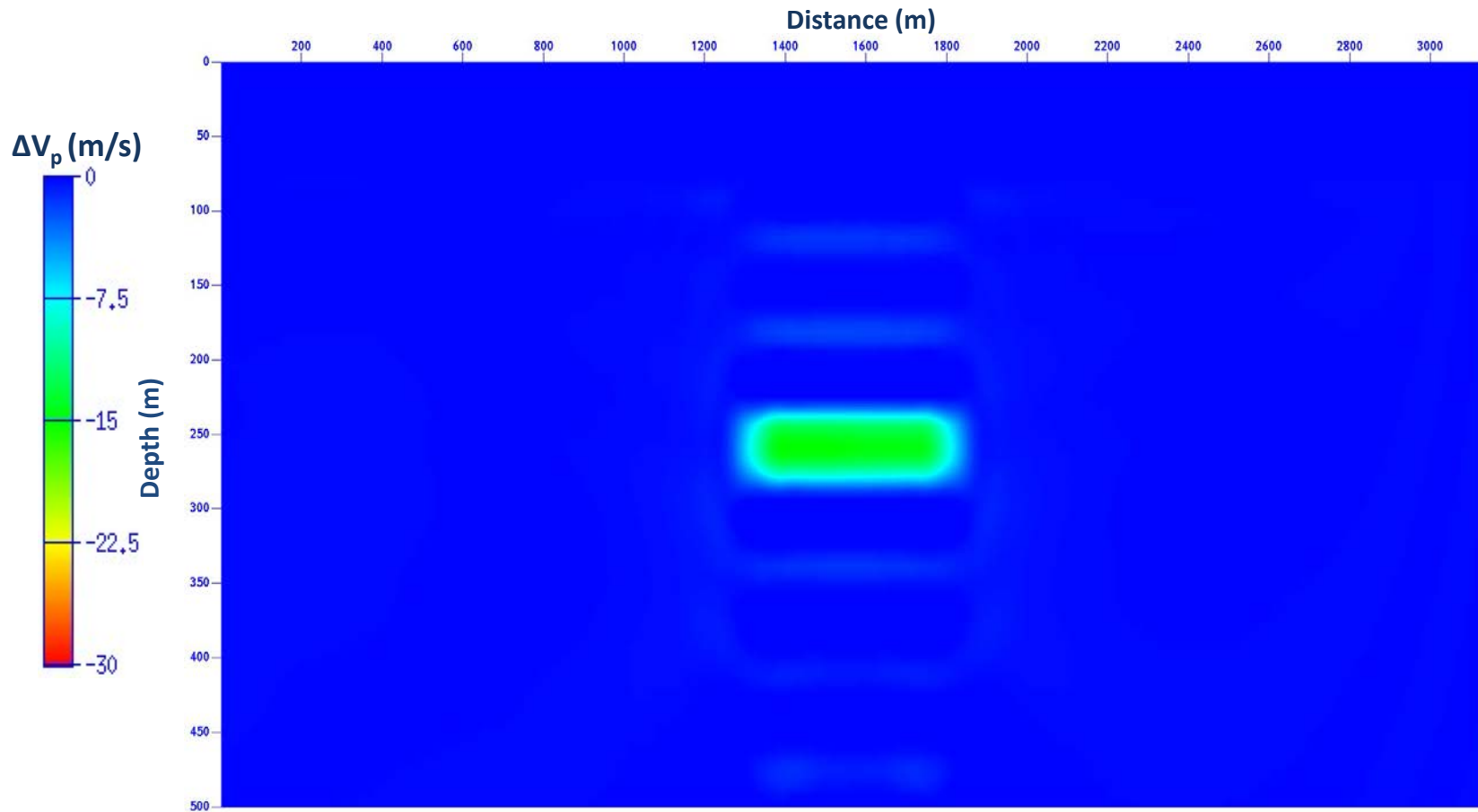
# 4D Anomaly1:

(Vp) Difference=30 m/s (~2%)



# 4D Anomaly1 (Inverted):

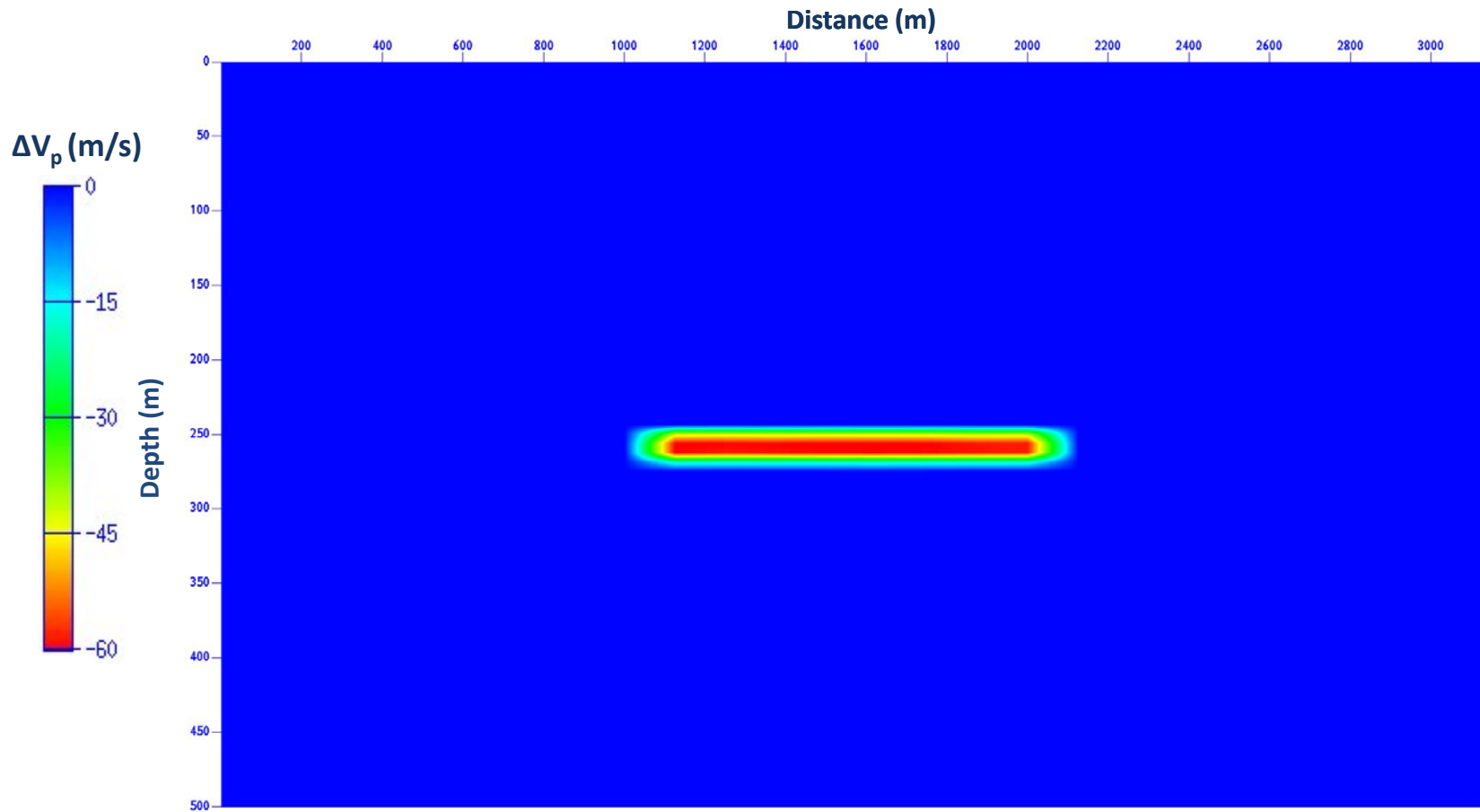
*Detected* ( $V_p$ ) Difference=15 m/s ( $\sim 1\%$ )



# Test 1.2: Detectability with respect to Lateral Extent

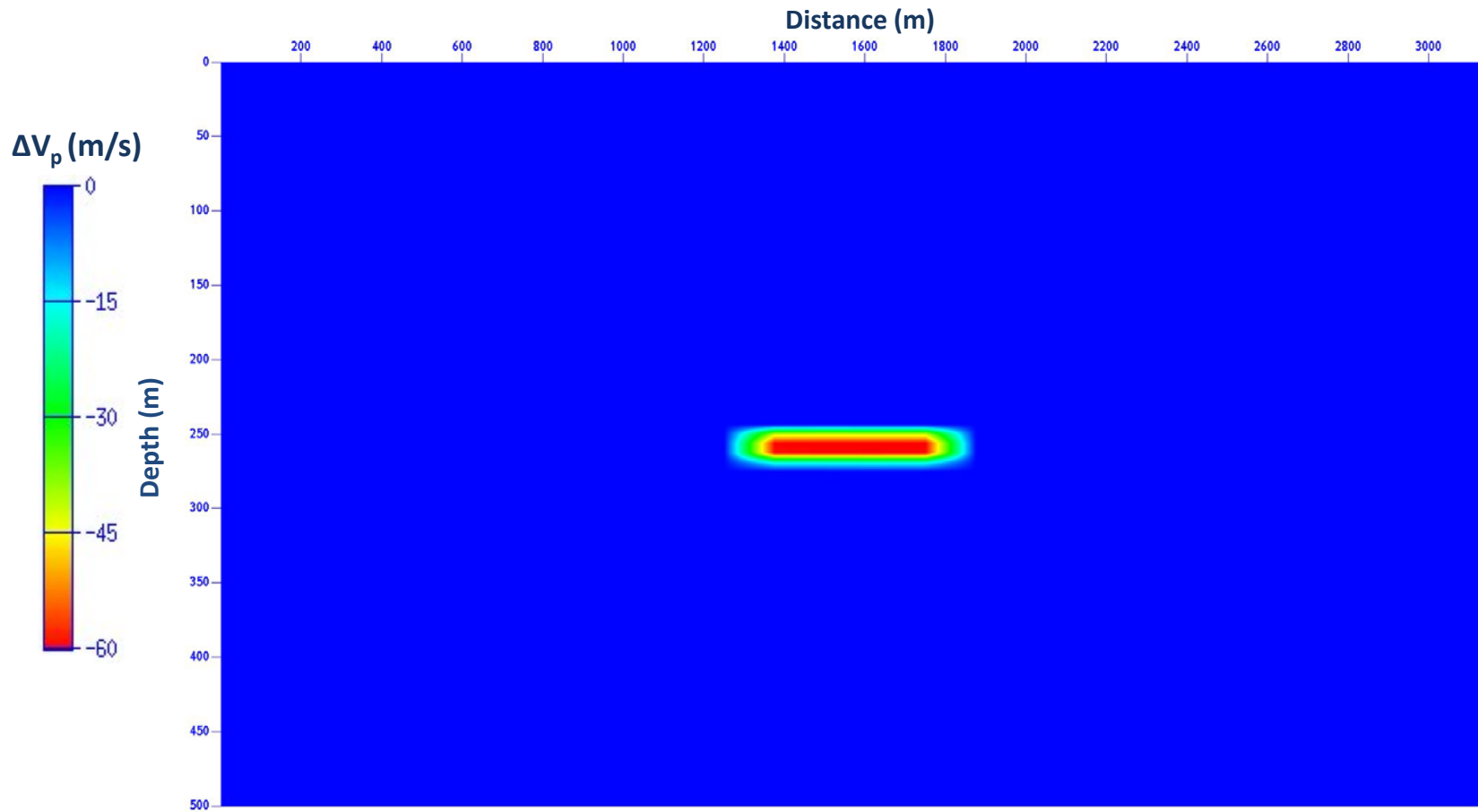
- Run FWI on multiple synthetic Data (Monitor):
- **4D Anamoly 1: 1000 m**
- **4D Anamoly 2: 500 m**
- **4D Anamoly 3: 250 m**
- **4D Anamoly 4: 125 m**

# 4D Anomaly1: length=1000 m

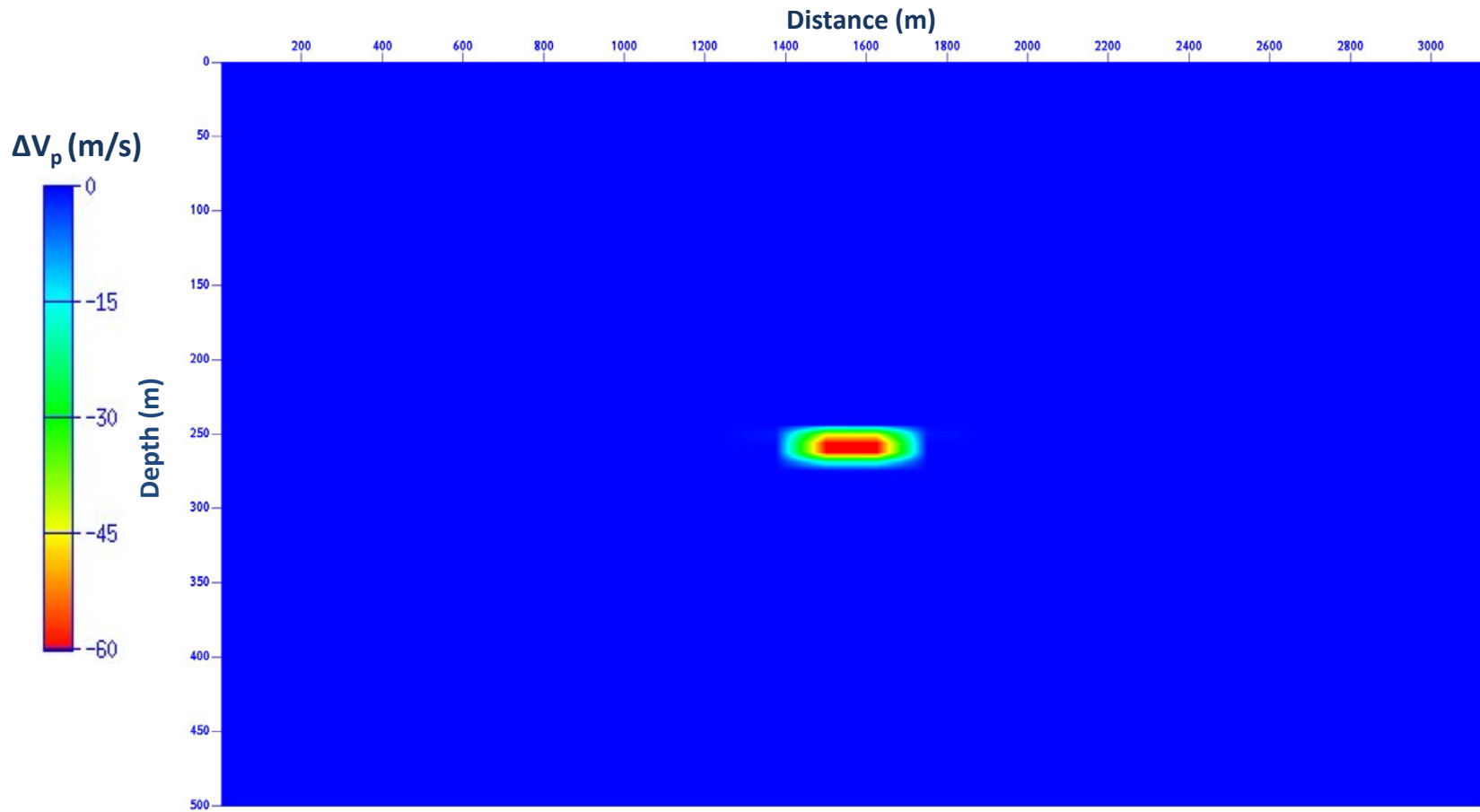




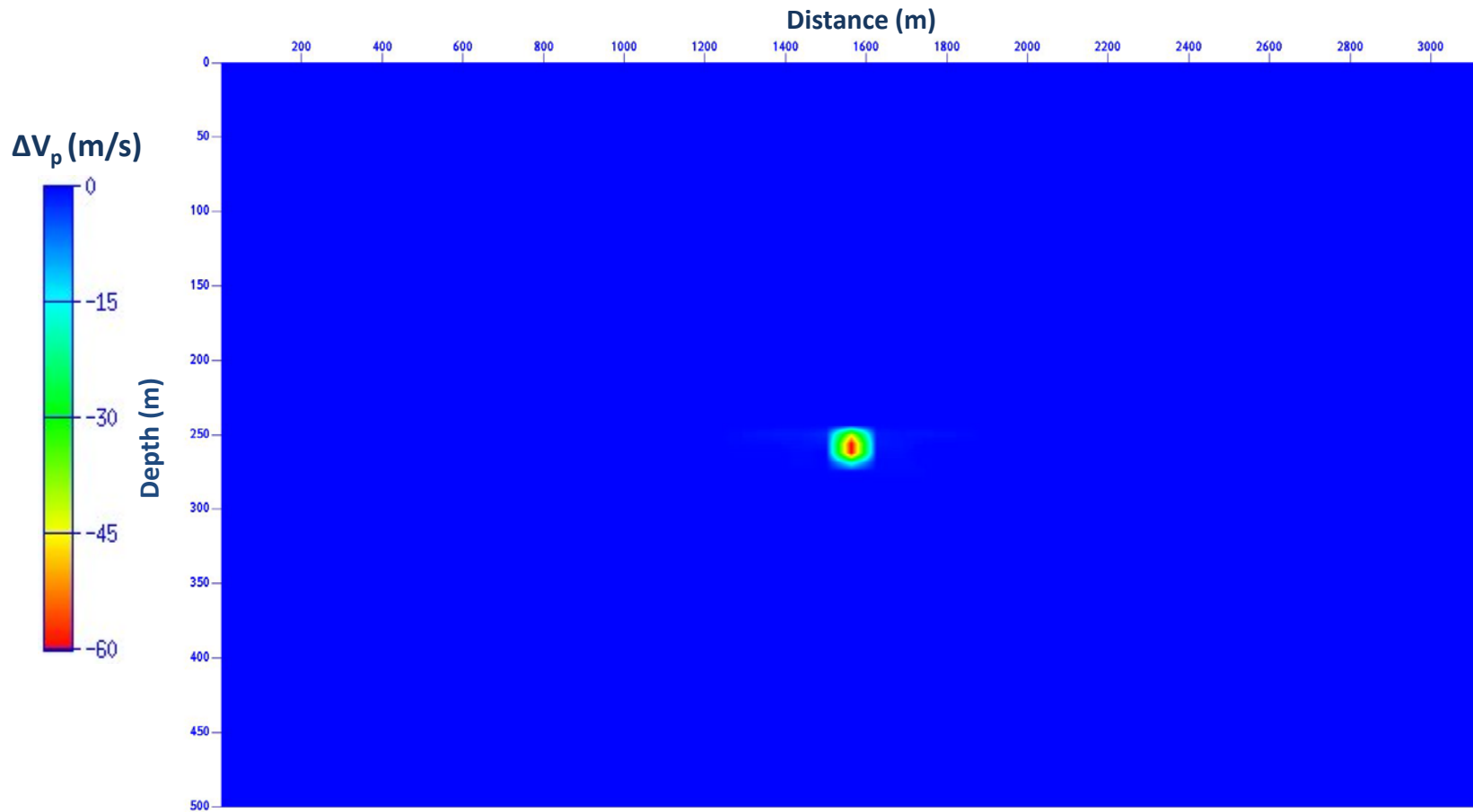
# 4D Anomaly2: length=500 m



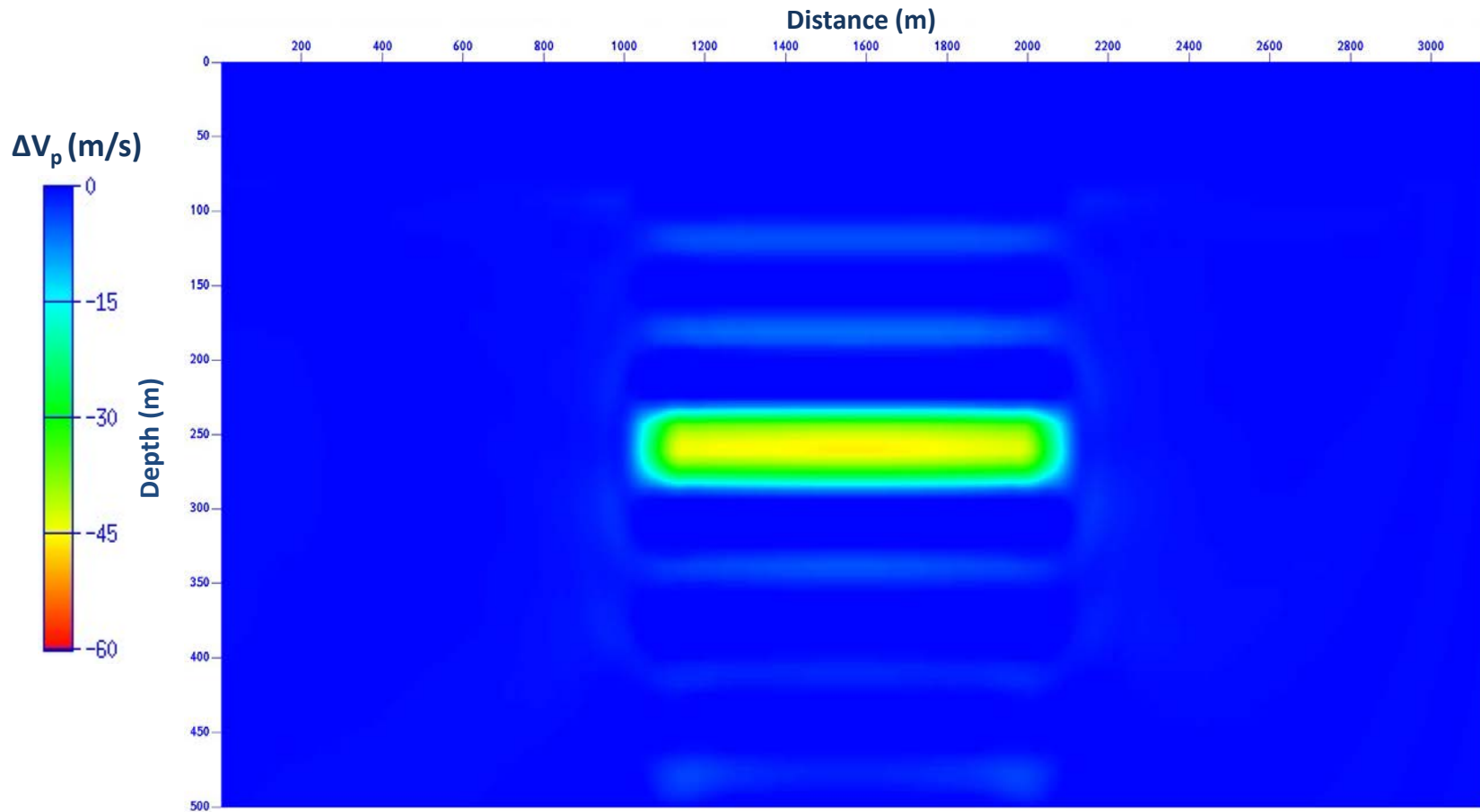
# 4D Anomaly3: length=200 m



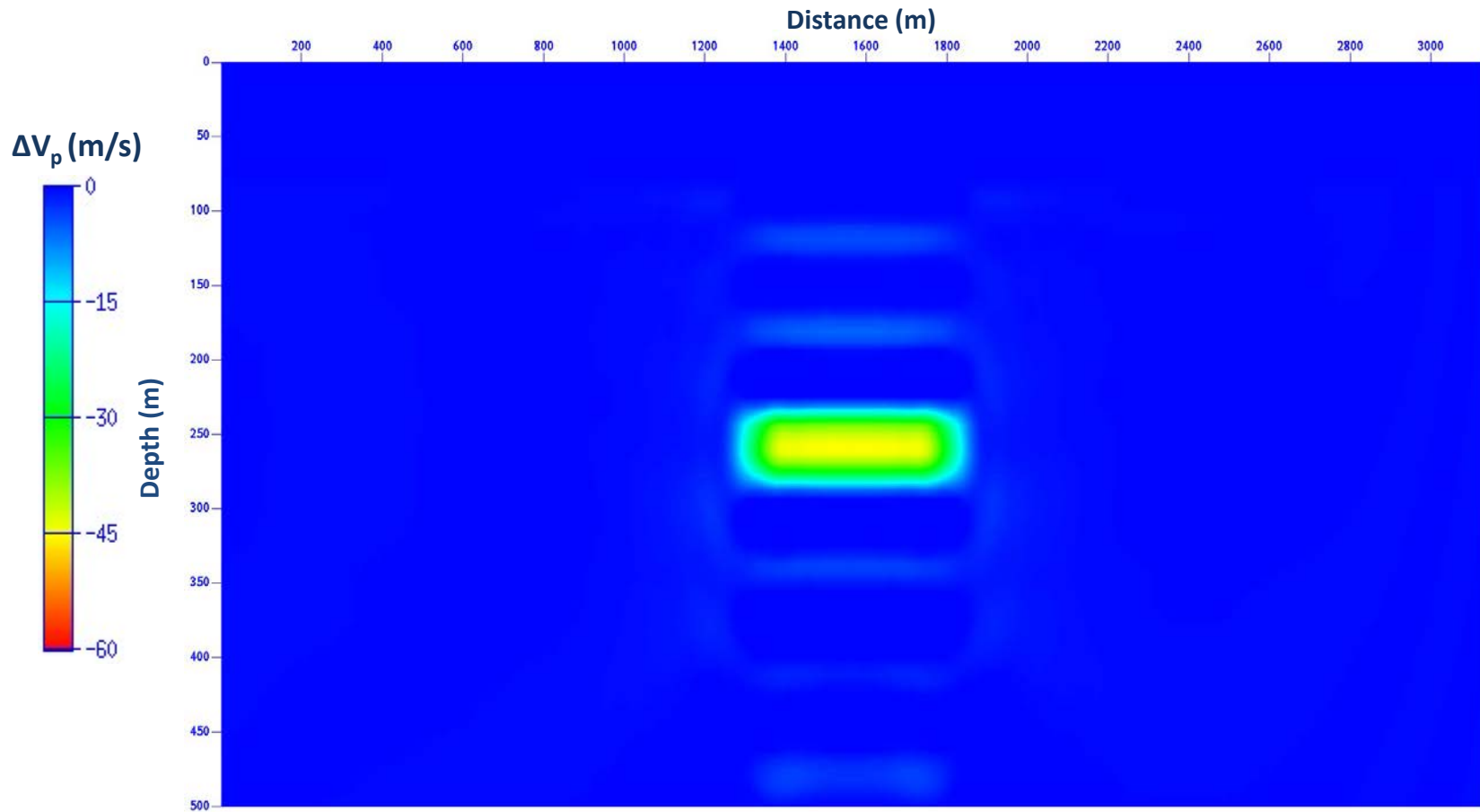
# 4D Anomaly4: length=100 m



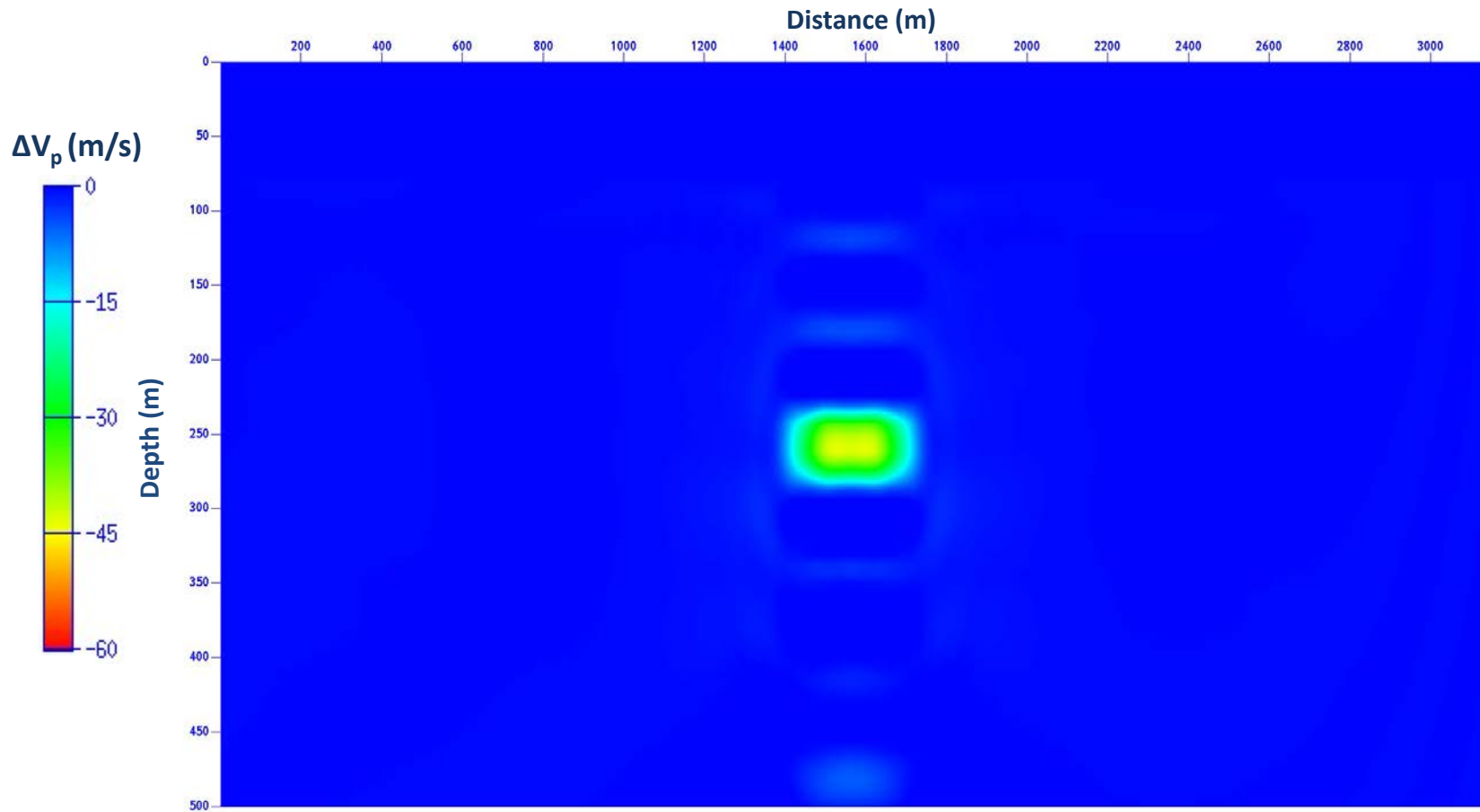
# 4D Anomaly1 (Inverted): length=1000 m



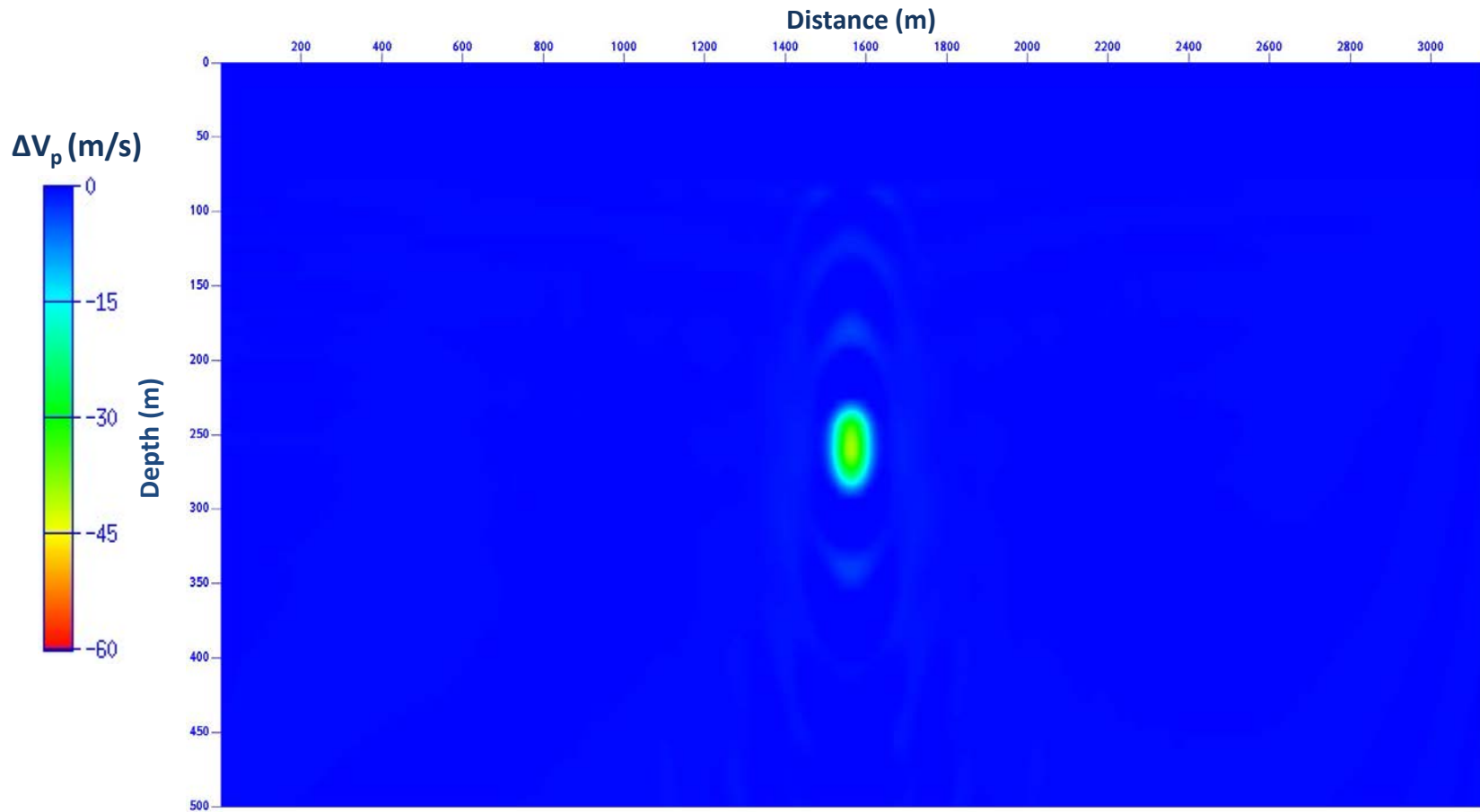
# 4D Anomaly2 (Inverted): length=500 m



# 4D Anomaly 3 (Inverted): length=250 m



# 4D Anomaly (Inverted): length=125 m

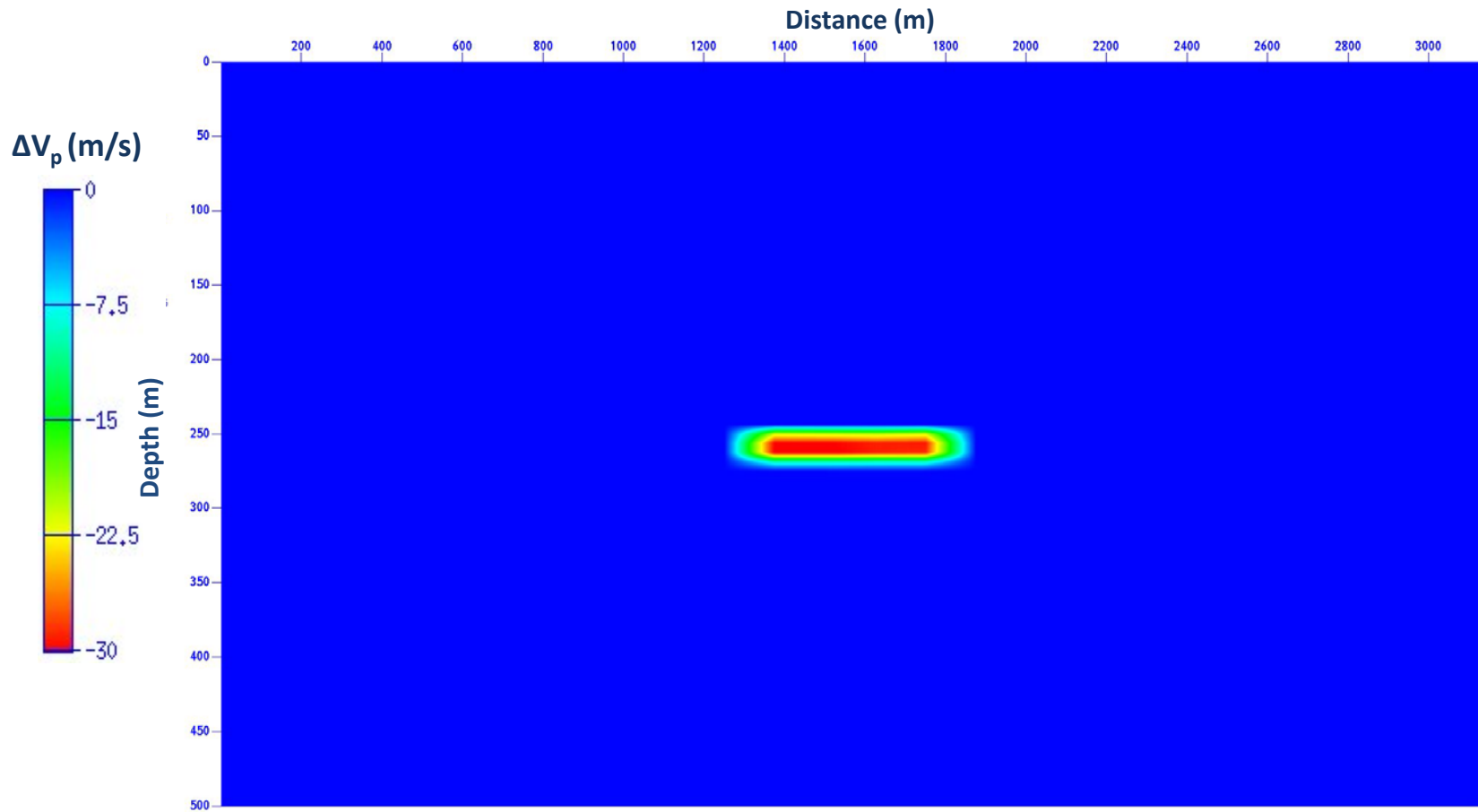


# Part2: Frequency Rang Tests

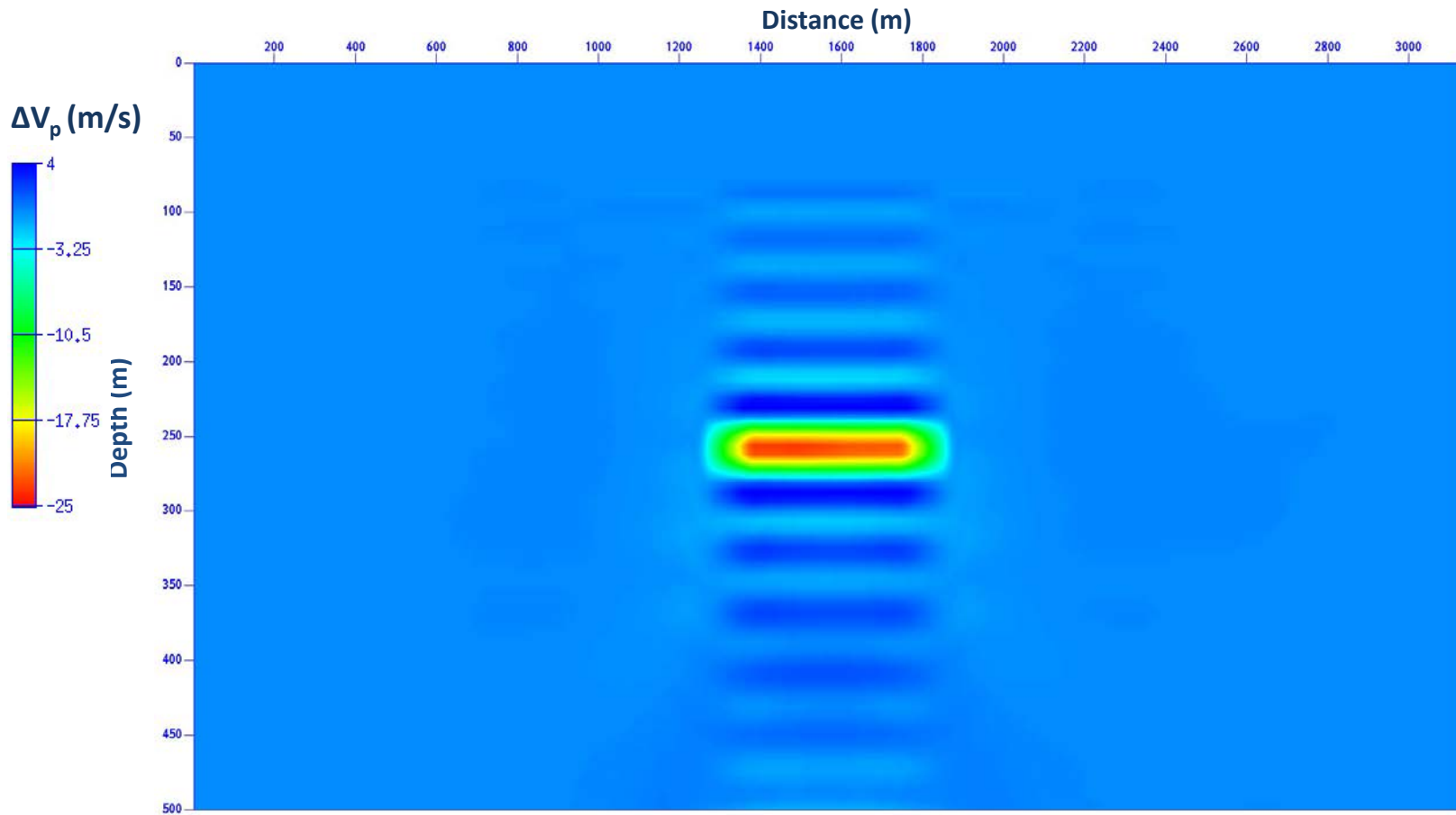
- **Test:** Run FWI scenarios Using multiple synthetic Data (Monitor) with following Bandpass filters applied:
  - **Input 1:** Filter applied [0-5-25-30Hz] (Center Freq =15Hz)
  - **Input 2:** Filter applied[0-5-20-25Hz] (Center Freq =12.5Hz)
  - **Input 3:** Filter applied[0-5-15-20Hz] (Center Freq =10Hz)
  - **Input 4:** Filter applied[0-5-10-15Hz] (Center Freq =7.5Hz =Notch Freq)
  - **Input 5:** Filter applied[5-10-15-20Hz] (Center Freq =12.5Hz)



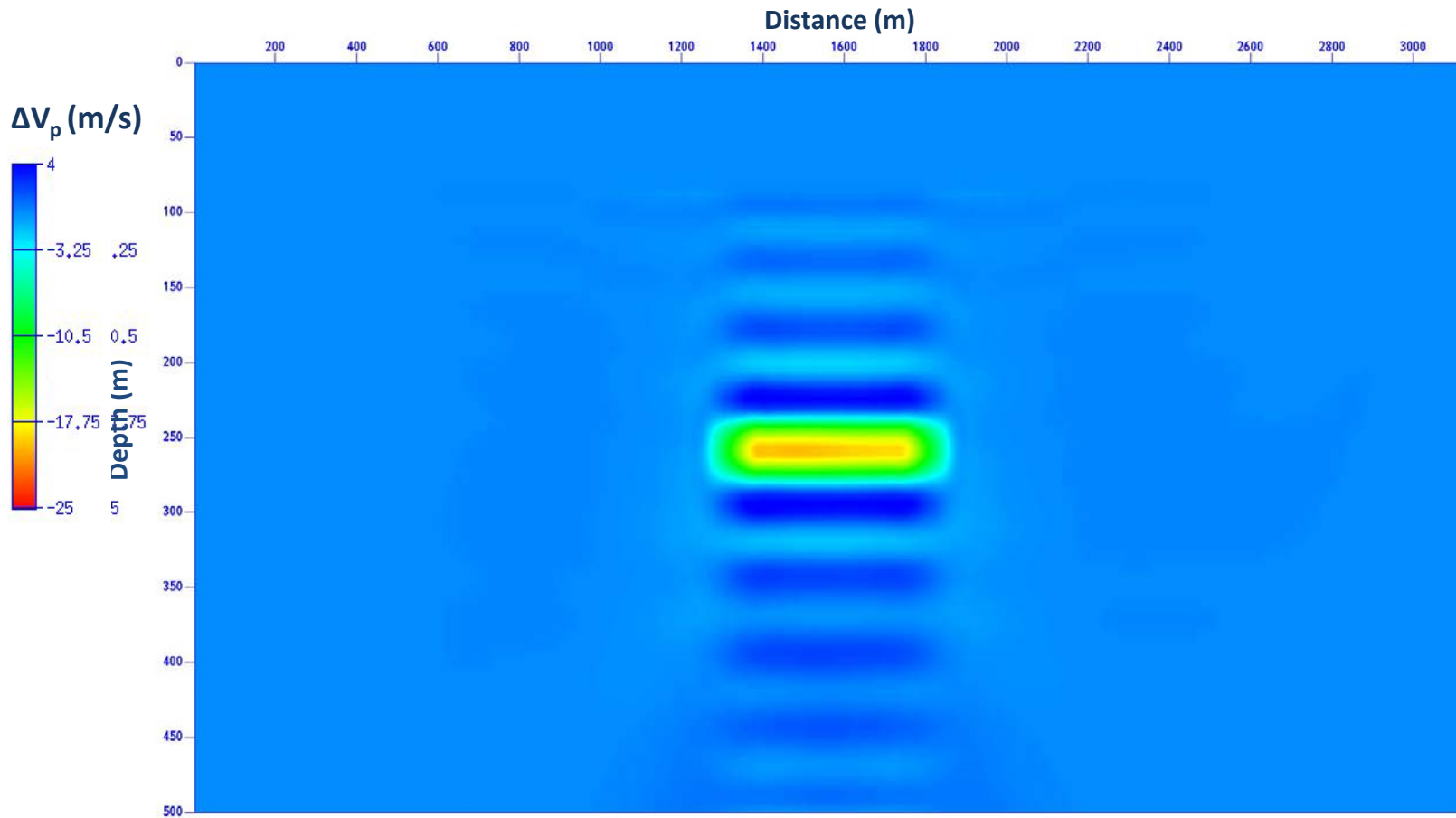
# Vp Difference: Monitor (Vp)- Base (Vp)



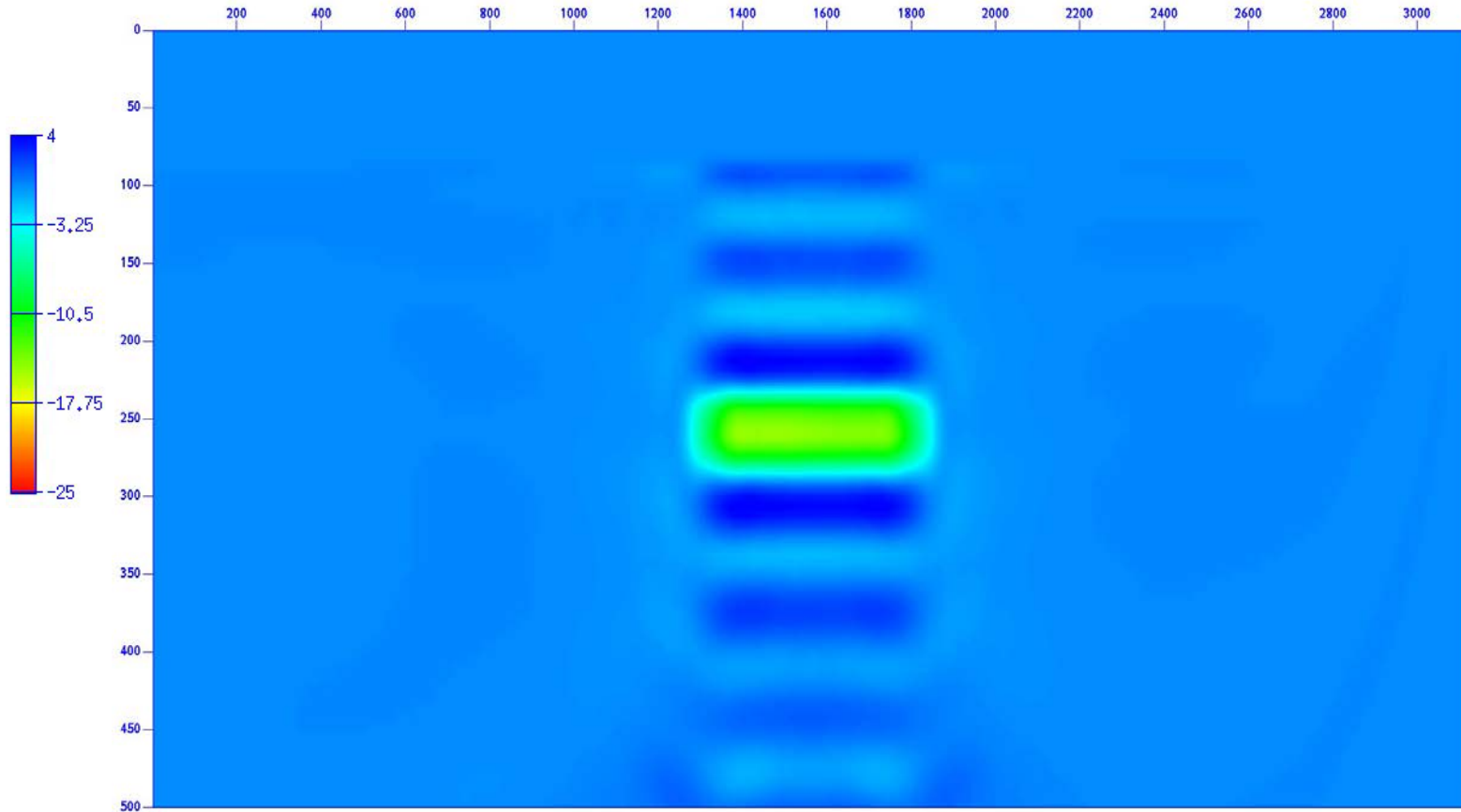
# Input 1: Filter applied [0-5-25-30Hz] (Center Freq = 15Hz)



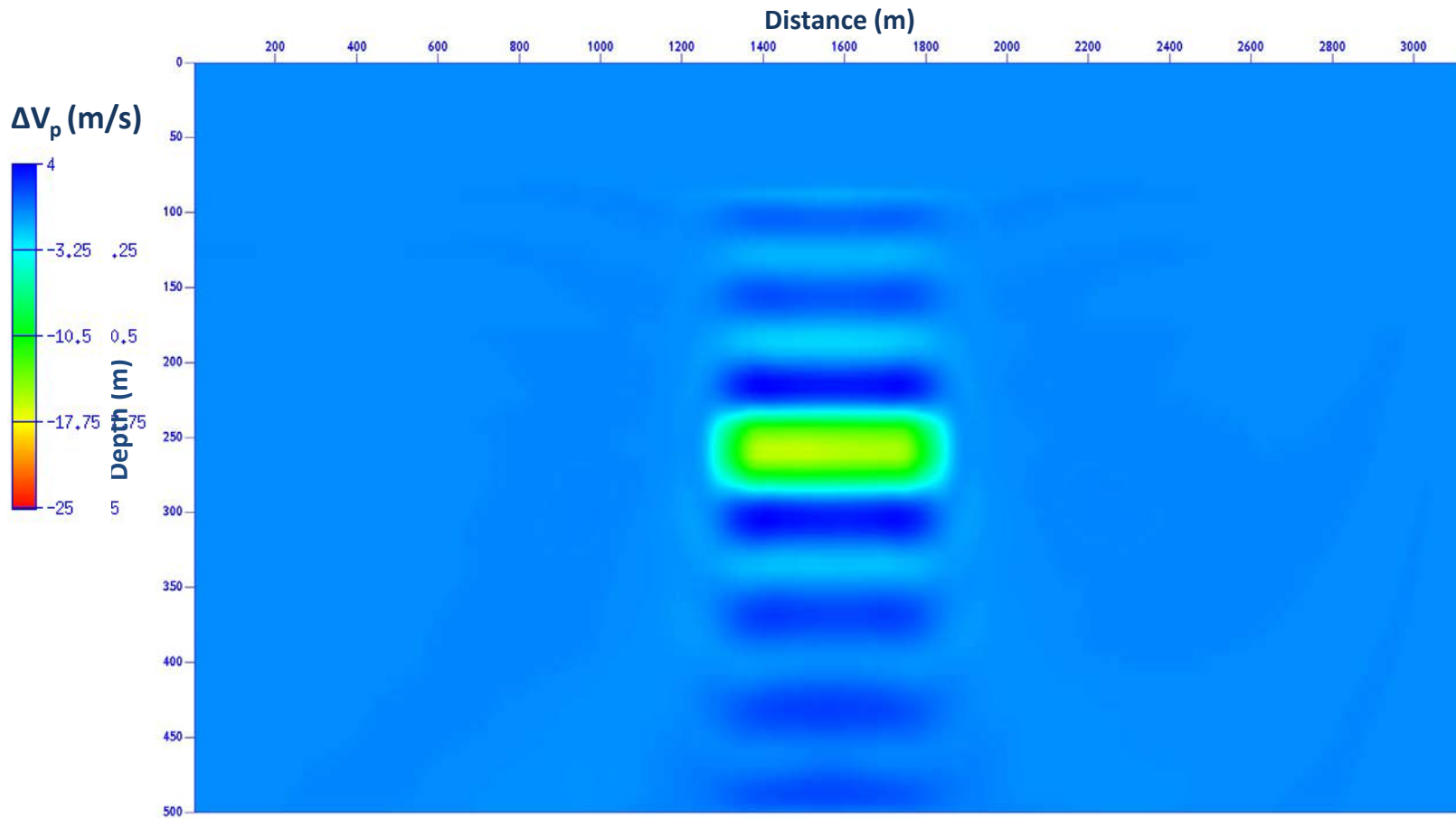
# Input 2: Filter applied[0-5-20-25Hz] (Center Freq =12.5Hz)



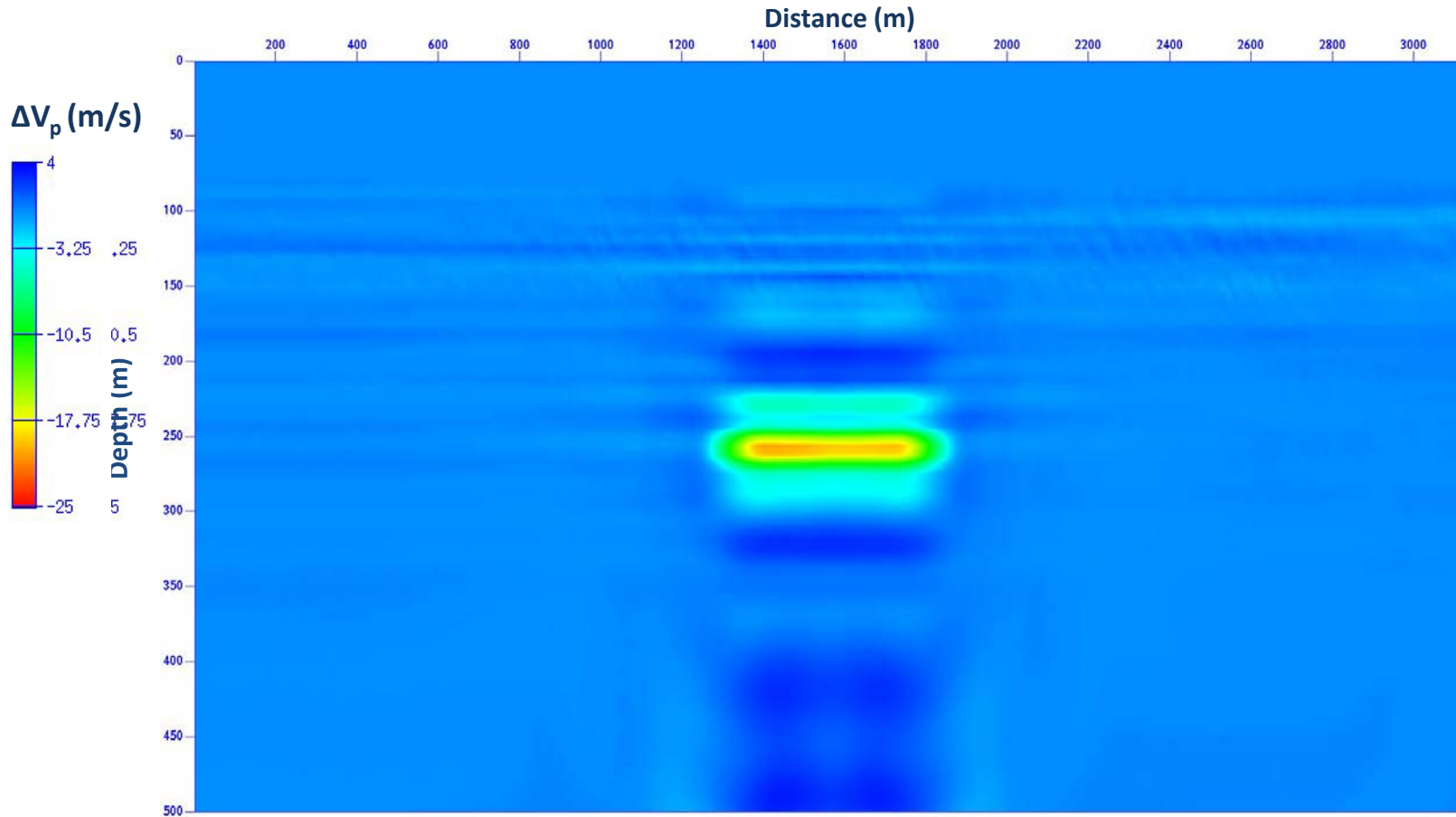
# Input 3: Filter applied[0-5-15-20Hz] (Center Freq =10Hz)



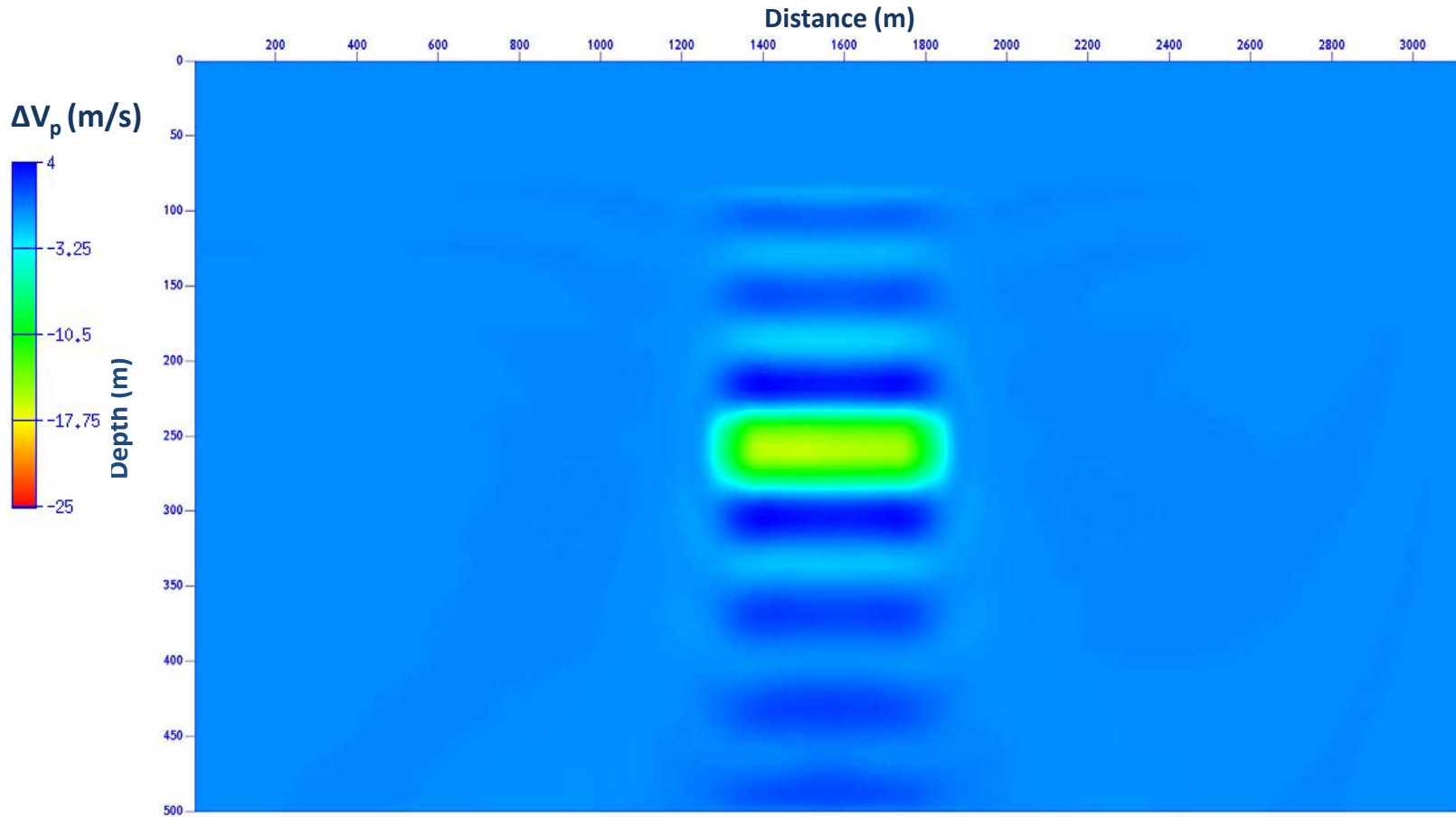
# Input 4: Filter applied[0-5-10-15Hz] (Center Freq =7.5Hz =Notch Freq)



# Input 4: Filter applied[0-5-10-15Hz] (Center Freq = 7.5Hz = Notch Freq)

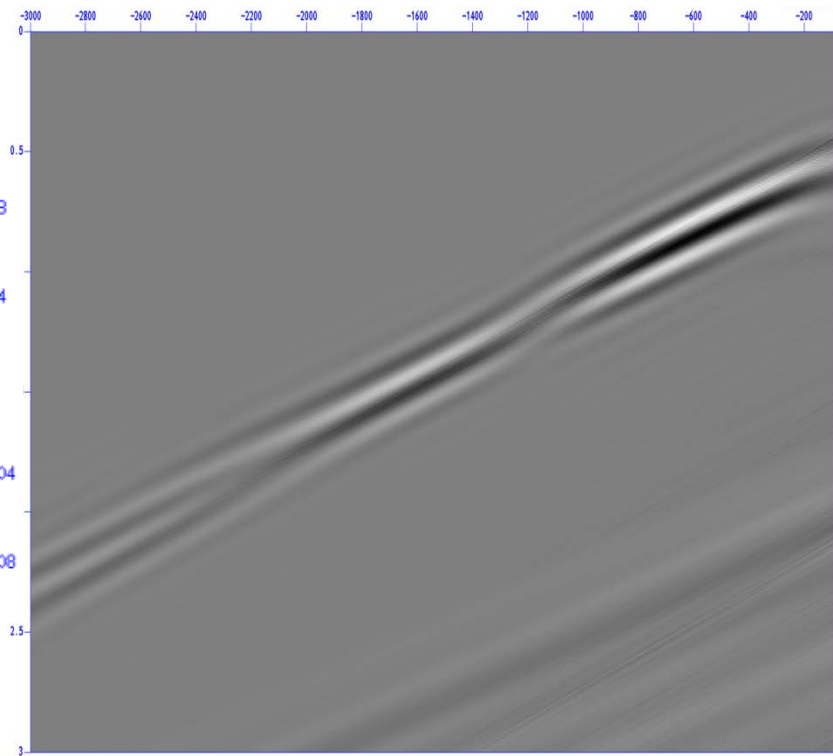


# Input 5: Filter applied[5-10-15-20Hz] (Center Freq =12.5Hz) = LOSEM data Freq Range



# Test 3: Modeling Free Surface (FS) Multiples

## Inversion Residuals (without FS)

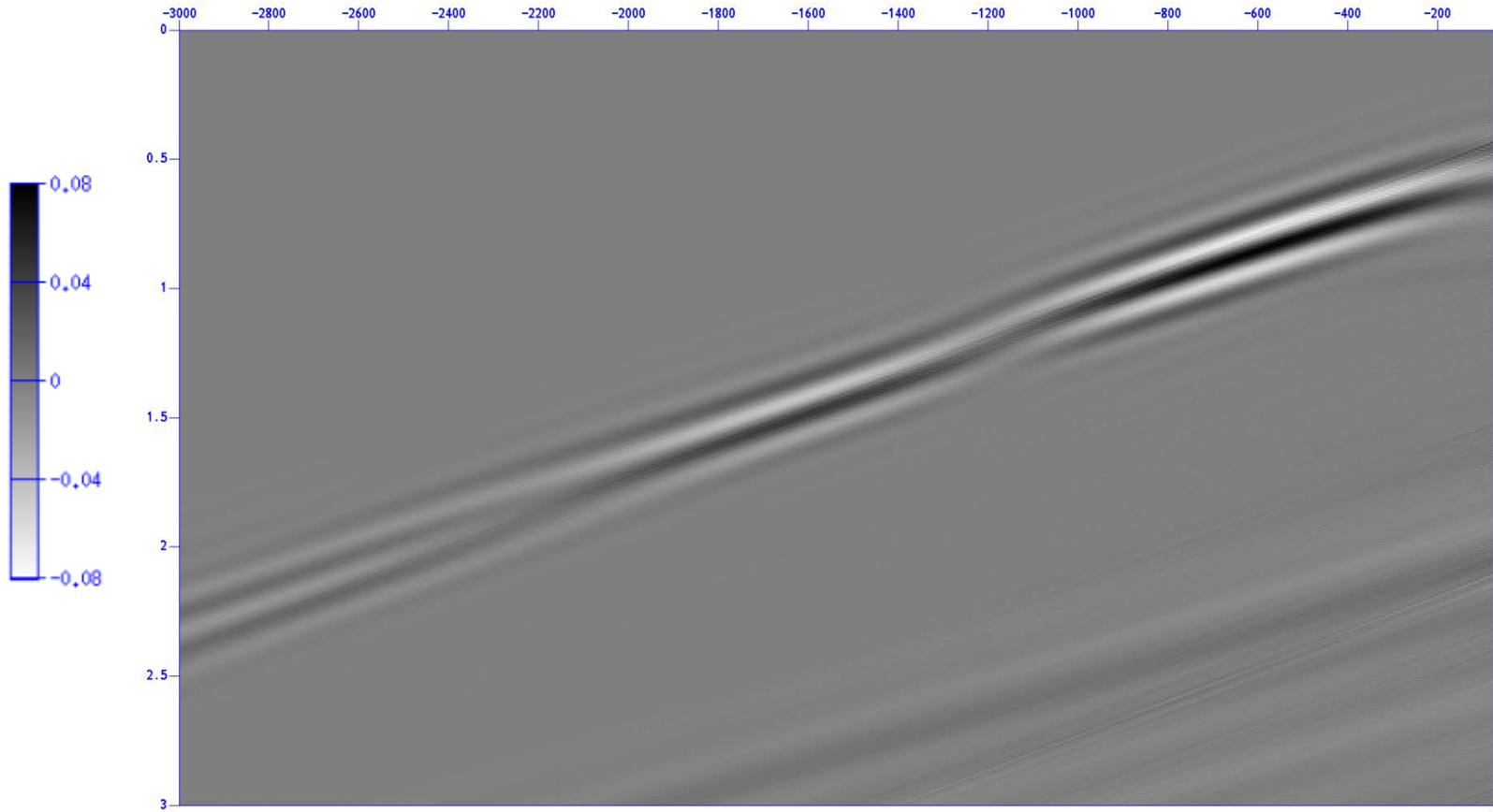


## Inversion Residuals (with FS)

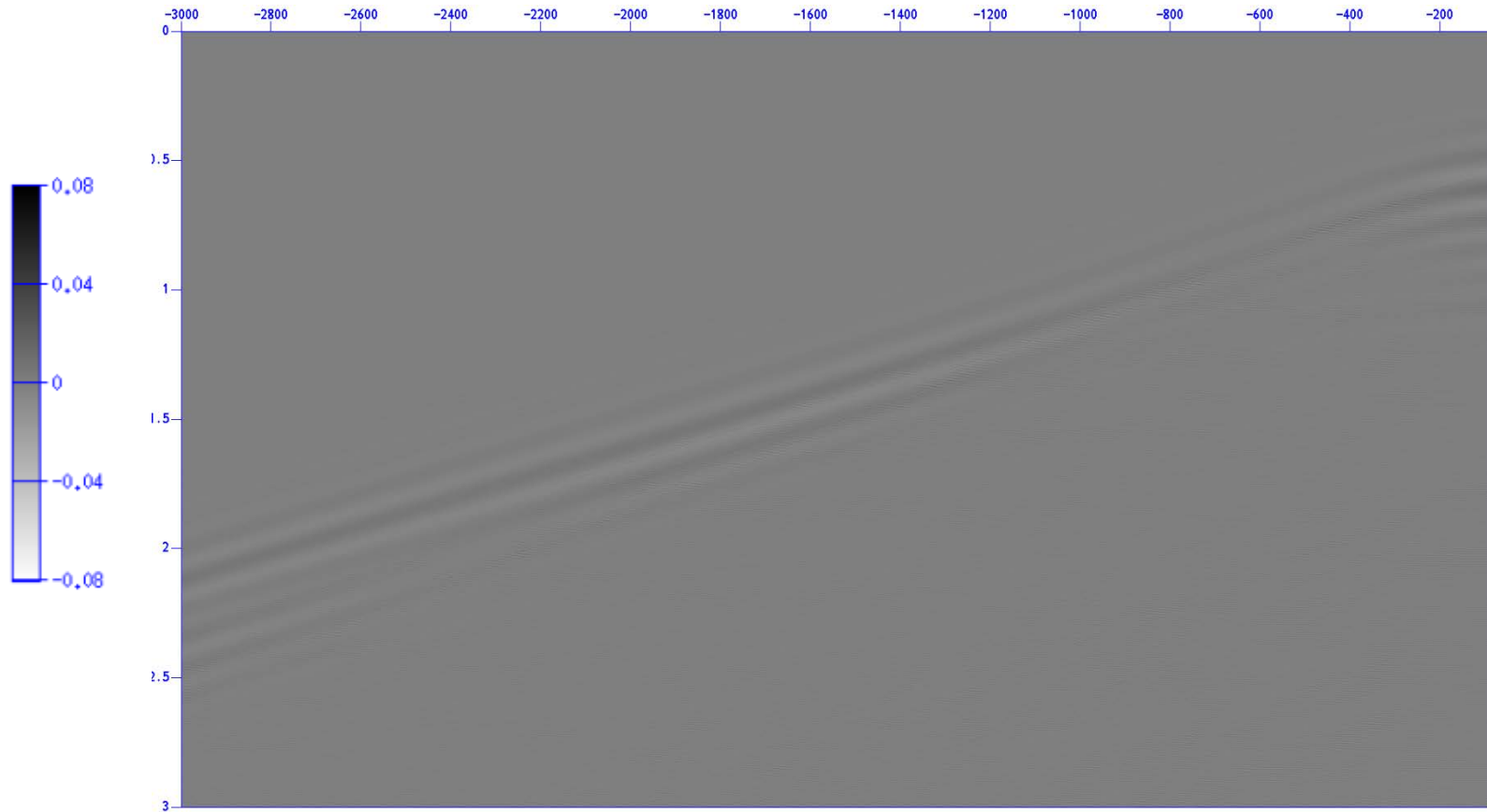




# Inversion Residuals (without FS)

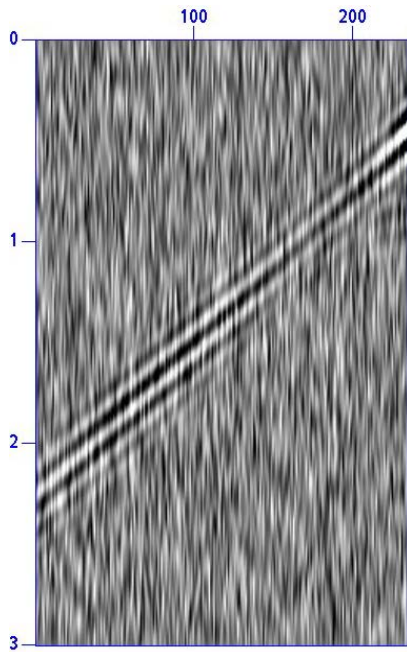


# Inversion Residuals (with FS)

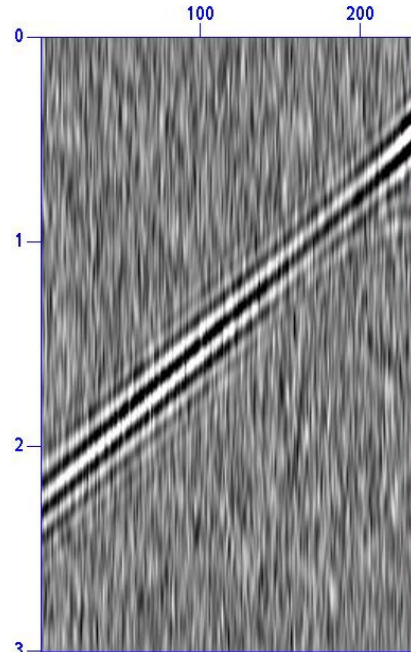


# Part4: Effect of Modeling Free Surface In presence of Noise

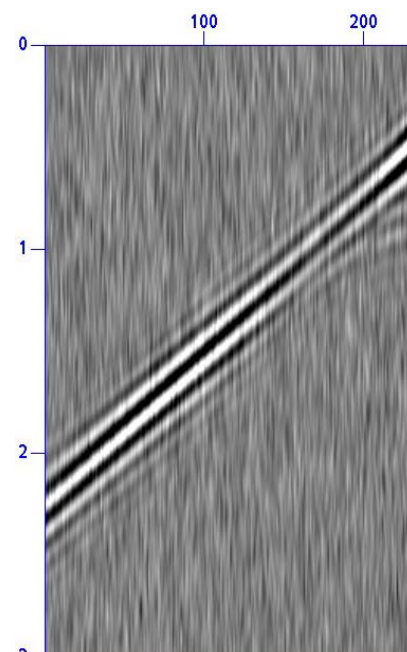
**SN=1**



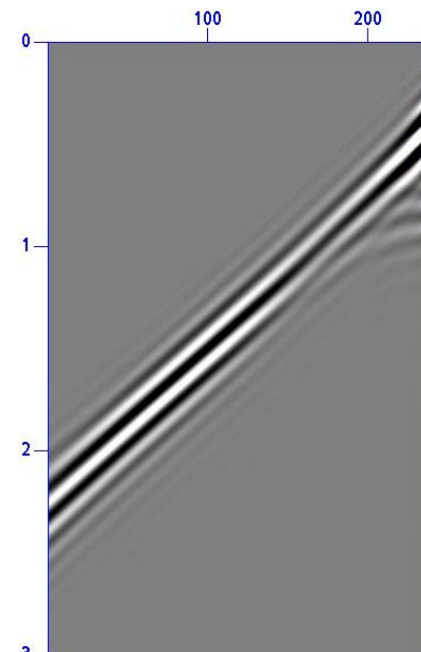
**SN=2**



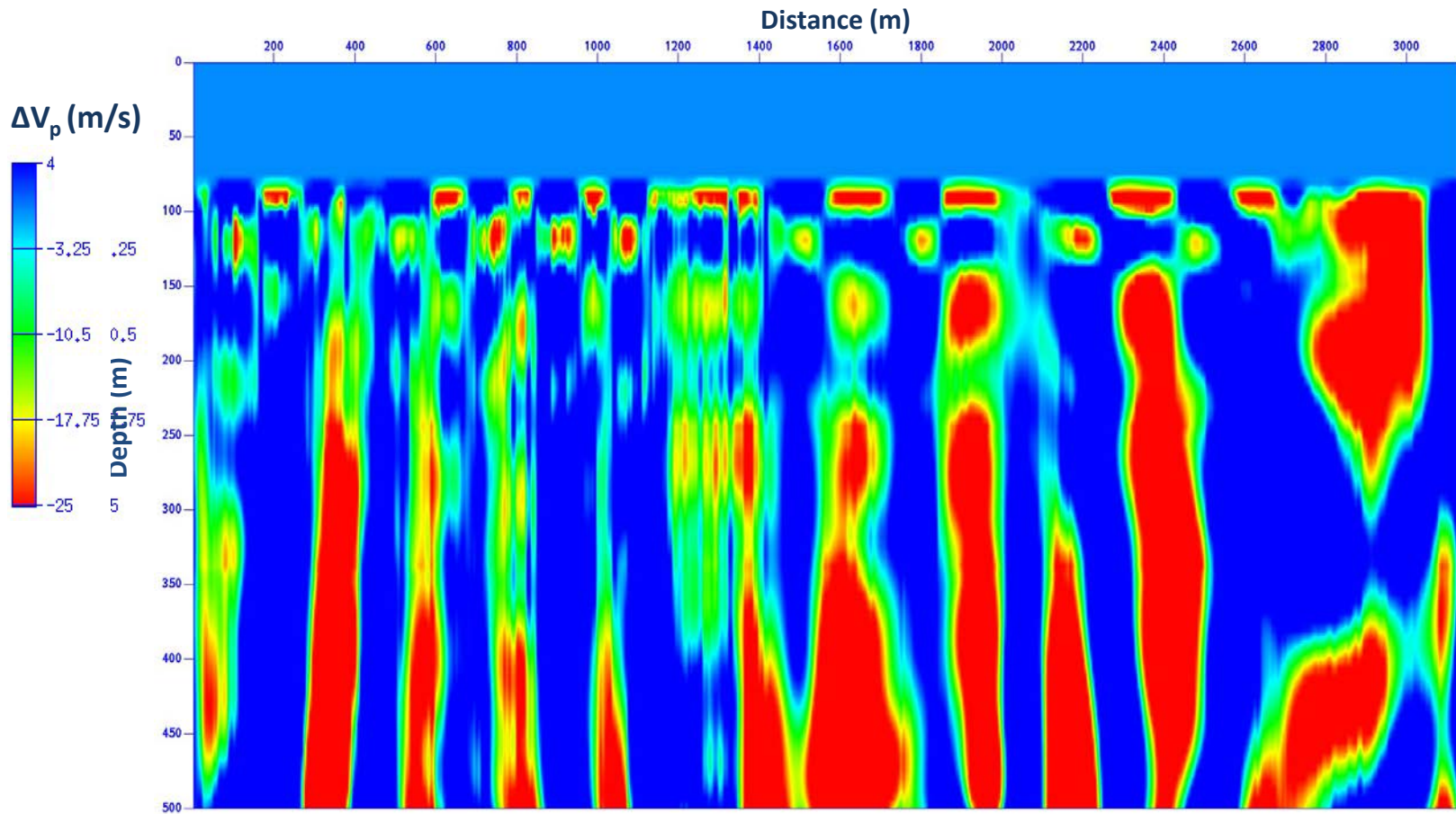
**SN=3**



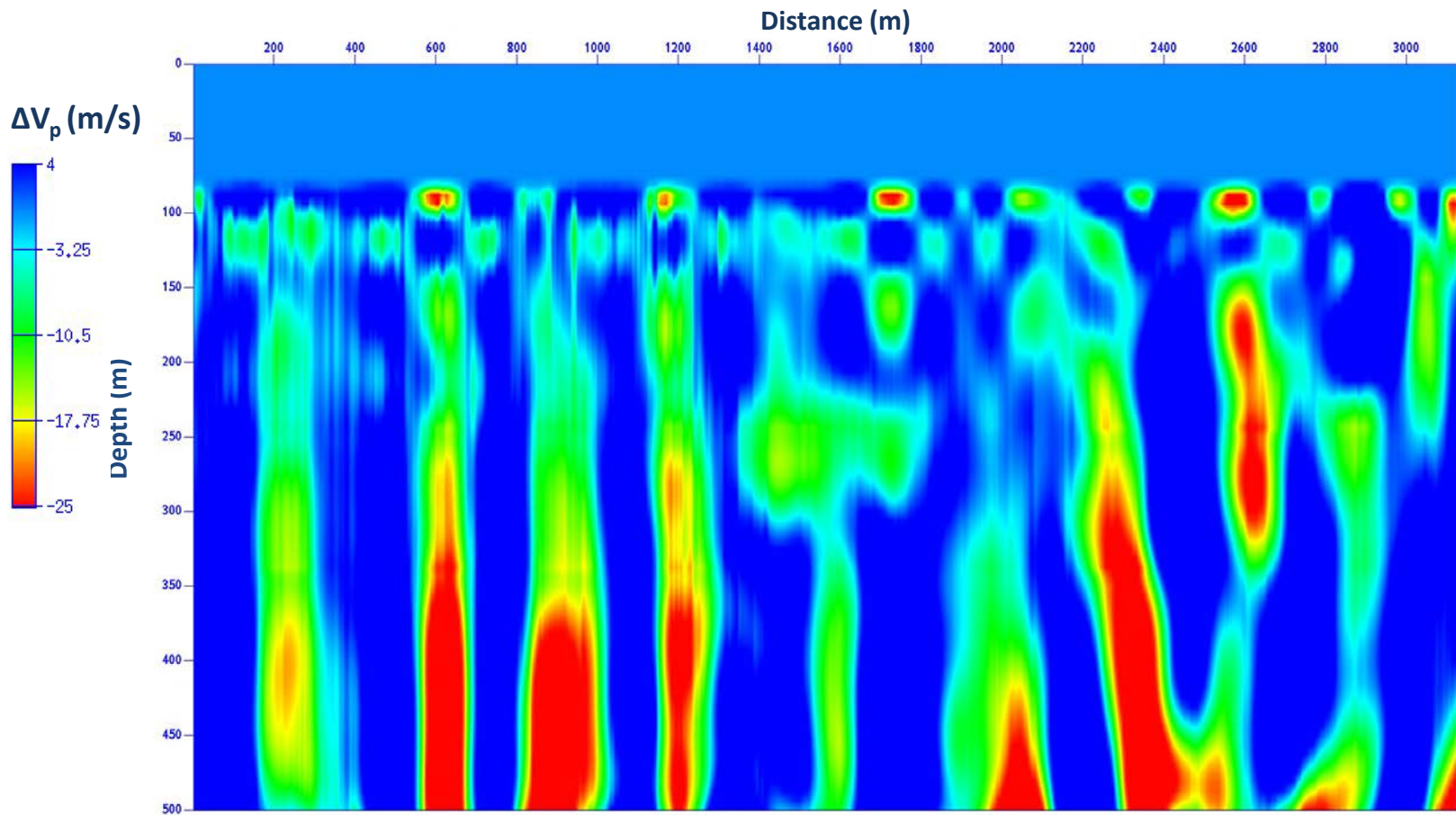
**No Noise**



# Test1: SN=1 /No FS

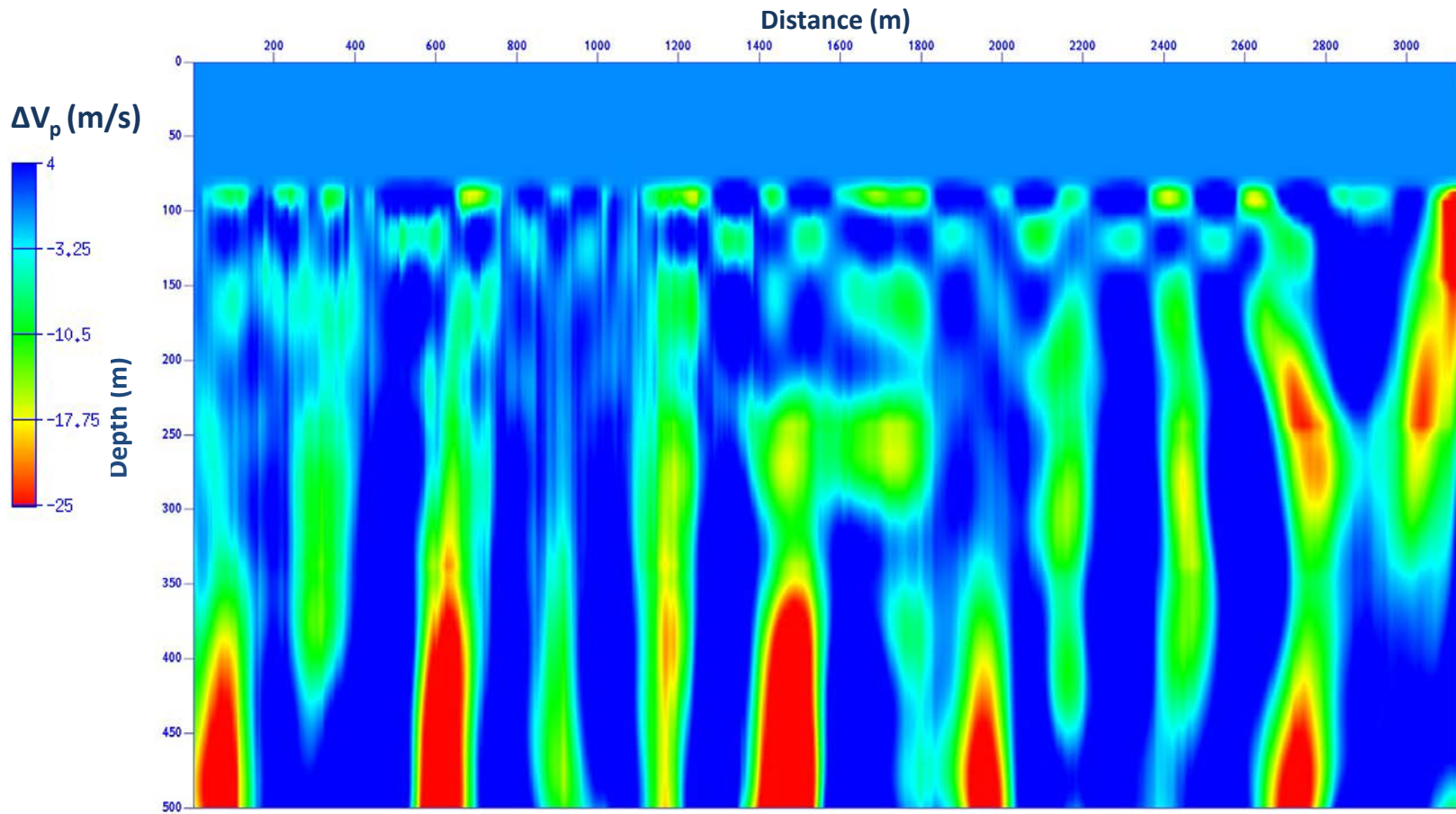


# Test2: SN=2 /No FS

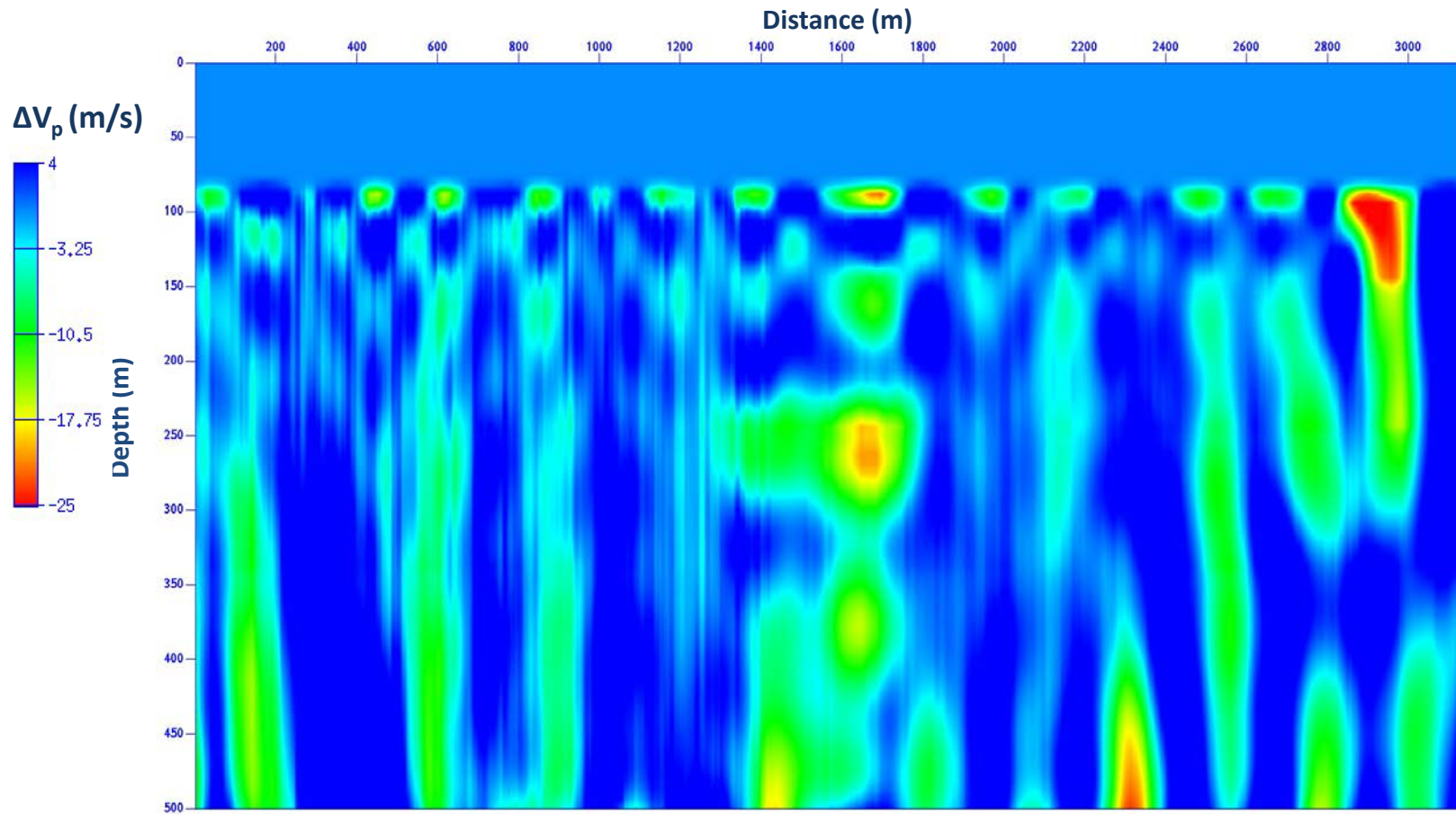




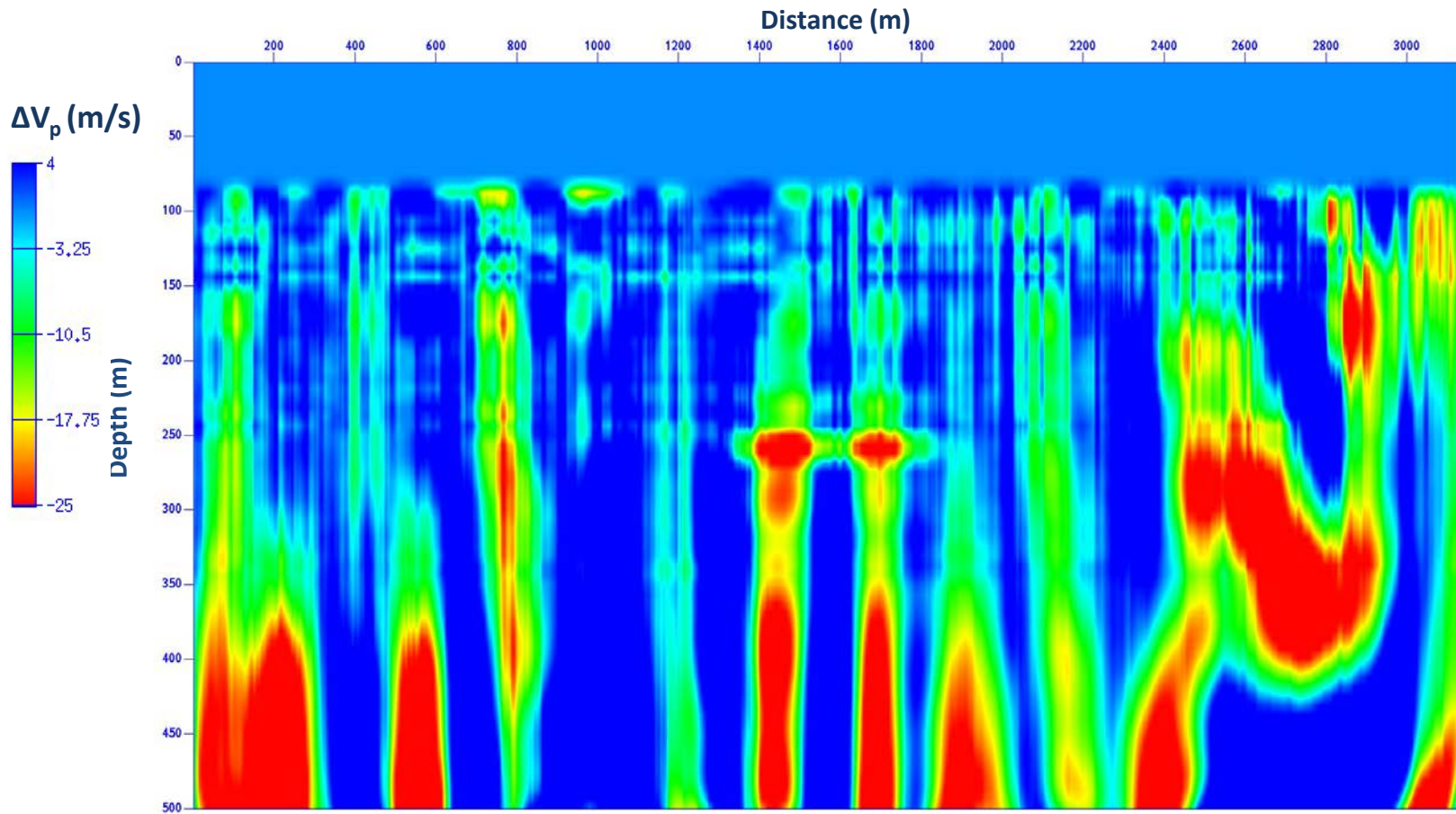
# Test3: SN=3 /No FS



# Test4: SN=4 /No FS

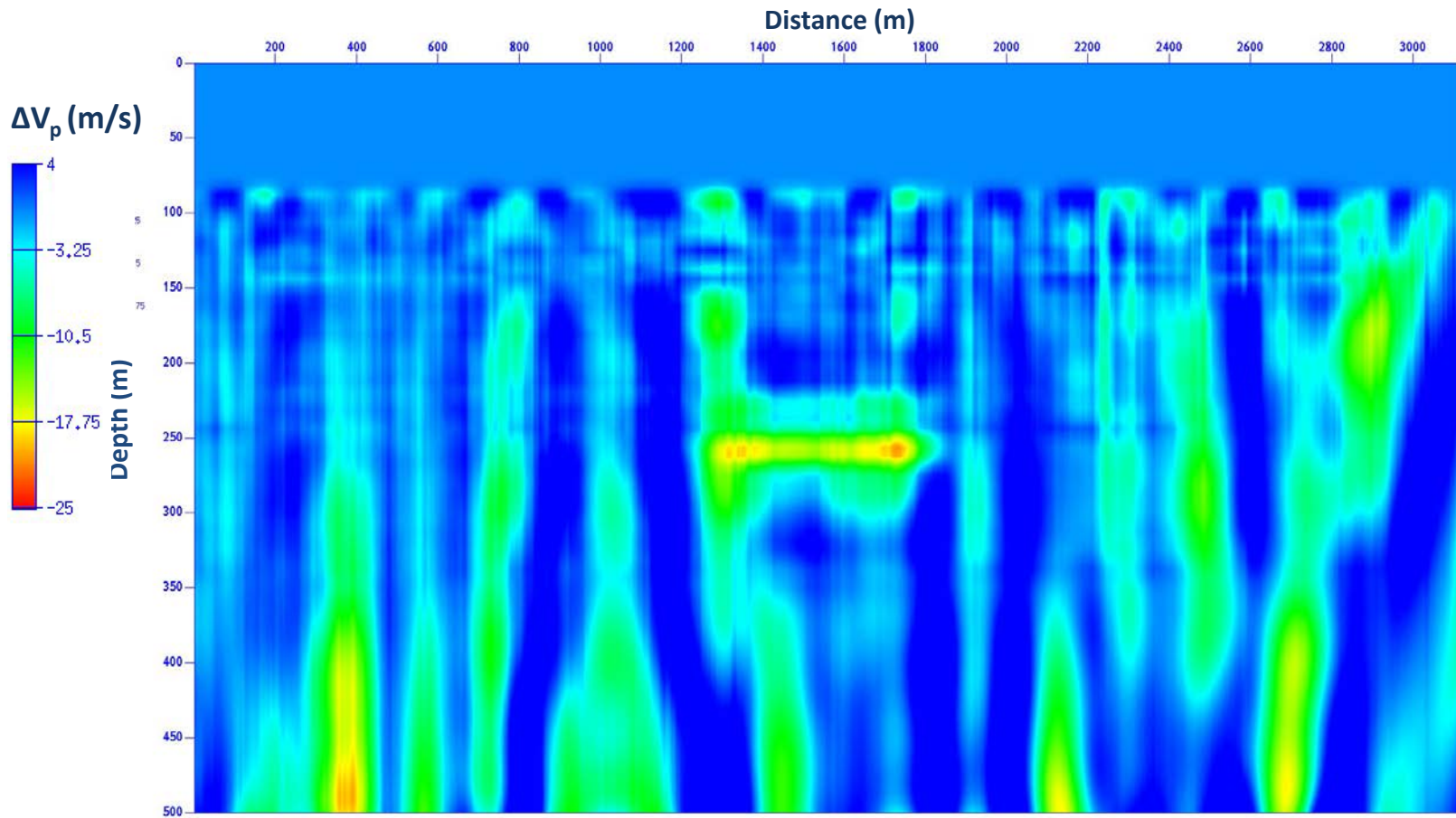


# Test 5: SN=1 /with Free Surface

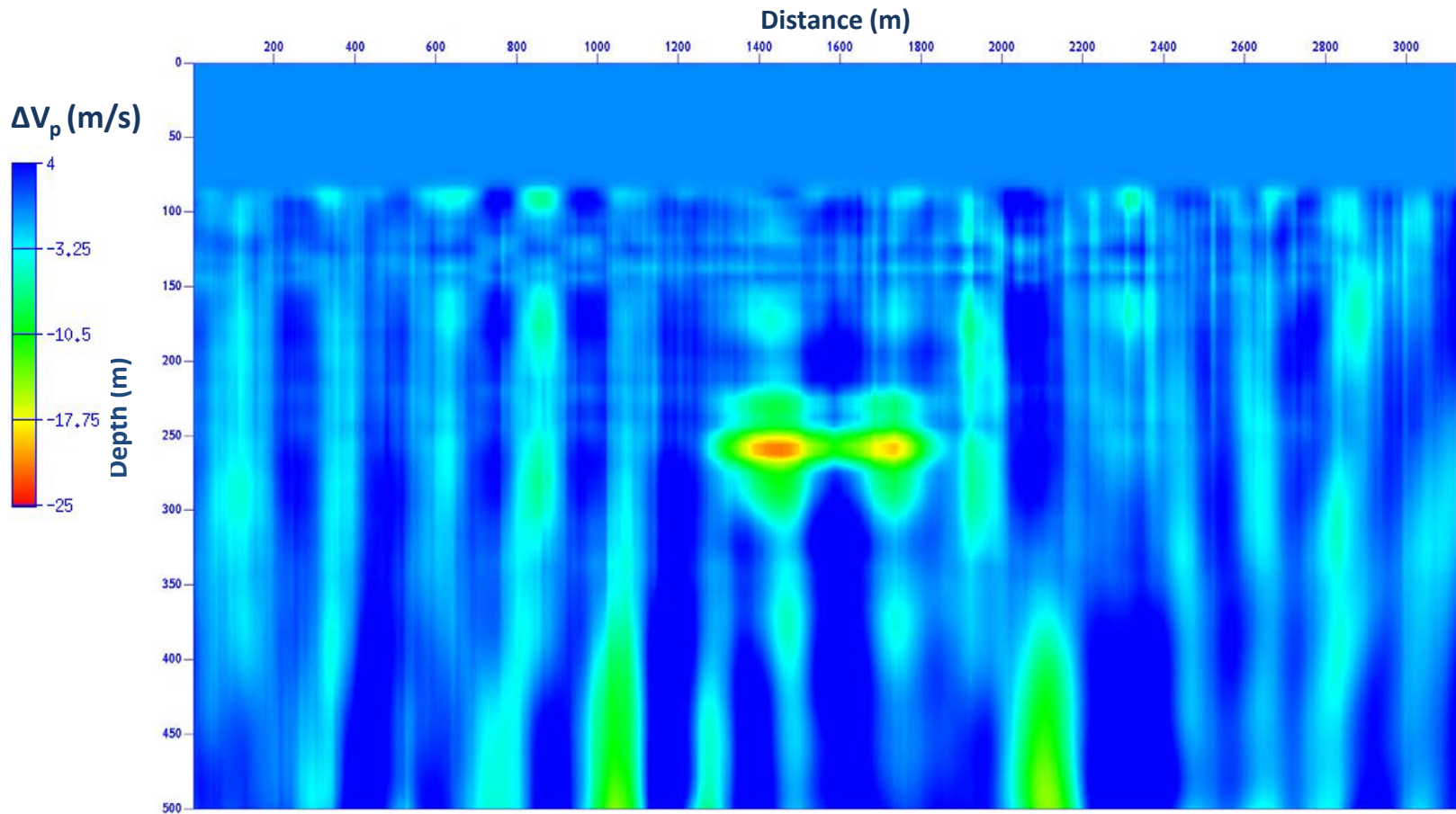




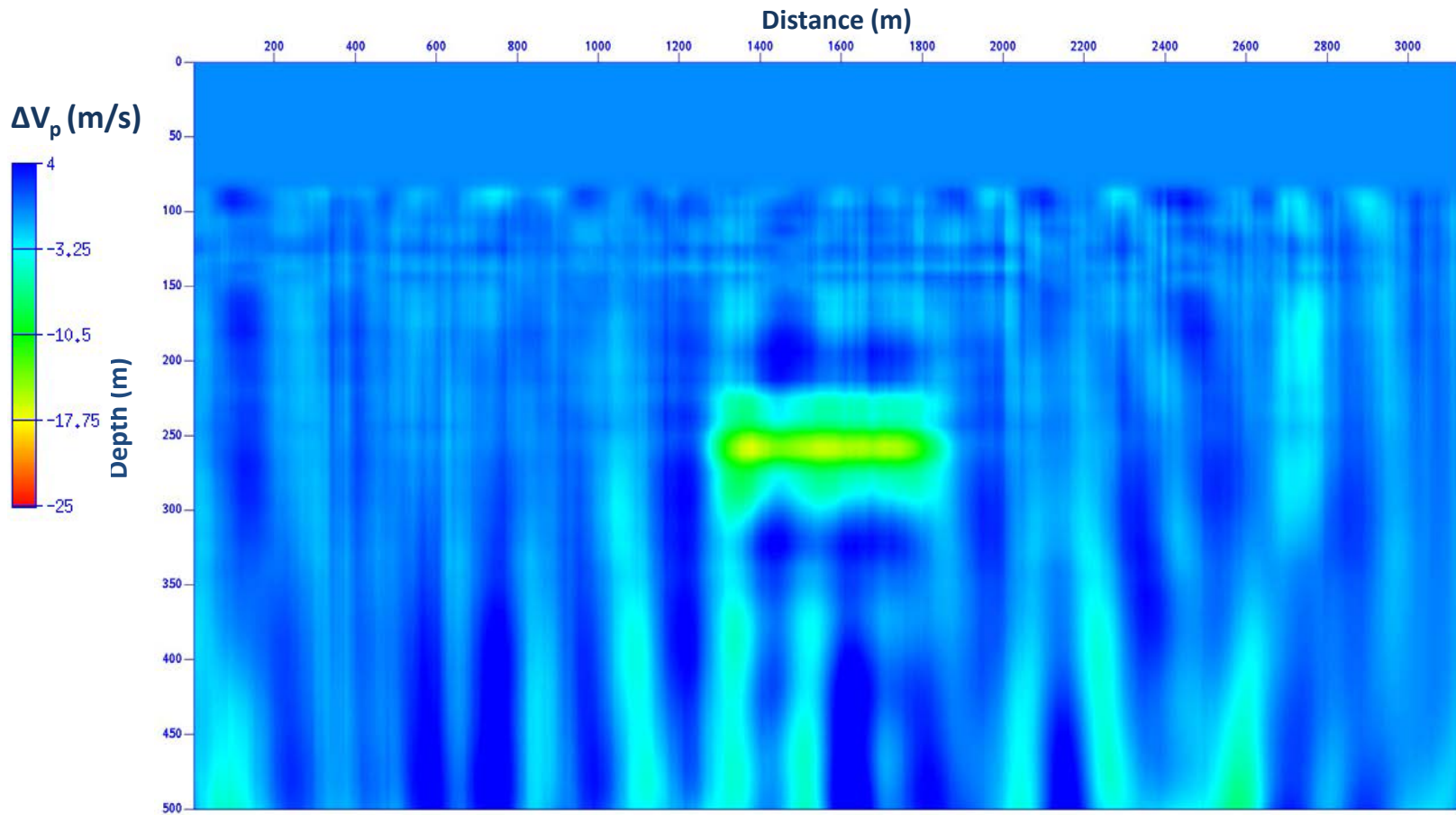
# Test 6: SN=2 /with Free Surface



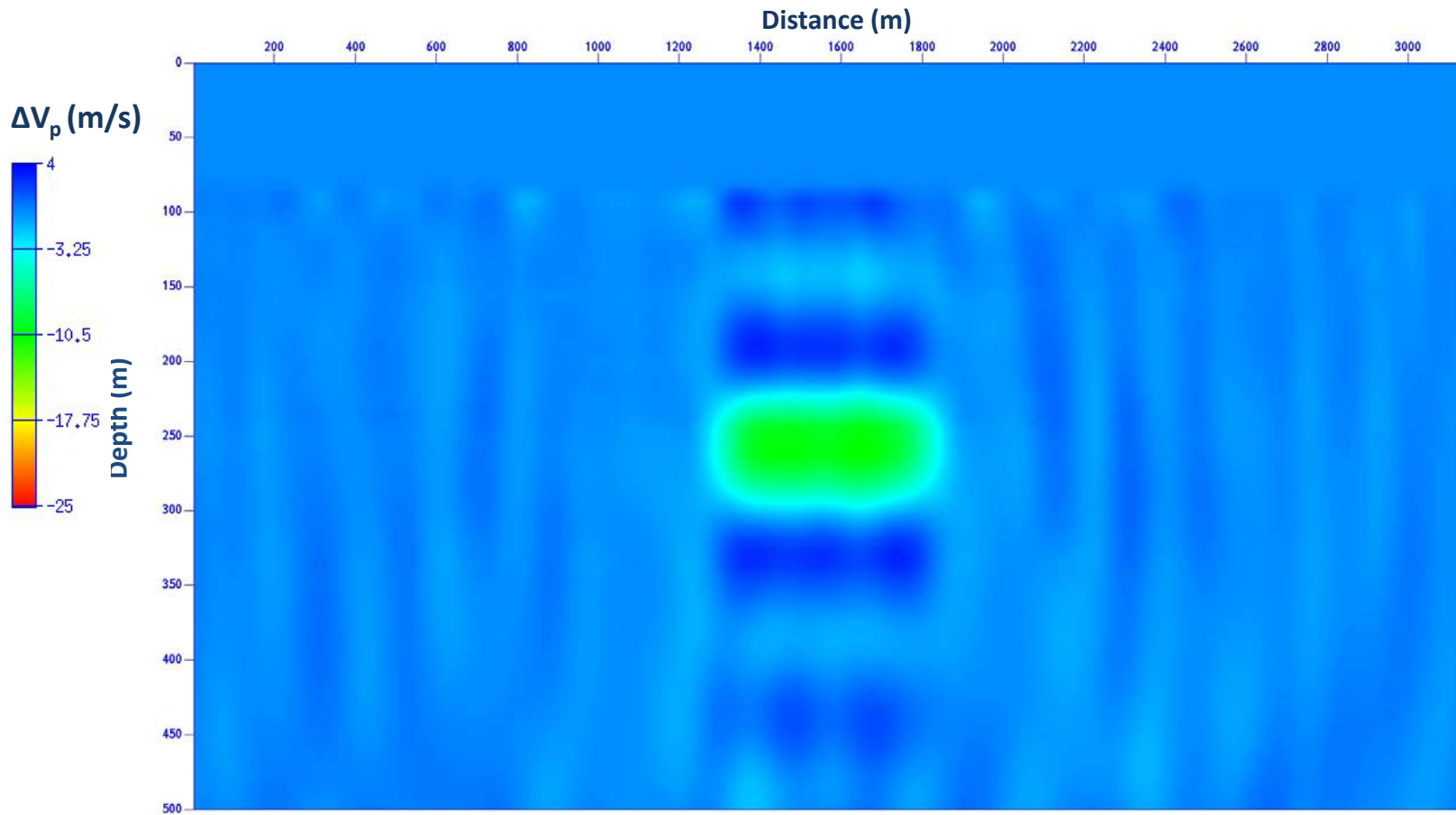
# Test 7: SN=3 /with Free Surface



# Test8: SN=4 /with Free Surface

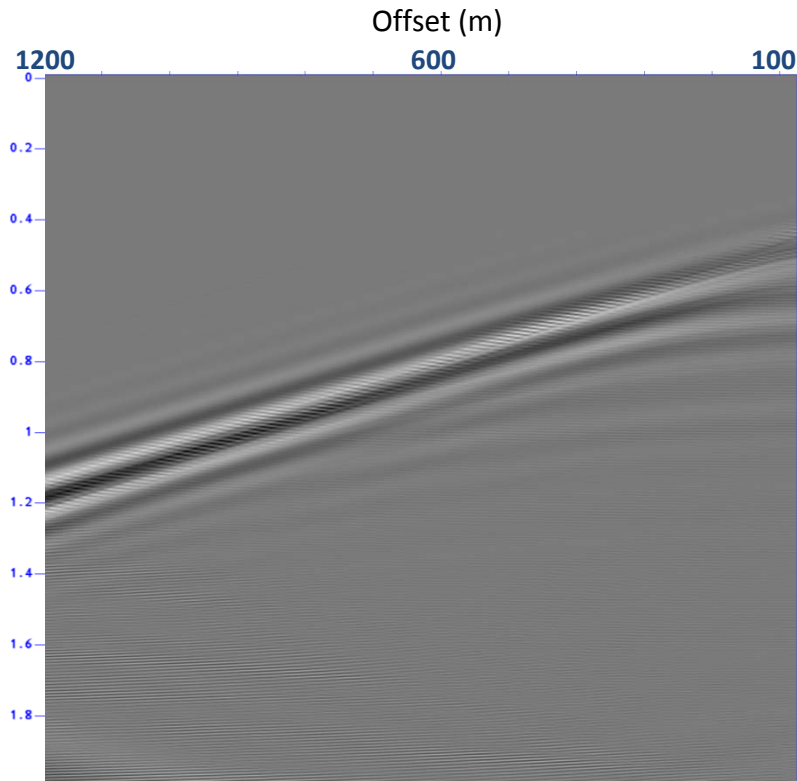


# Run 18: SN=4 / with /with Free Surface (Max offset 3000 m)

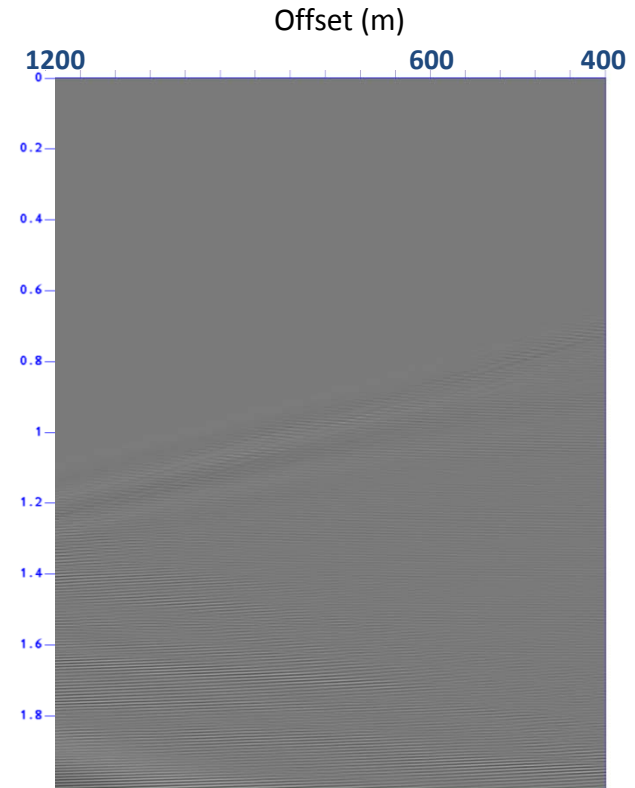


# Inversion Residuals with and without Reflection Events

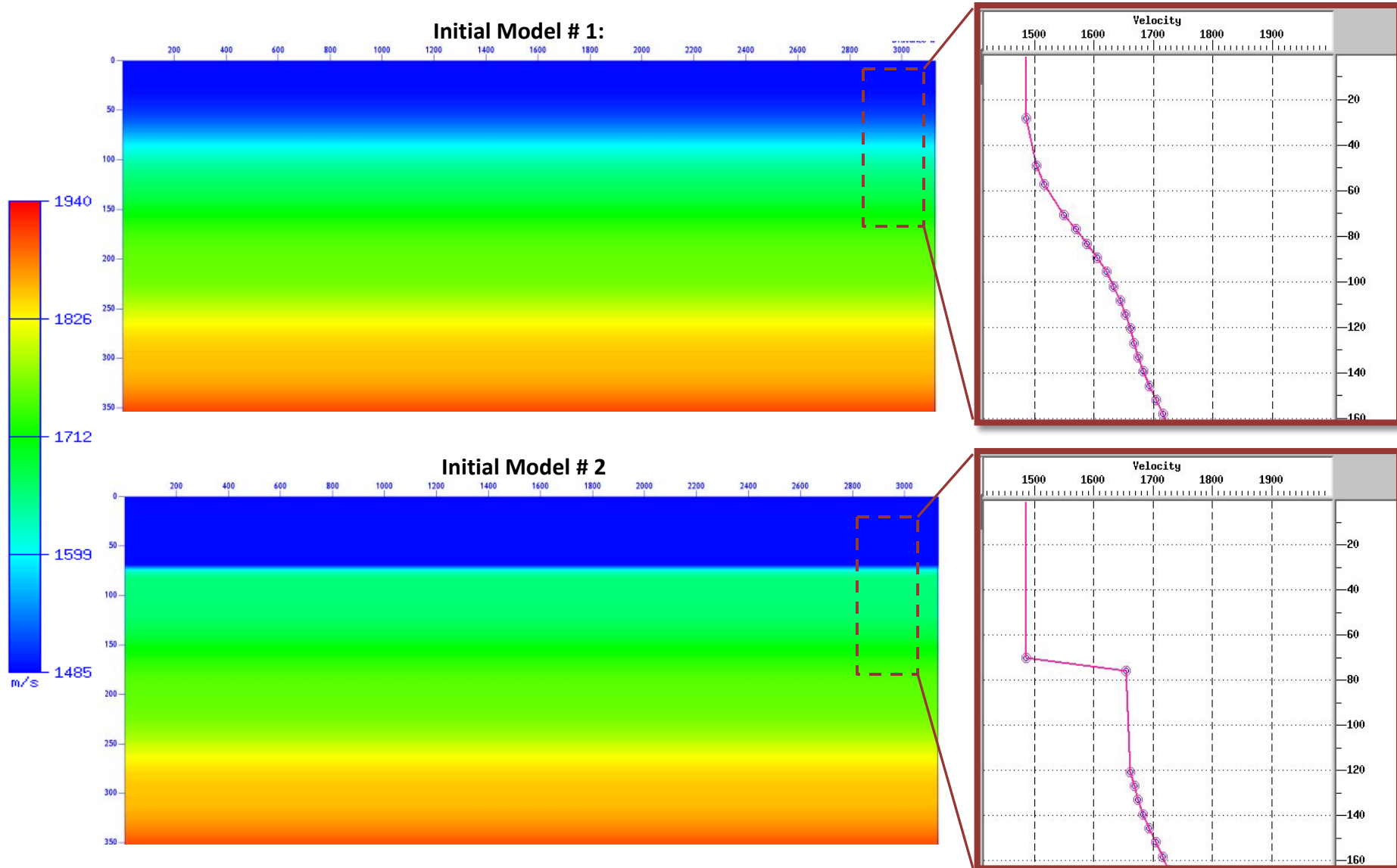
**Inversion Residuals  
Full Offset Range (75-1200 m)**



**Inversion Residuals  
Mid and Far offsets (400-1200 m)**



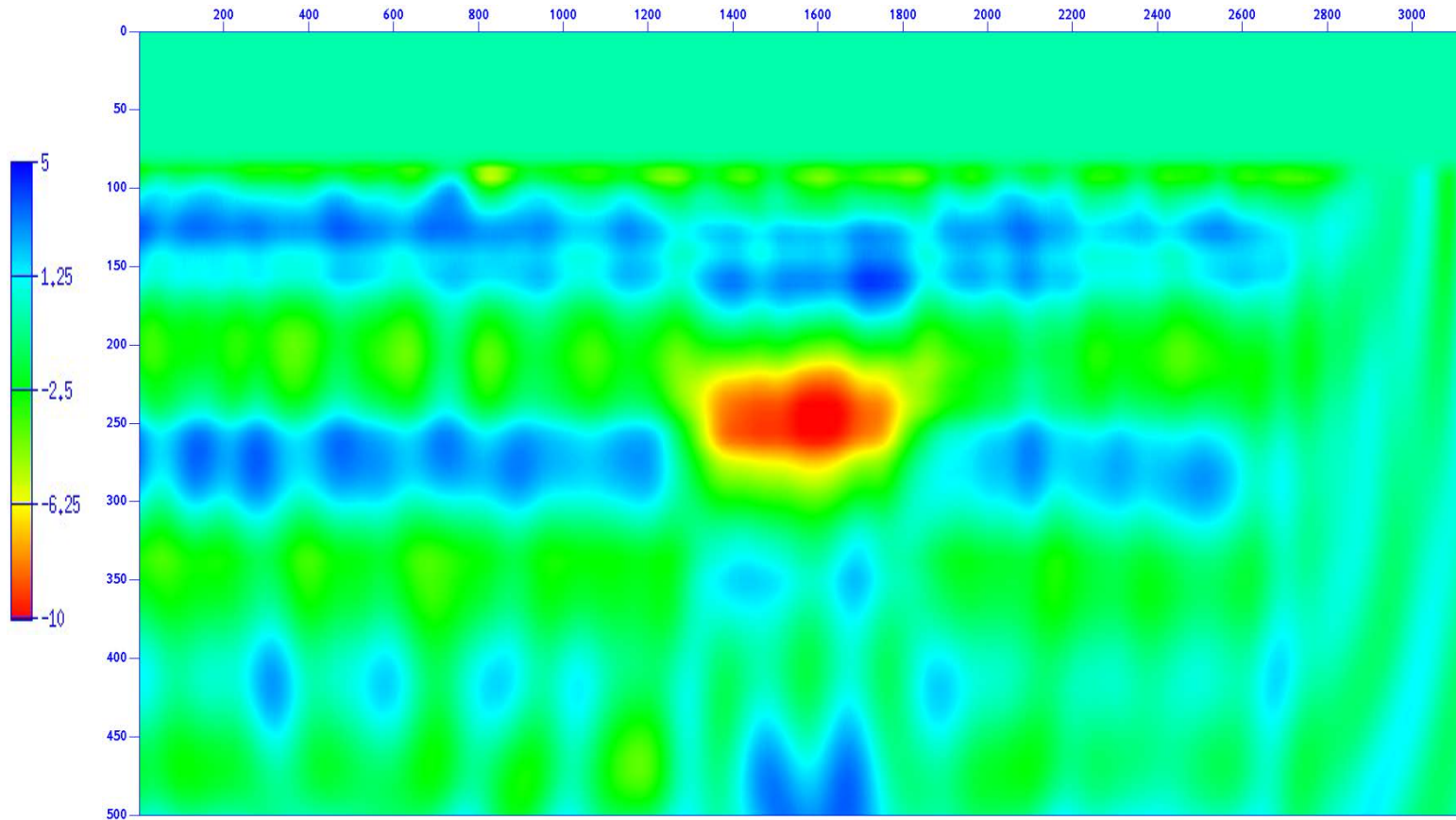
# Test: Initial Model Smoothing



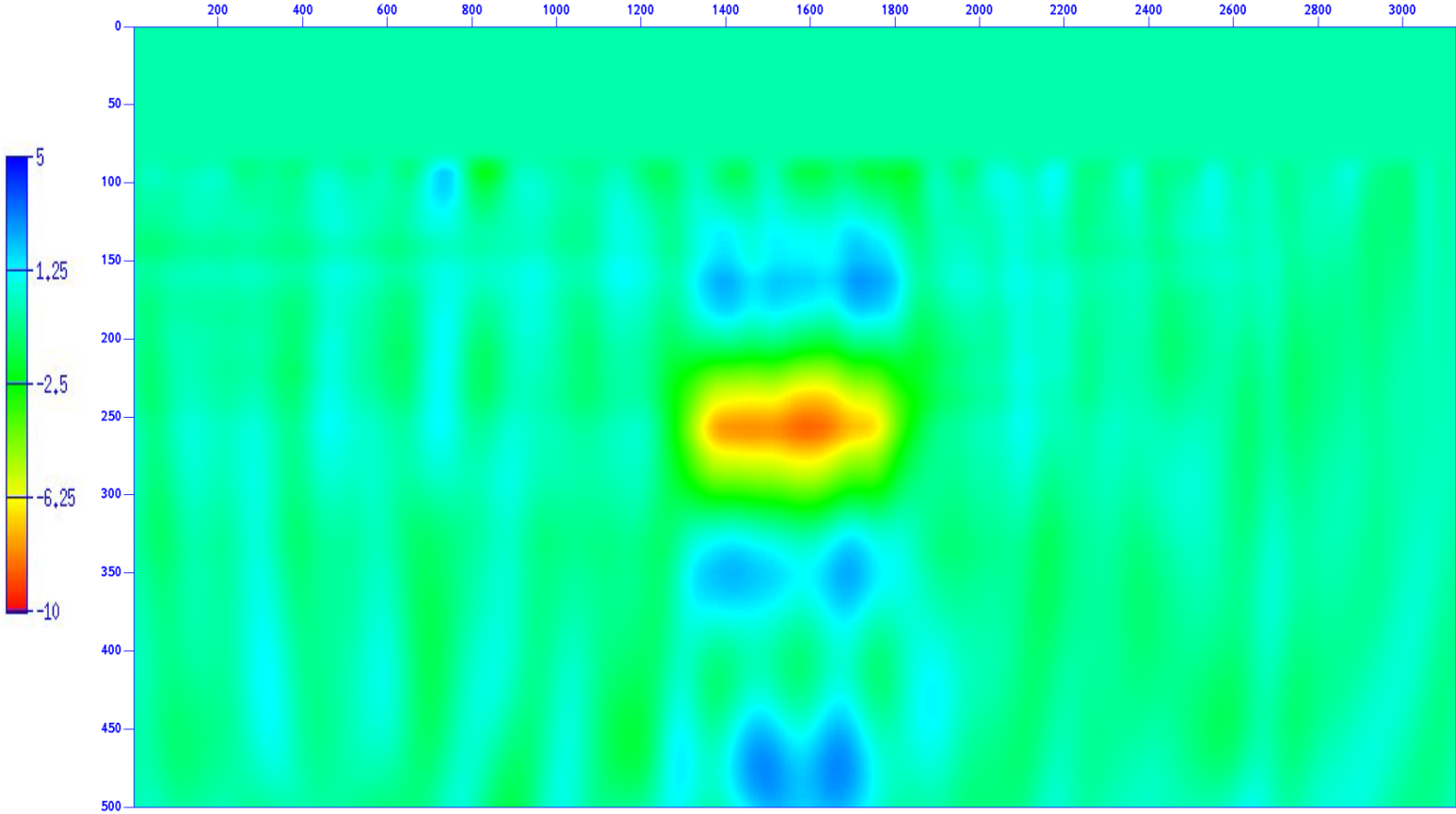


# Inversion Result#1 ( $\Delta V_p$ )

(Using Initial Model 1: Smooth Sea-Bed)

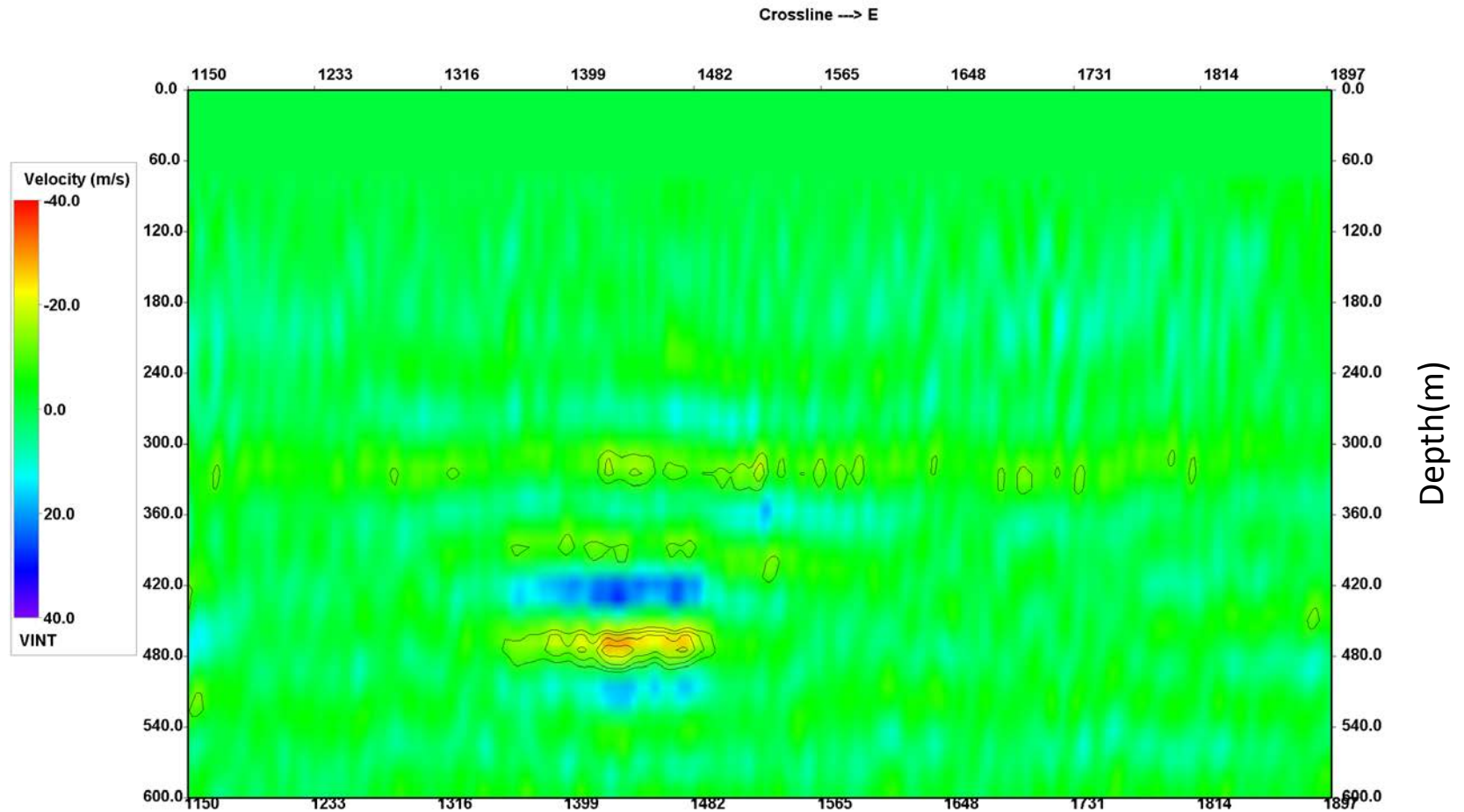


# Inversion Result#2 ( $\Delta V_p$ ) (Using Initial Model 2: Smooth Sea-Bed)





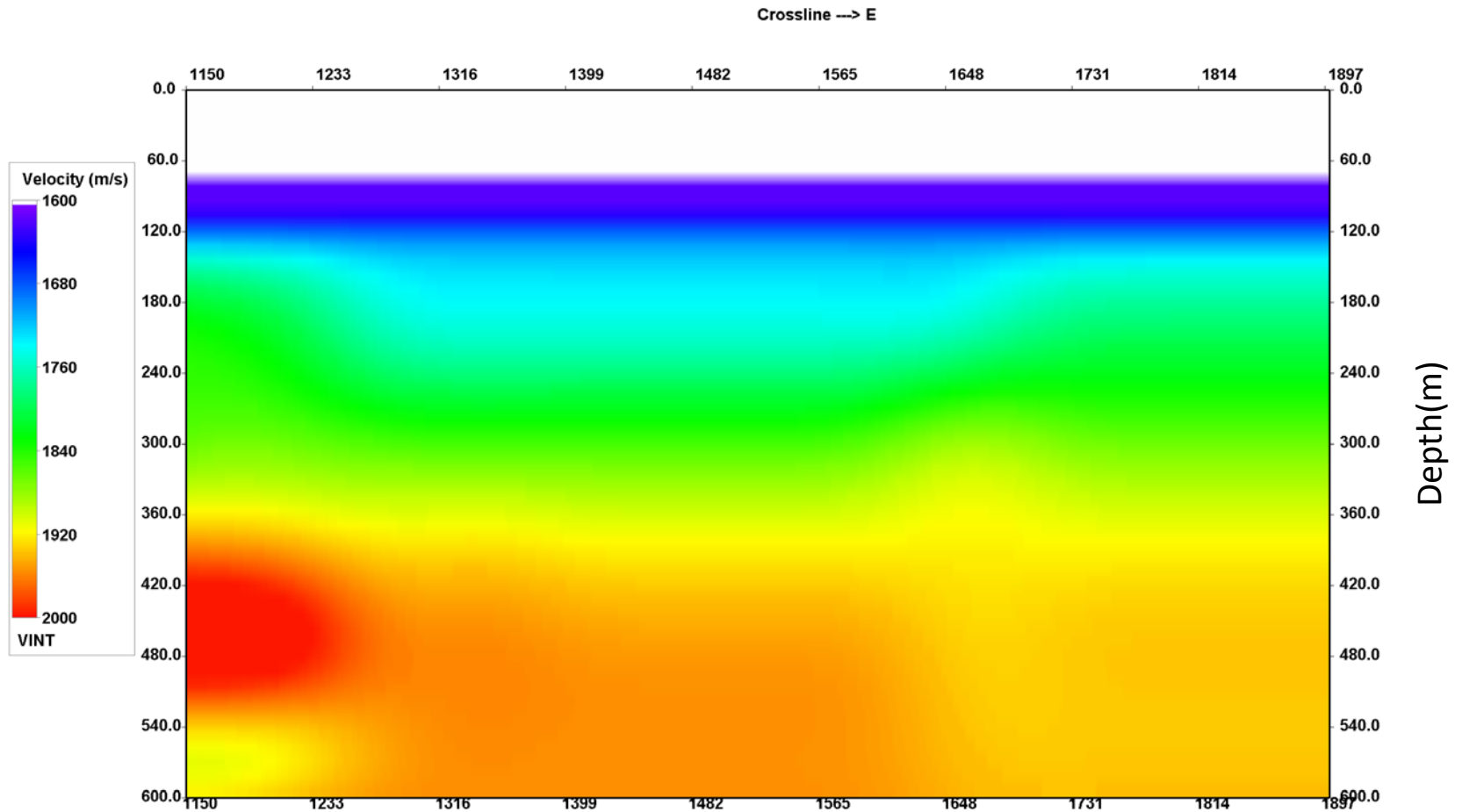
## Inversion Run#2: Velocity difference (m/s) after 16 iterations:



# Field Data Example (LOSEM Project)

- Apply 4D FWI to map the Gas migration pattern, into the shallow section, by making use of the seismic **transmitted energy (refracted & diving waves)**.

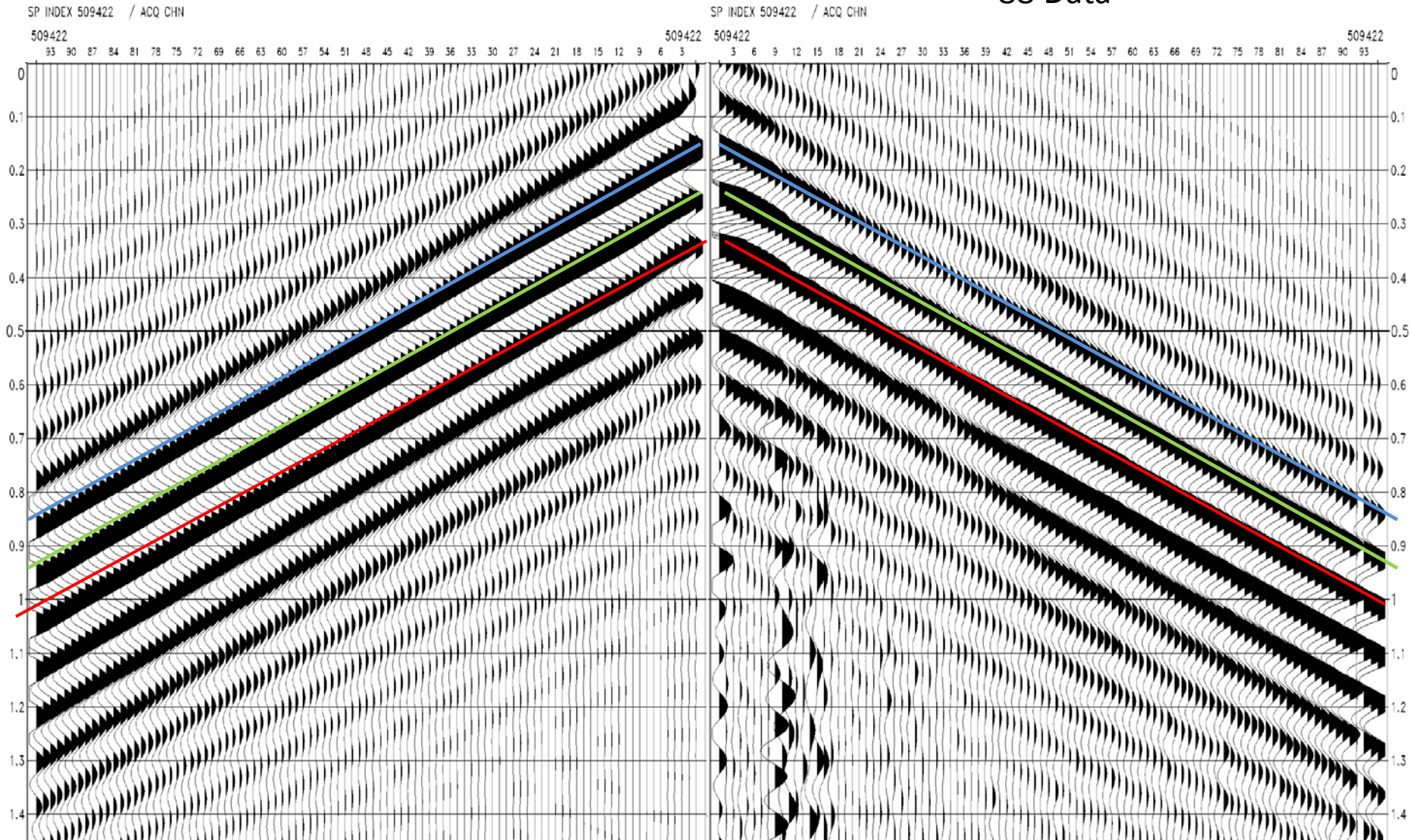
# Initial Velocity Model



# QC: Synthetic 1 (used for inversion run1) Vs 88 data

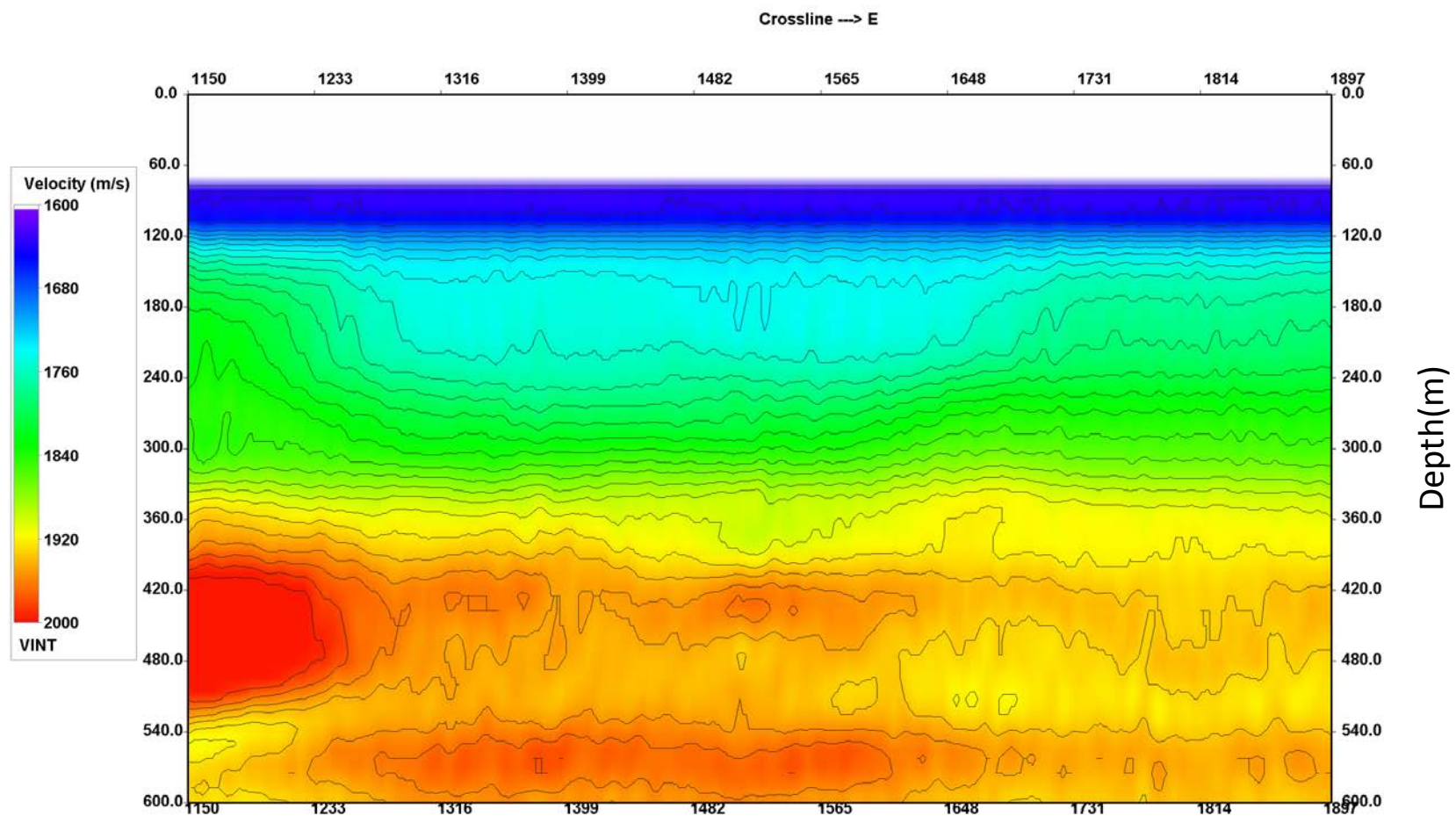
Synthetics 1

88 Data

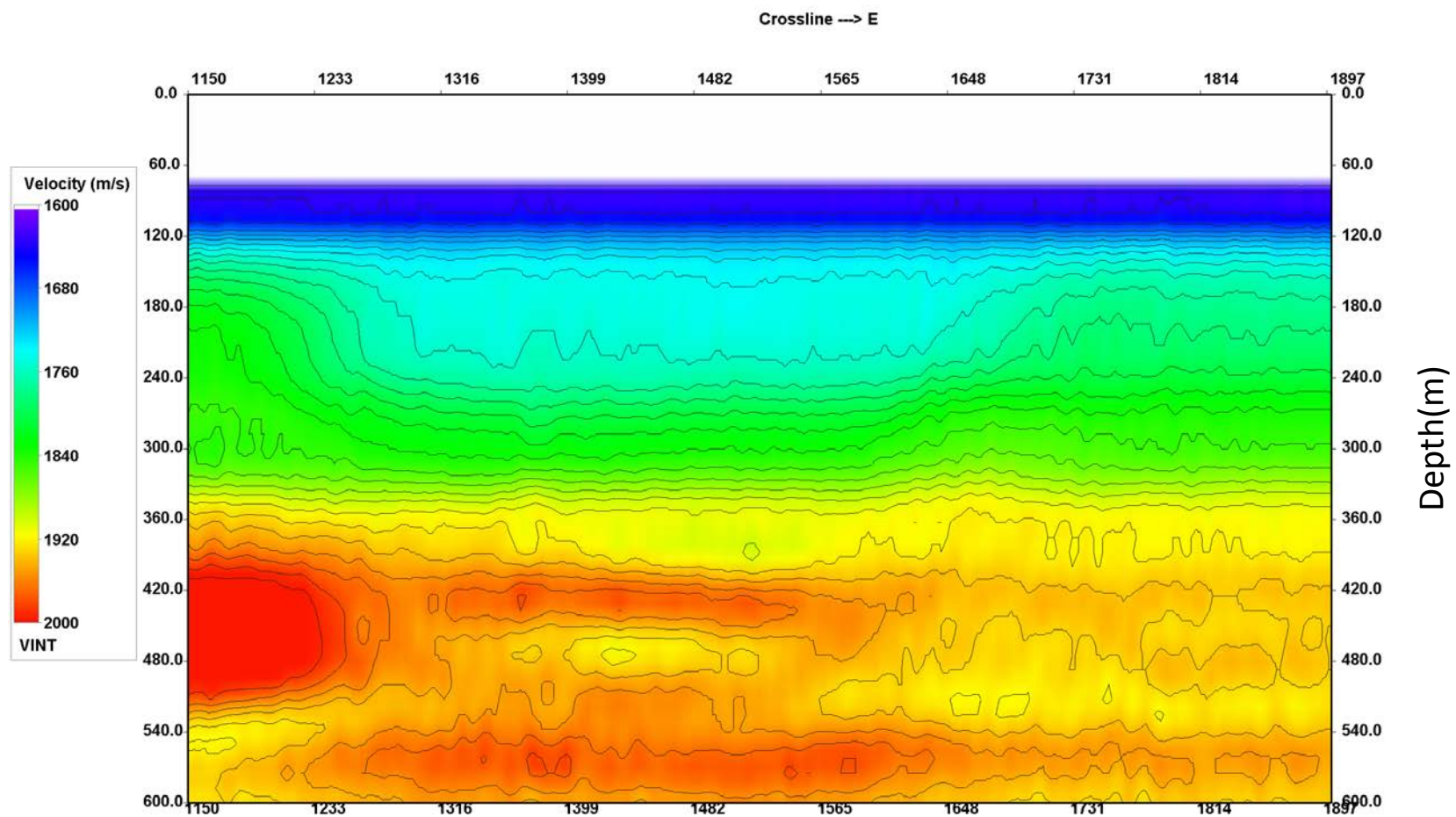




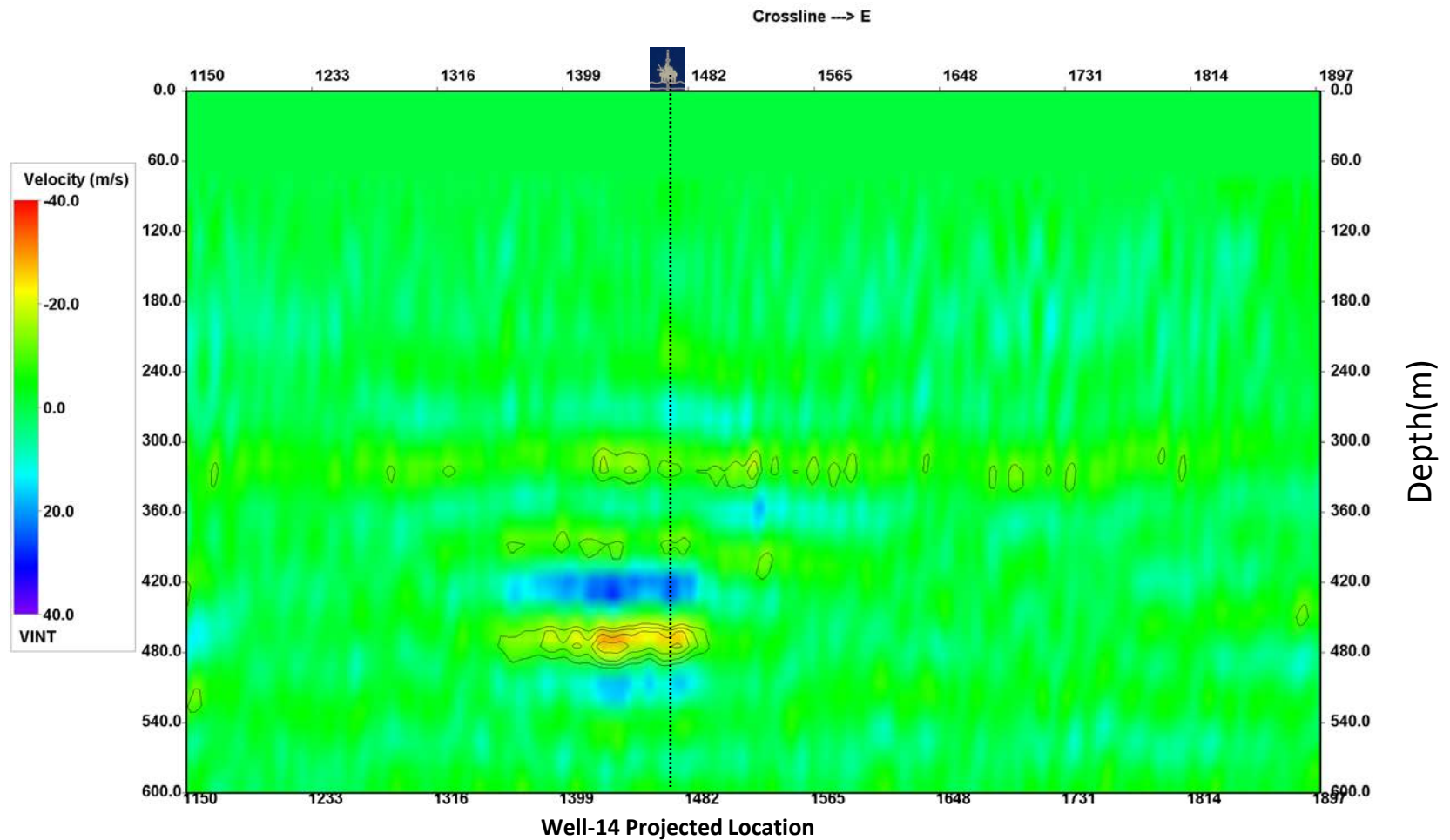
# 88 Data (Inverted Vp)



# 90 Data (Inverted Vp)

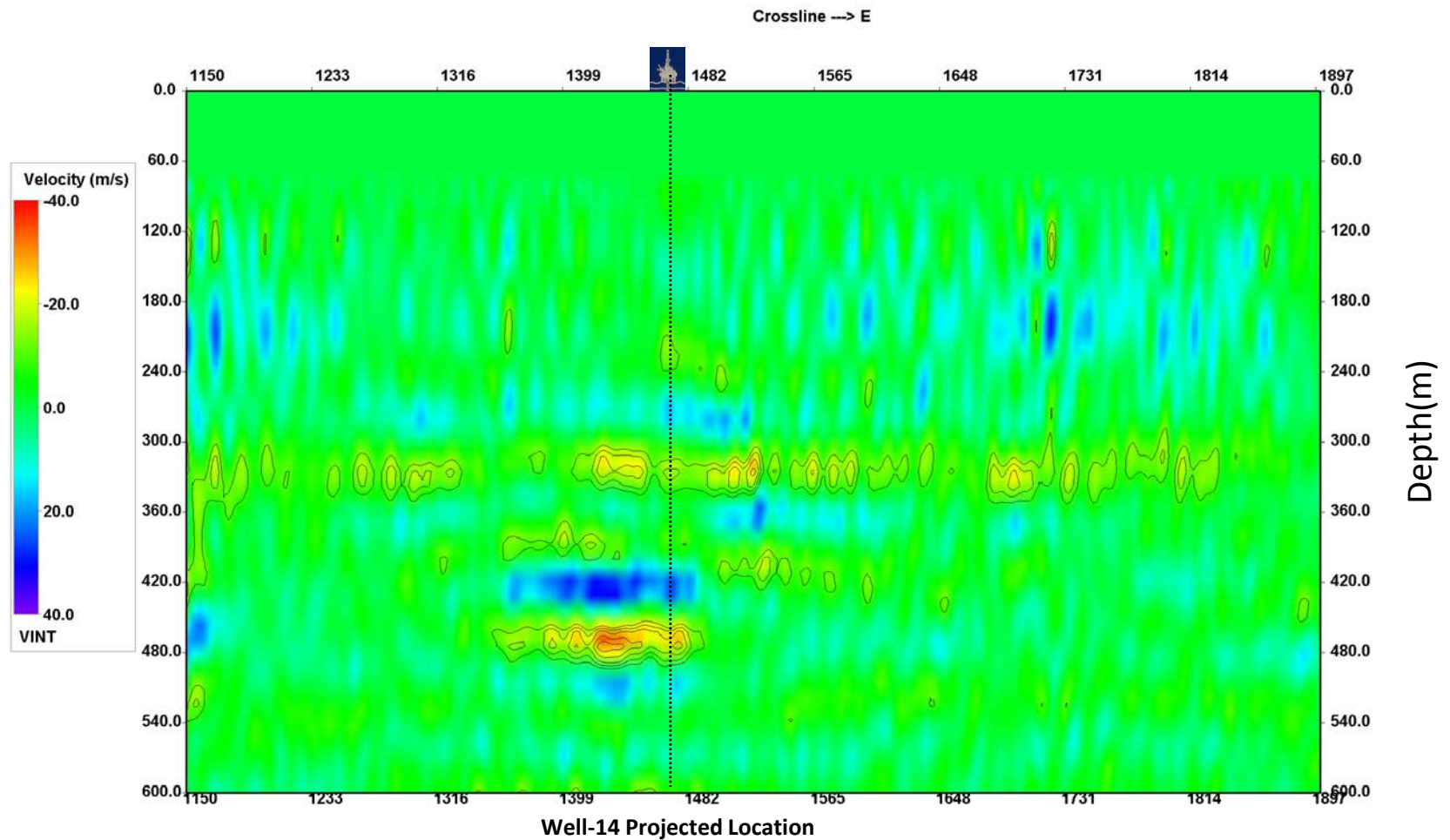


# Field Data Inversion Result ( $\Delta V_p$ ): **After 16 iterations**





# Field Data Inversion Result ( $\Delta V_p$ ): **After 32 iterations**





# Conclusions

- Based on Synthetic tests, it is possible to detect the expected 4D anomaly for the LOSEM project (Assuming everything is done properly in practice!)
- Broader frequency range for input seismic data gives better estimate of the 4D anomaly ( $\Delta V_p$ ), yet is it still detectable with available frequency range in LOSEM project data
- Incorporation the free surface multiples into the modeling seems to improve the inversion results in this case
- Muting the reflection events and focusing on transmitted energy (refracted & Diving) improves the FWI.
- Beware of improper smoothing sea bed: Keep a sharp (bulky Sea Bed layer)

# Acknowledgments

- **LOSEM-Consortium partners** for financial support :  
BayernGas, BP, Det Norske, CGGVeritas, Lundin,  
Statoil and Total
- **CGGVeritas**
- **Statoil** and **Total** for permission to use the data
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