4D Seismic Monitoring of In-Situ Combustion of Heavy Oil Reservoirs*

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Abstract

In-situ combustion is a process that is quickly gaining interest in the industry as a relatively straightforward EOR method, especially in heavy-oil reservoirs. Of critical importance to the success of this process is the effective monitoring of the reservoir zone affected by the combustion. Since in-situ combustion alters the elastic properties of the rocks and generates combustion gases (in addition to the air injected in the reservoir), the seismic response of the affected area is expected to be different before and after this process.

We will show in this presentation the results of the first 4D seismic project carried out in Colombia as part of the STAR pilot project of synchronized in-situ combustion in the Eastern Llanos basin in Colombia. We will present an overview of the design, acquisition and processing of the seismic data and show how the 4D seismic generates a clear three-dimensional image of the area affected by the combustion process. In particular, we will show that the affected area is nowhere close to the nice spherical shape we would expect if the reservoir were homogeneous and isotropic. Instead, the affected area shows preferential flow directions and flow barriers, which demonstrate the heterogeneity and anisotropy of the thin reservoir unit. This information is of the utmost importance to synchronize and optimize the combustion process by optimally placing injector and producer wells to reduce bypassed oil.

4D seismic monitoring of in-situ combustion of heavy oil reservoirs

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Seismic monitoring (4D seismic): overview

- It's the repeated acquisition of a seismic volume at "reasonable" time intervals.
- Absent a physical process that could alter the subsurface, the seismic volumes should be the same (or nearly so).
- If a physical process capable of altering the subsurface (steam injection, in-situ combustion, etc) is carried out, the difference between the seismic volumes should reflect the effect of such process.
- The repeated seismic volumes allow the monitoring of the physical process as a function of repetition time interval.

What do we obtain from the 4D-3C seismic?

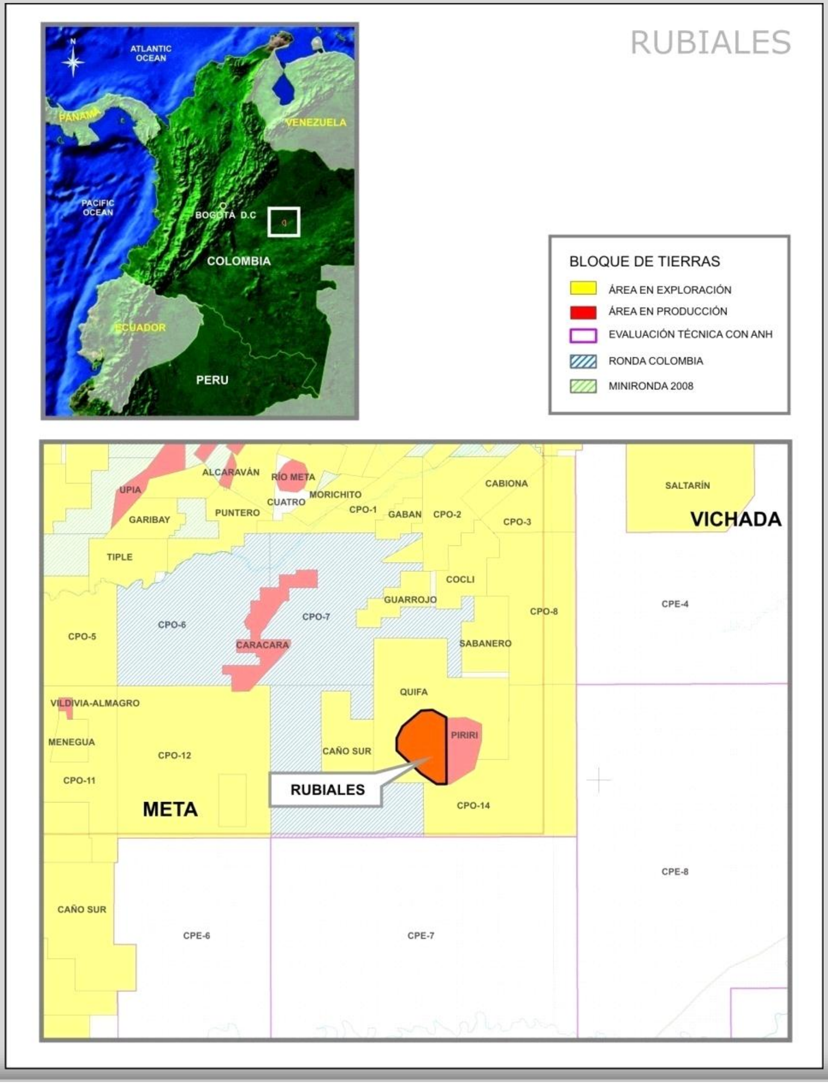
- Seismic volumes of each repetition and volumes of the difference between the base case and each repetion and between repetitions.

- The difference volumes can be obtained for any elastic parameter associated to the propagation of the seismic waves: seismic amplitudes, impedances, elastic modulii (Young’s modulus, volumetric modulus, stiffness modulus, etc), Poisson’s ration, Vp/Vs ratio, etc.

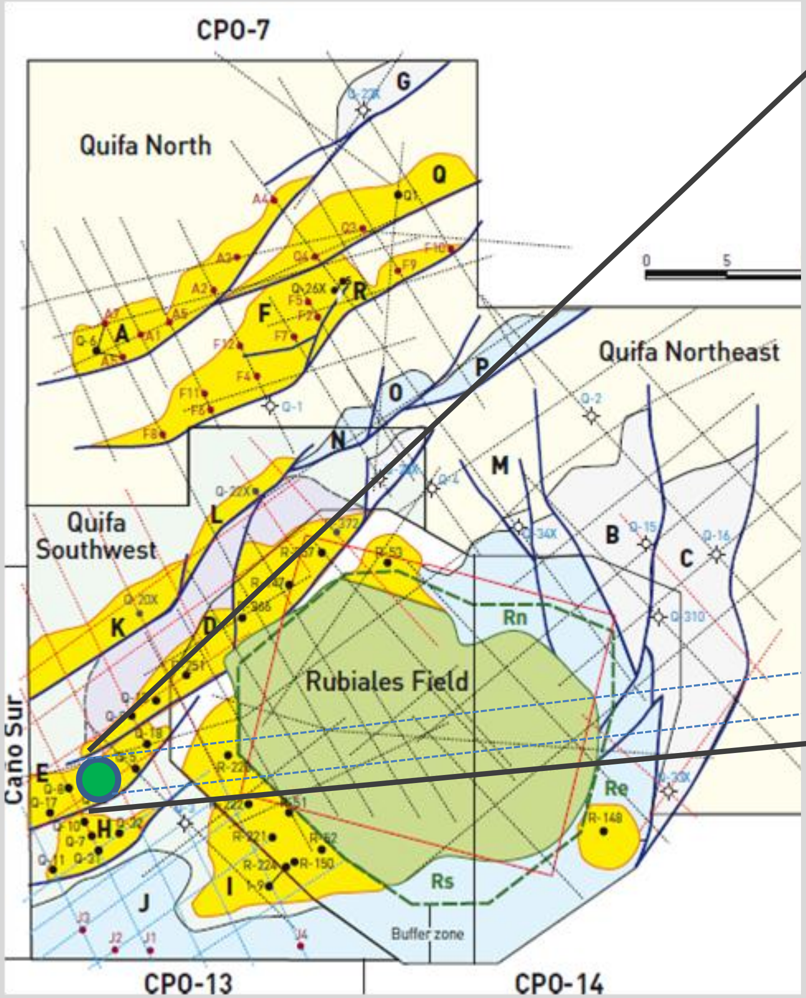
- These volumes provide direct information about the geometry, depth and thickness of the subsurface layers affected by the physical process.

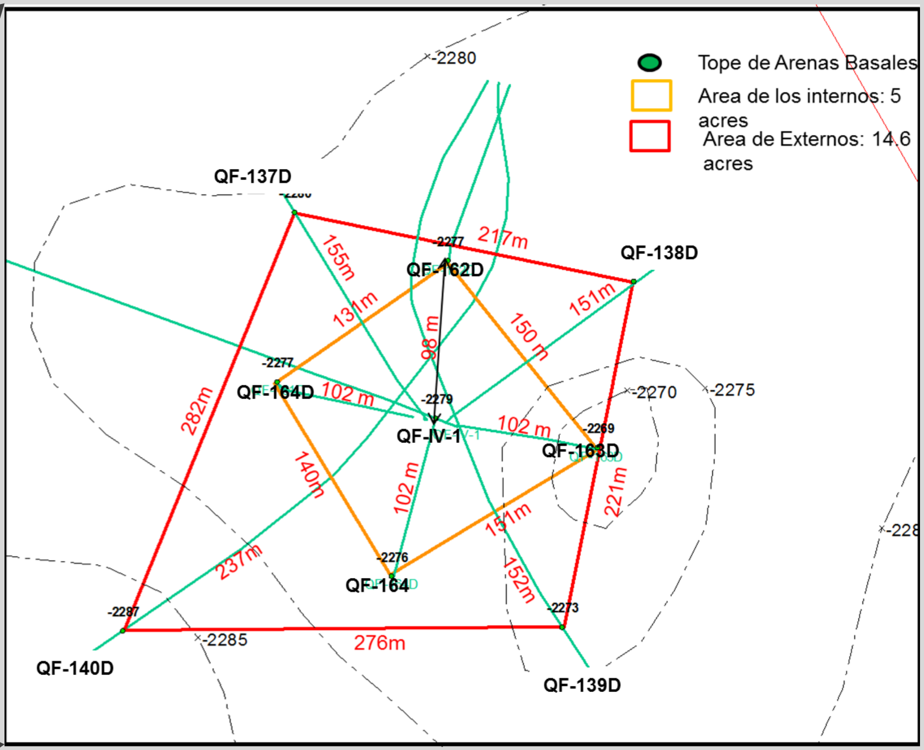
Project Location. Llanos Basin, Colombia

Location Map



Project Location





Seismic monitoring. Geometry.

Main acquisition parameters

Survey area: 4.7 km2 ~ 2.2 by 2.2 km

Bin size: 6x6 m2.

Nominal fold 24.

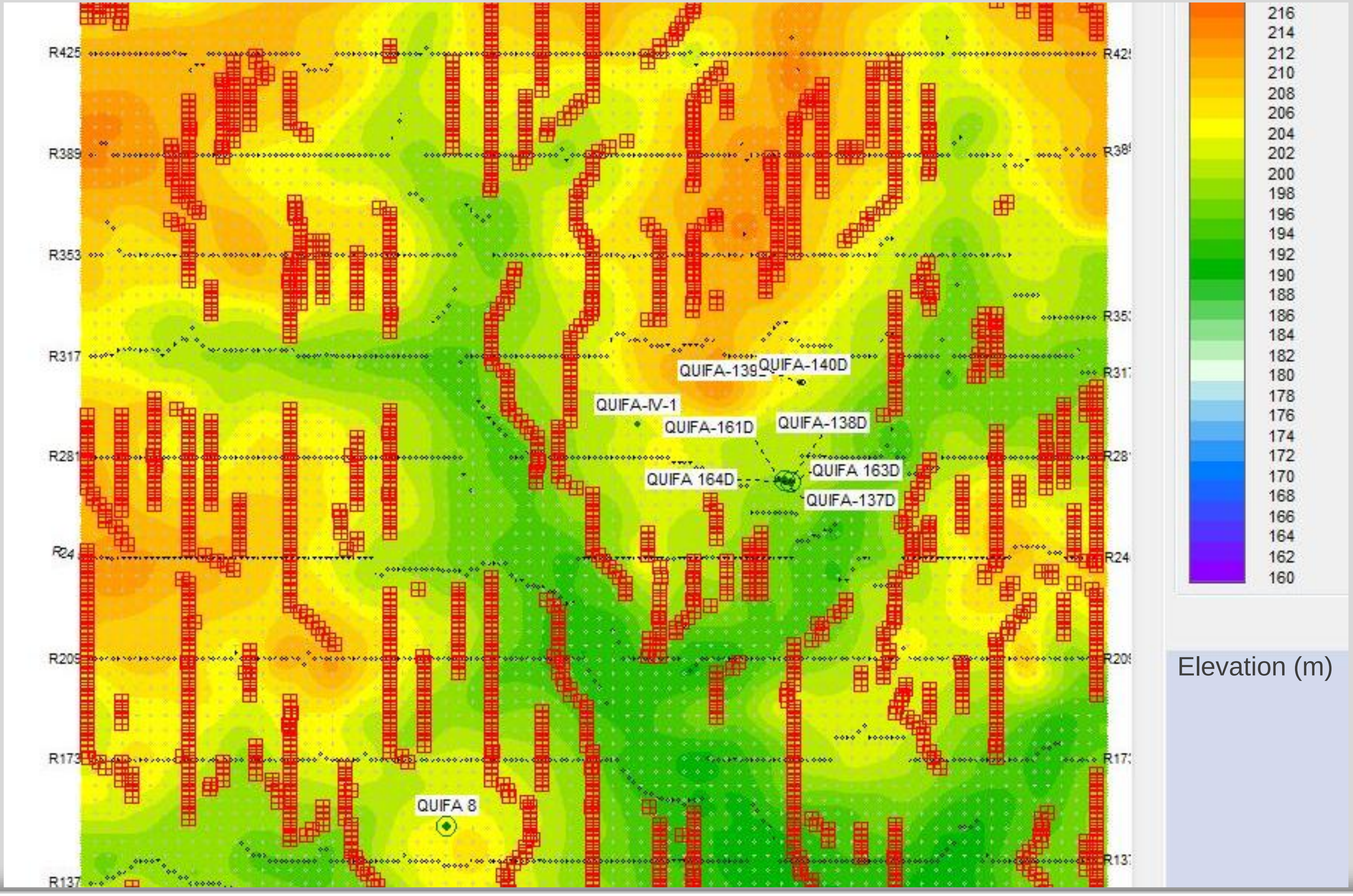
Source line distance = Receiver line distance = 216

Source type: explosives. 1 hole, 10 m, 1800 gr.

Recording patch: 10 lines, 180 ch each.

Receiver type: single 3C geophone buried 10 ft.

Acquisition Geometry – Base case



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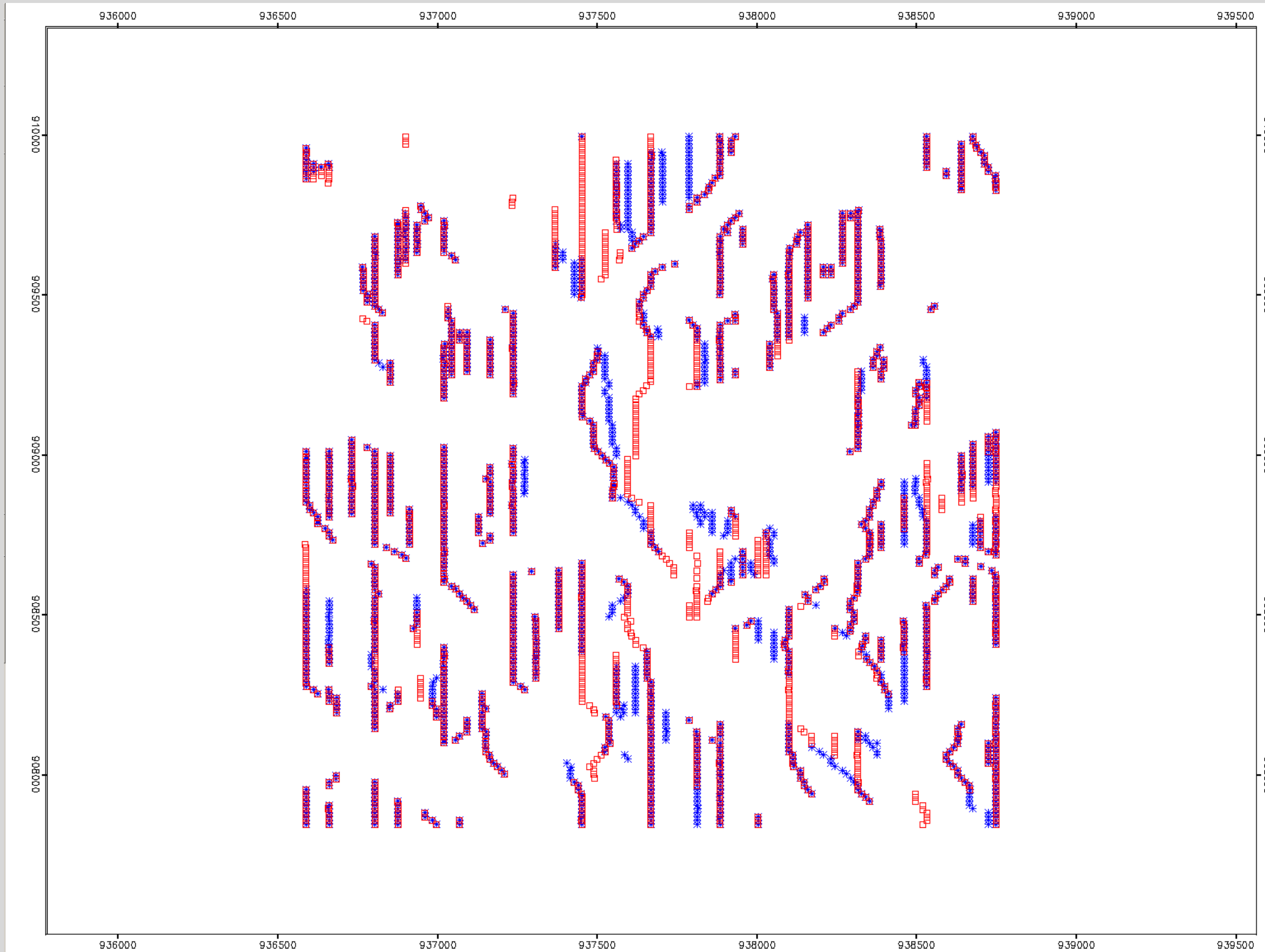
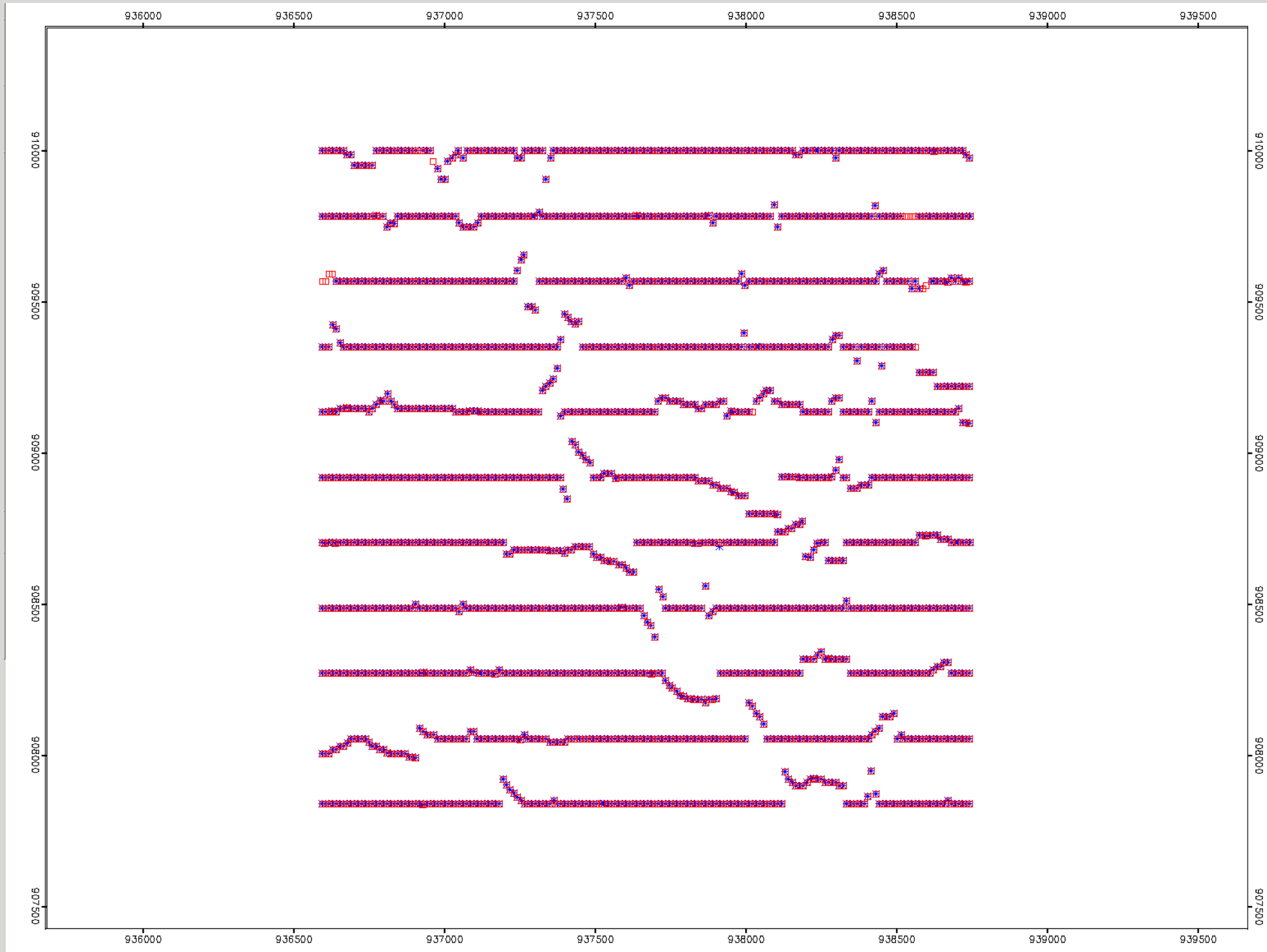
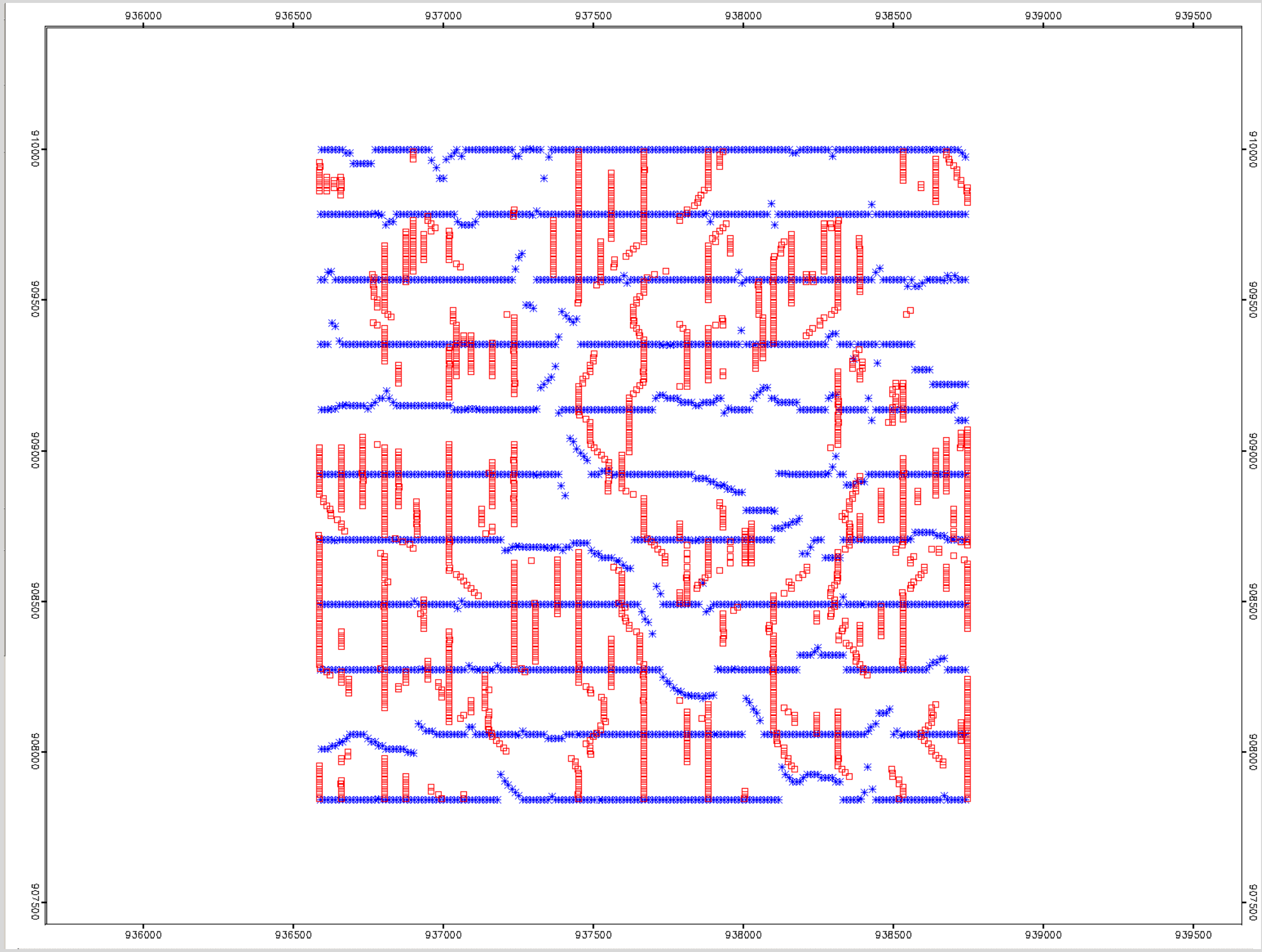
Source map: base-case (red), monitor 1 (blue)



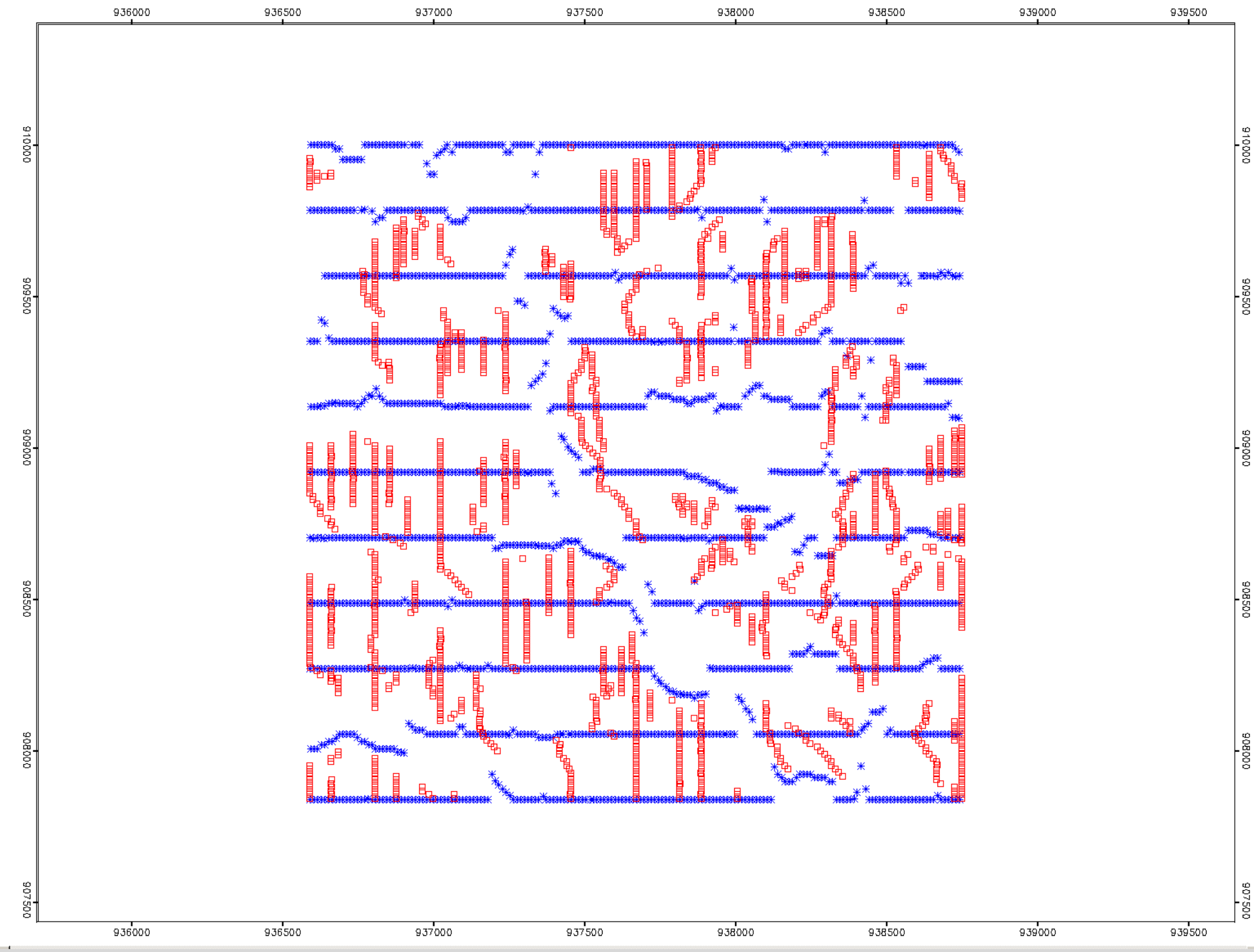
Receiver map: base-case (red), monitor 1 (blue)



Map of sources and receivers: base case



Map of sources and receivers: monitor 1



Seismic monitoring. Data processing.

Seismic processing: 4D-3C

Data processed at CGG in Calgary. Joint inversion in CGG Houston.

- PSTM PP component
- PSTM PS components
- PP elastic simultaneous inversion
- Joint PP-PS simultaneous inversion

Carried out for the base case and each monitoring. Difference volumes computed for all attributes.

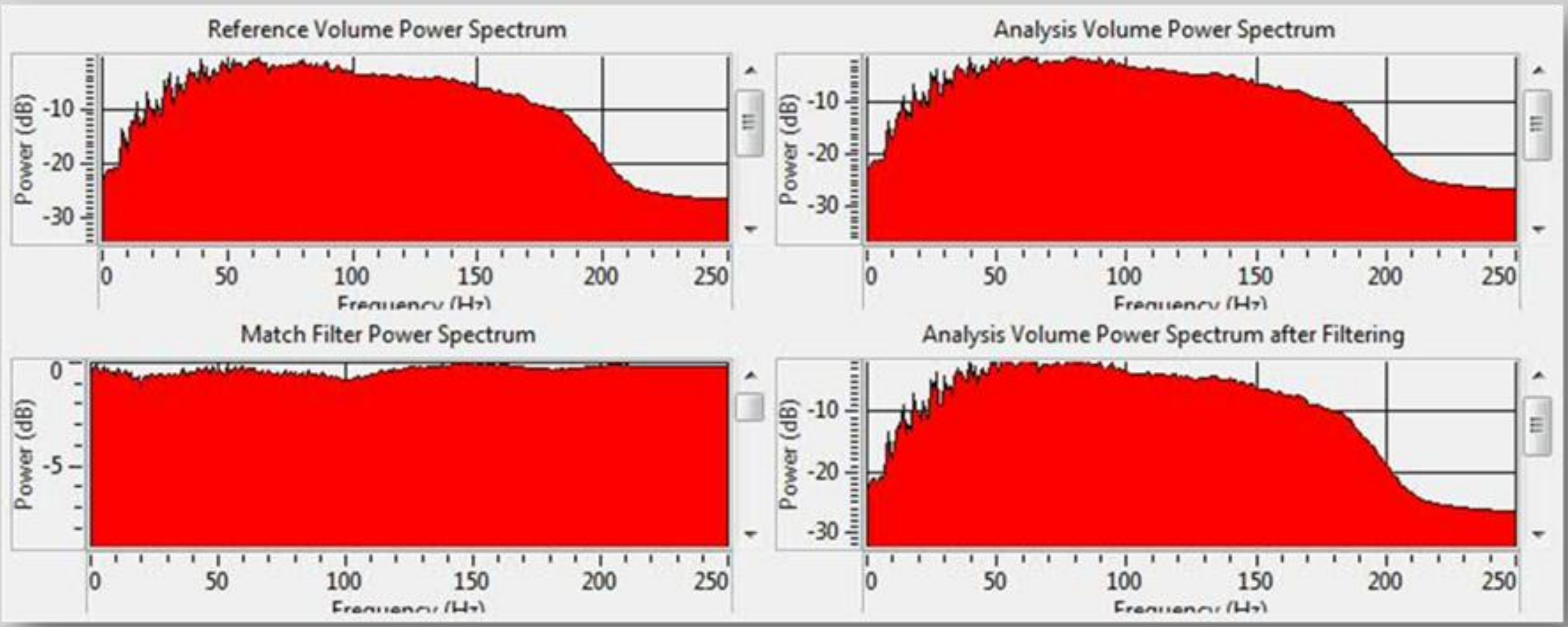
Comments on seismic processing

“Standard” land-data processing sequence. Emphasis on repeatibility on processes and parameters.

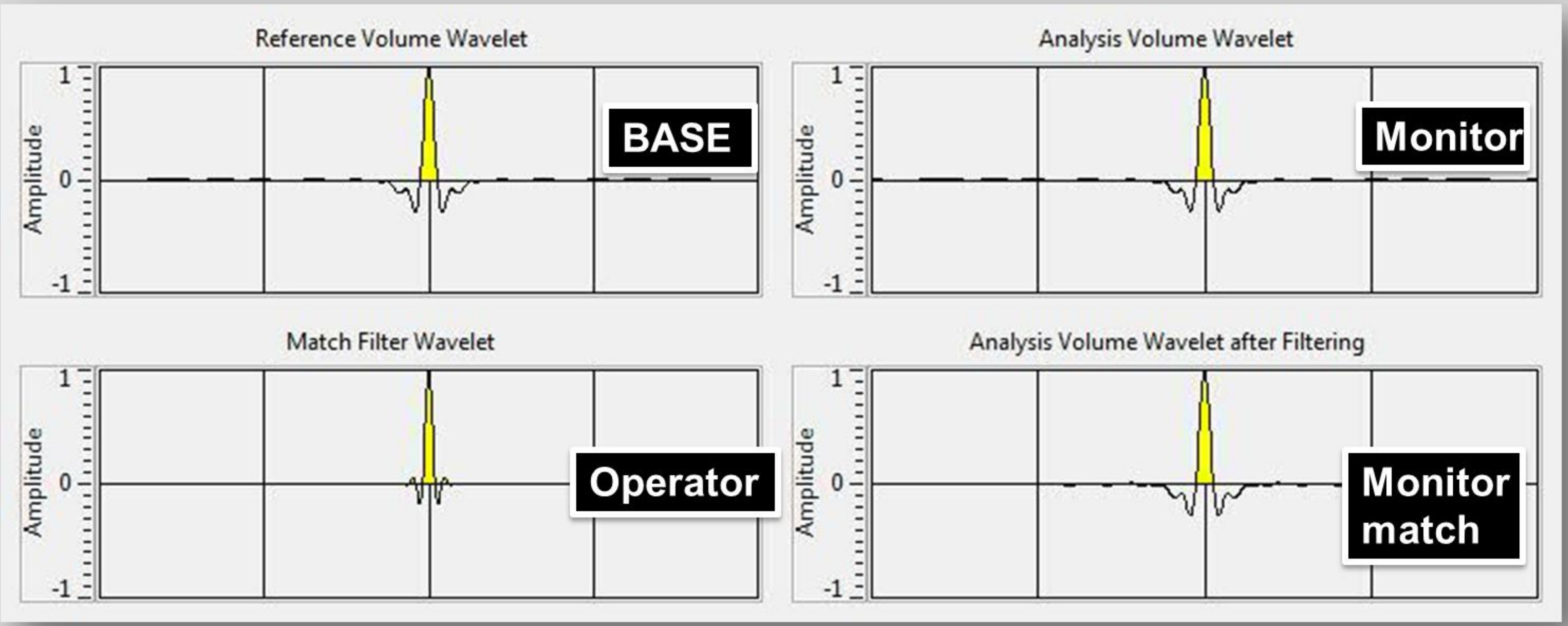
Compensation of wavelet phase and amplitudes between surveys.

Compensation for time-shift differences (statics) between surveys.

Filter operator for wavelet matching



Wavelet calibration



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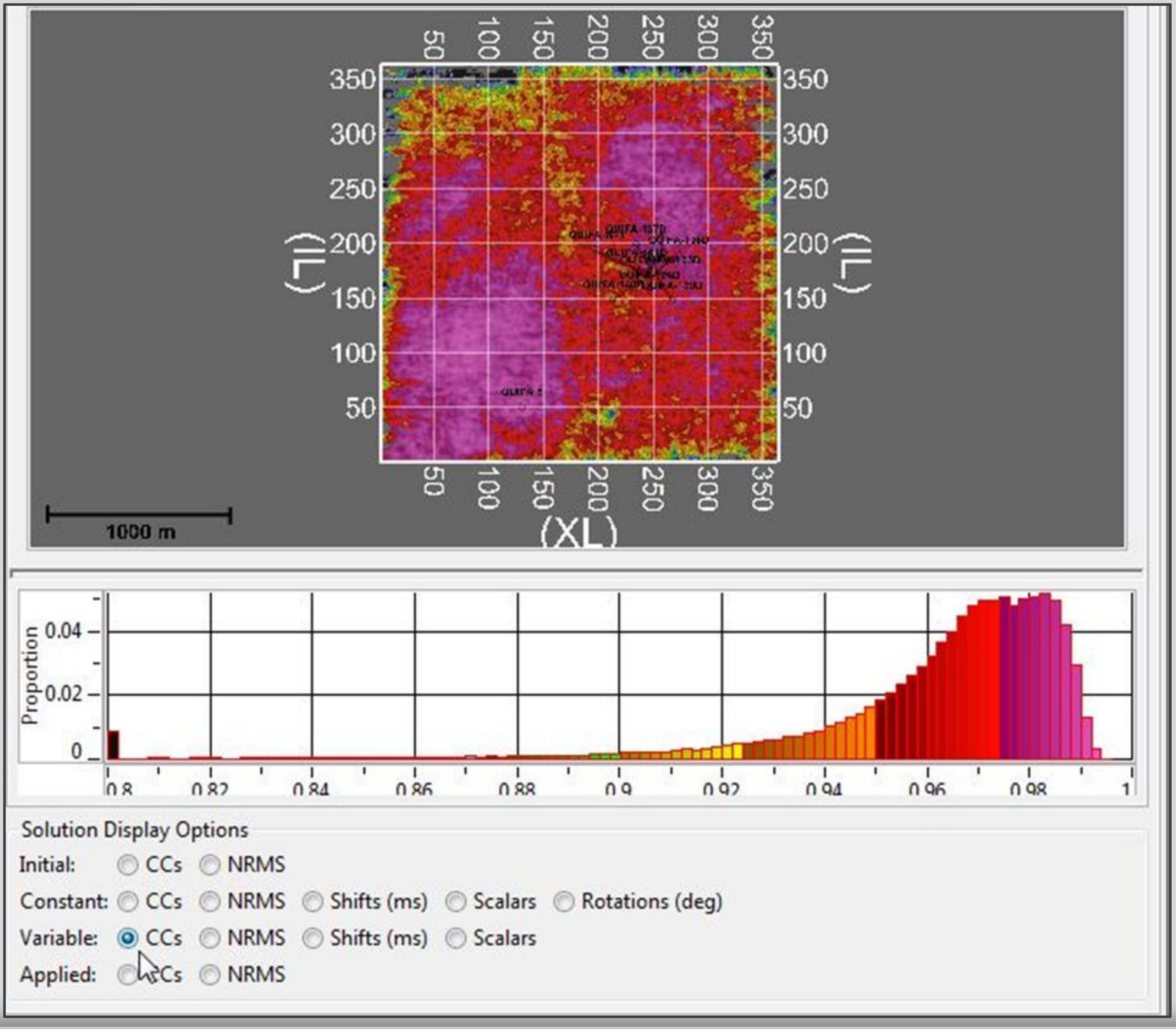
Cross-correlation between surveys



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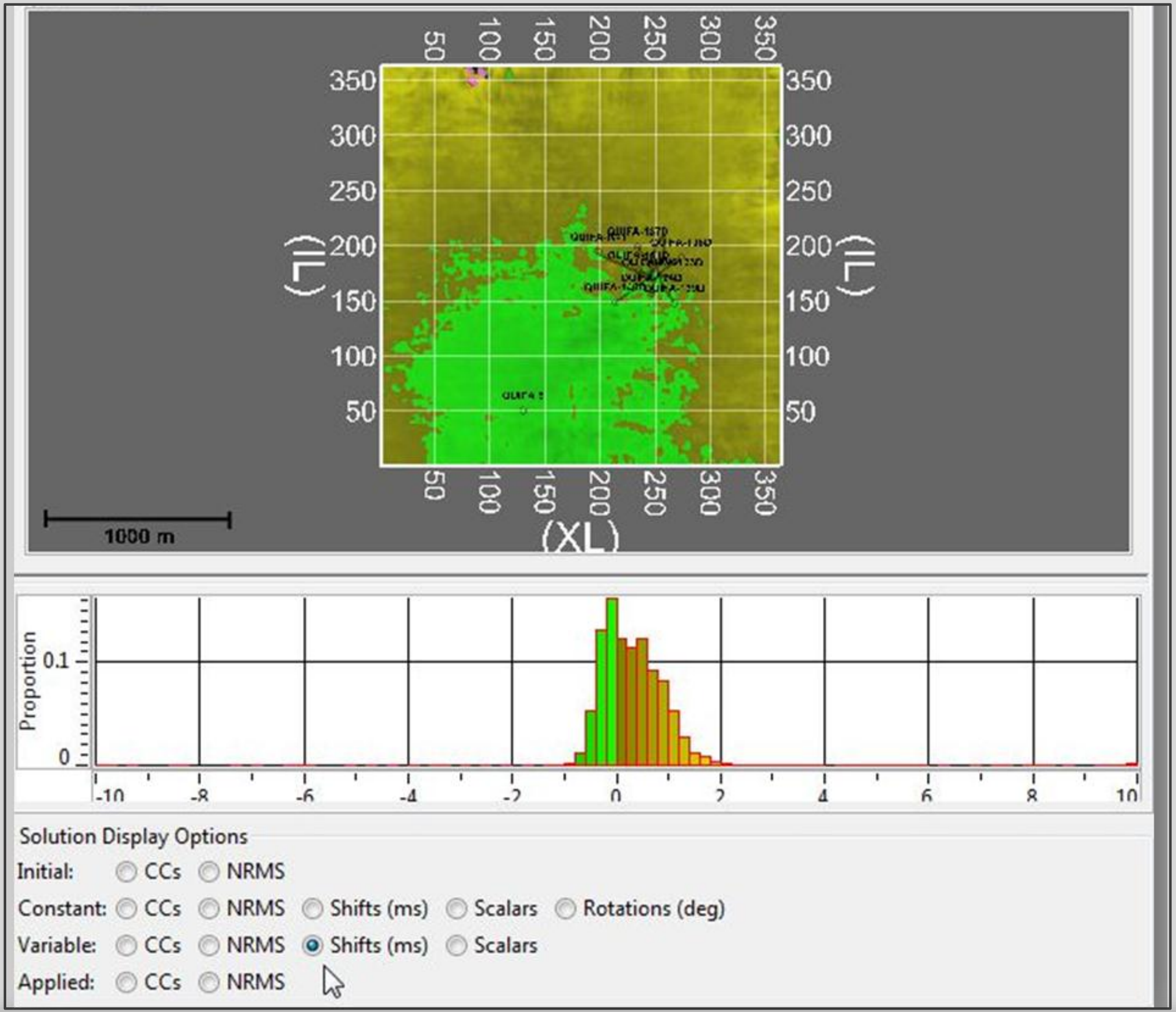
Time shift (statics) correlation



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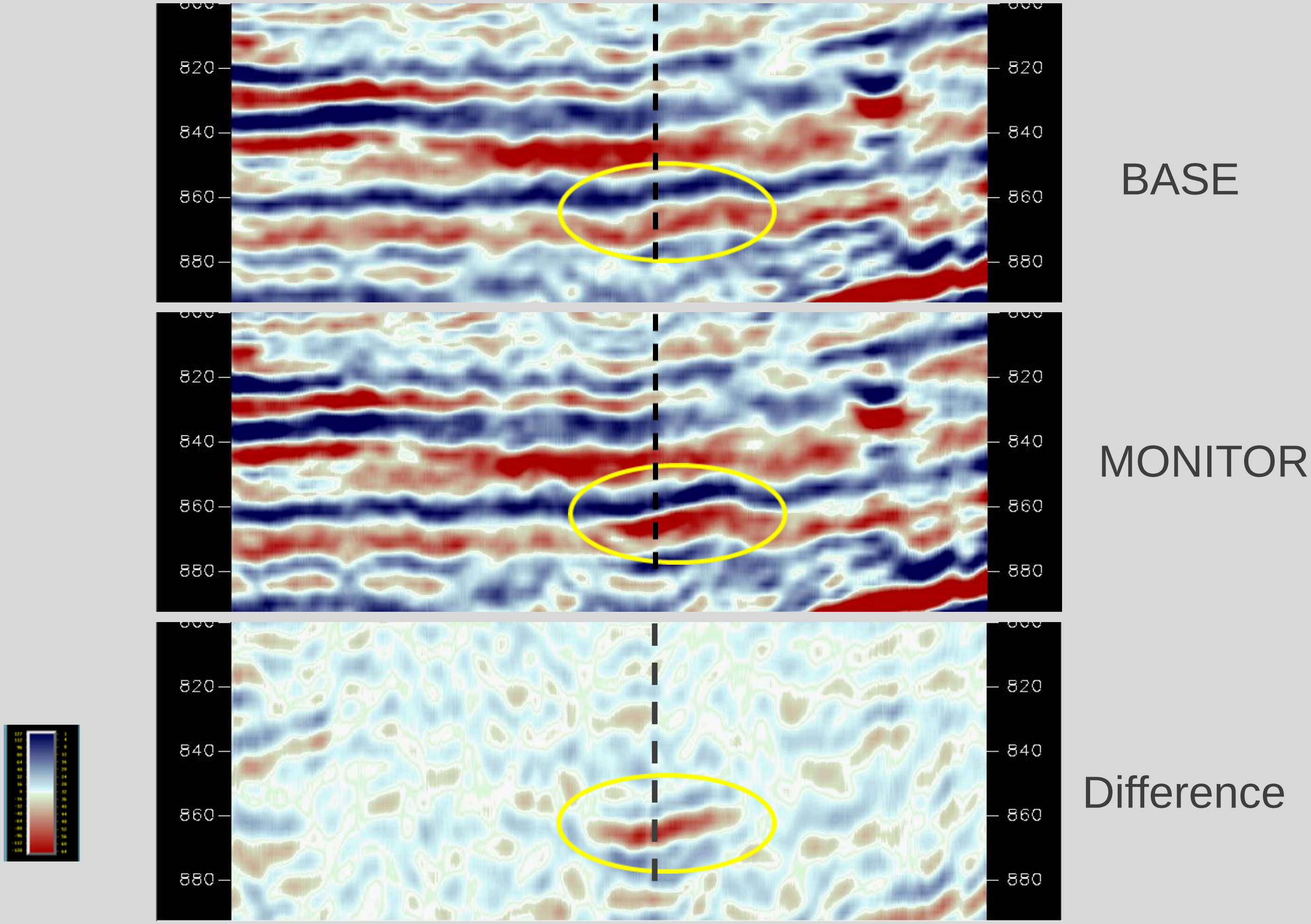
Comparison of matched volumes



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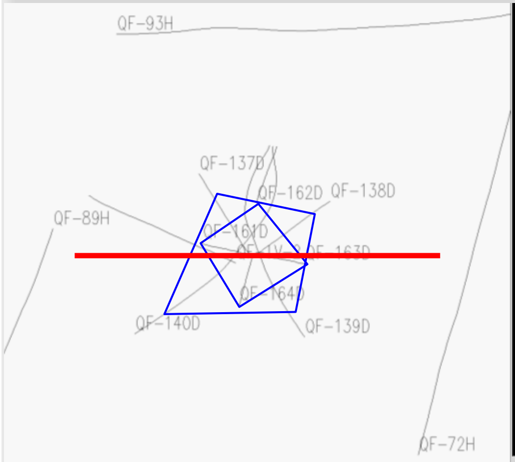
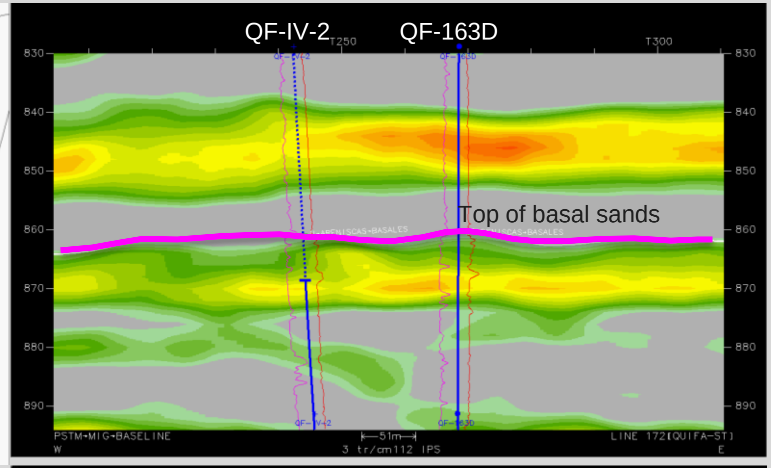
Seismic monitoring. Difference in PP volumes

Inline section inside the combustion area



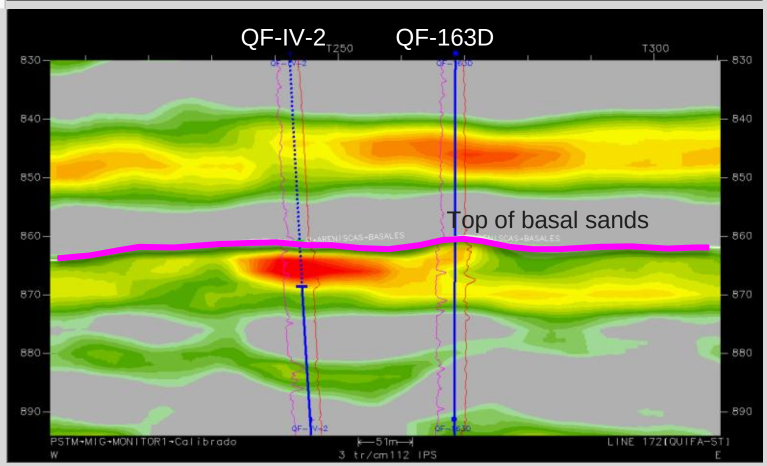


Seismic volume
July 2012
(Baseline)

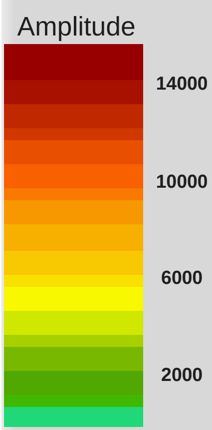
840 ms

860 ms

880 ms

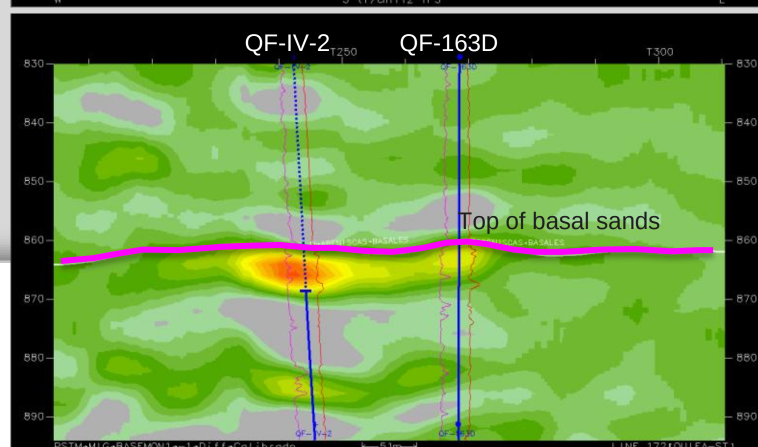


Seismic volume
November 2013
(Monitor 1)



High

Low



Difference (monitor1-baseline)
November 2013

100 m

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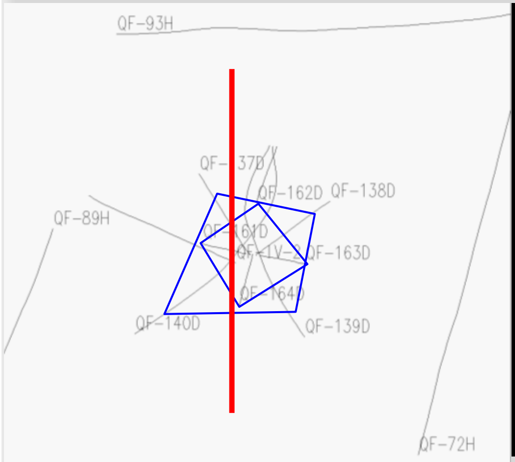
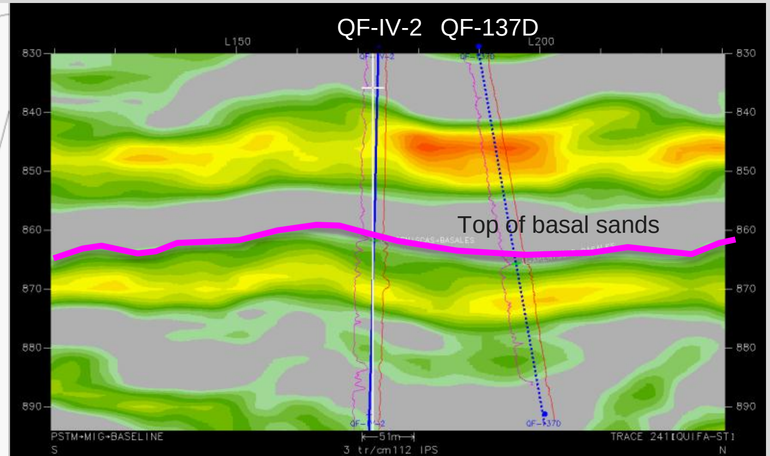
Xline section inside the combustion area



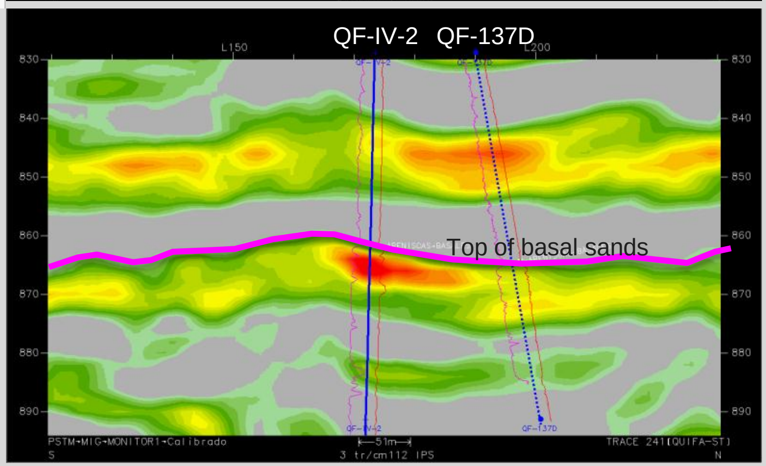


Seismic volume
July 2012
(Baseline)

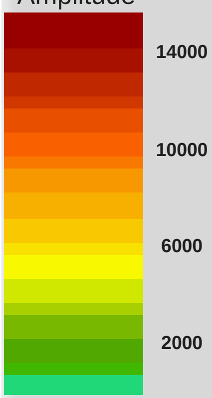
840 ms

860 ms

880 ms

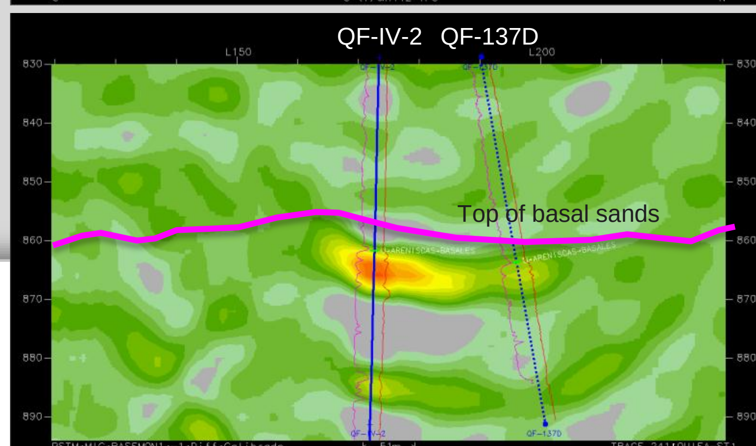


Seismic volume
November 2013
(Monitor 1)



High

Low



Difference (monitor1-baseline)
November 2013

100 m

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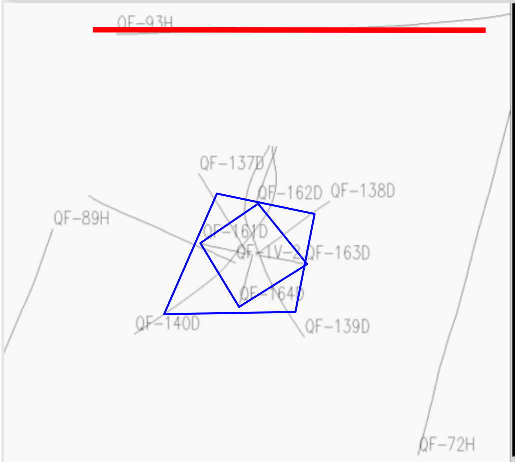
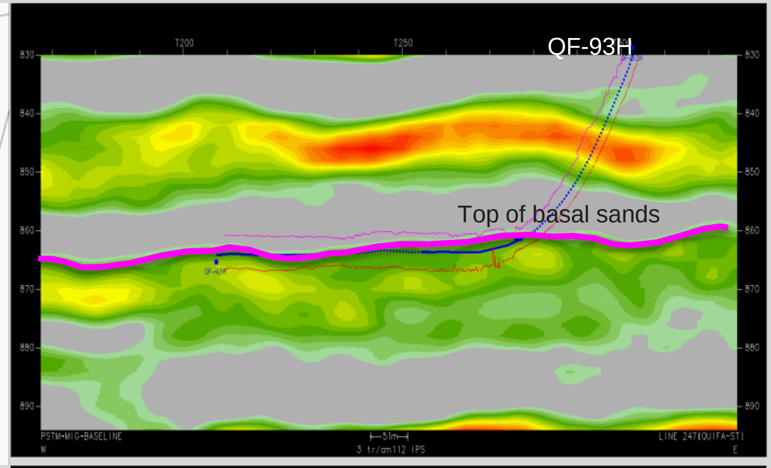
Inline section outside the combustion area



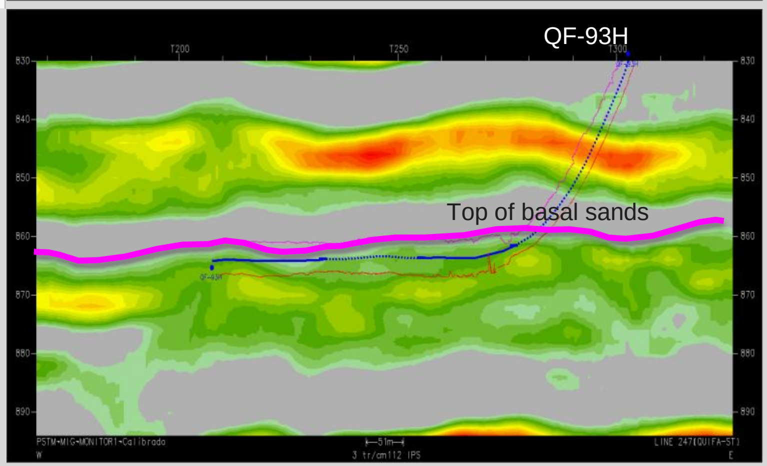


Seismic volume
July 2012
(Baseline)

840 ms

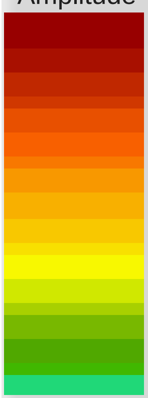
860 ms

880 ms



Seismic volume
November 2013
(Monitor 1)

Amplitude



High

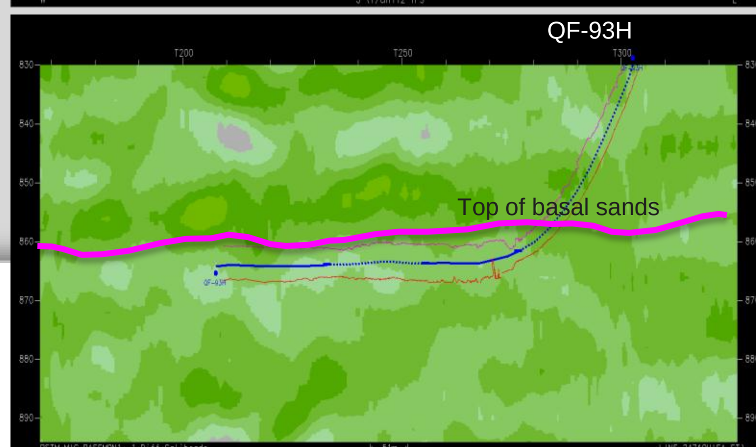
14000

10000

6000

2000

Low



Difference (monitor1-baseline)
November 2013

100 m

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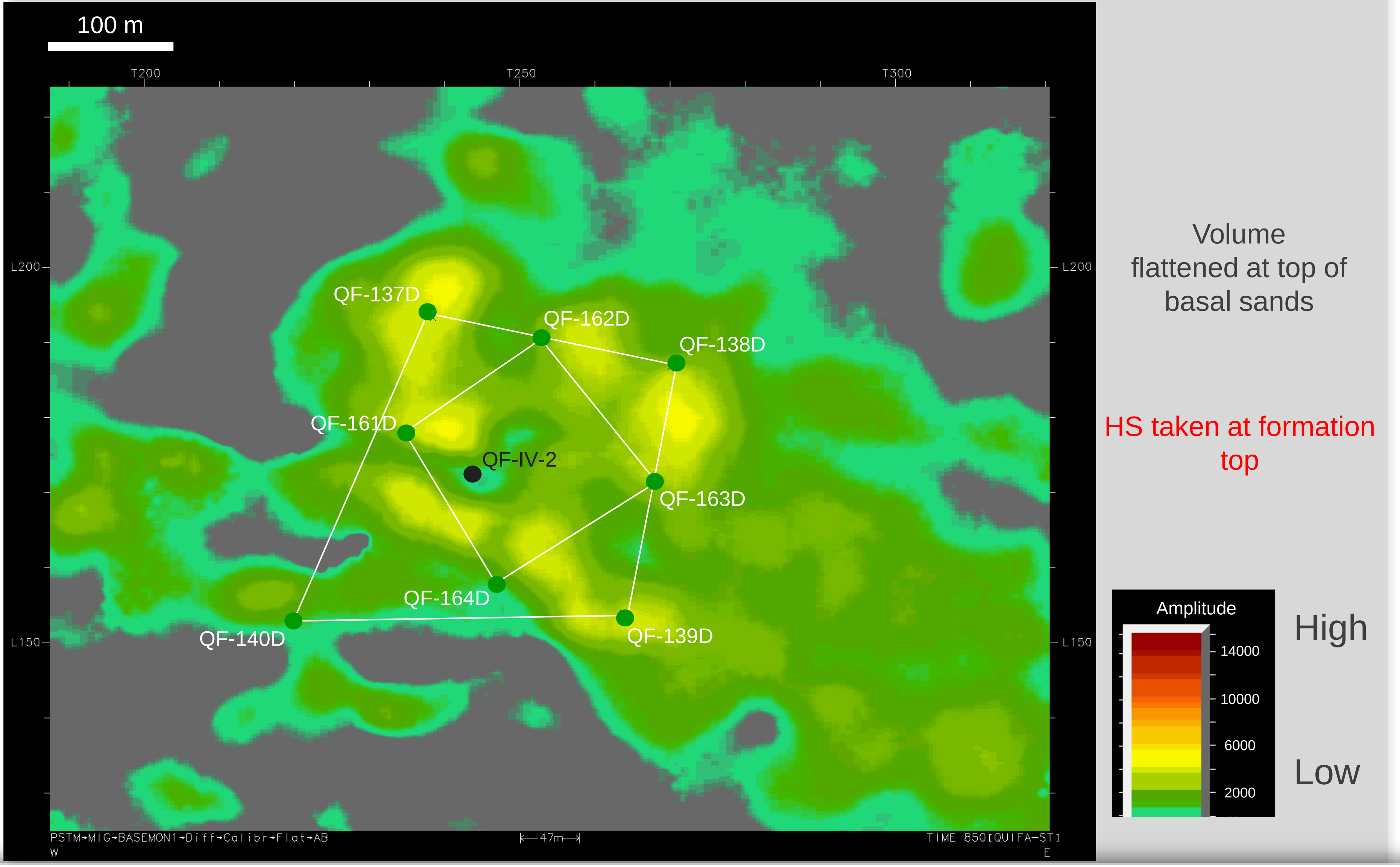
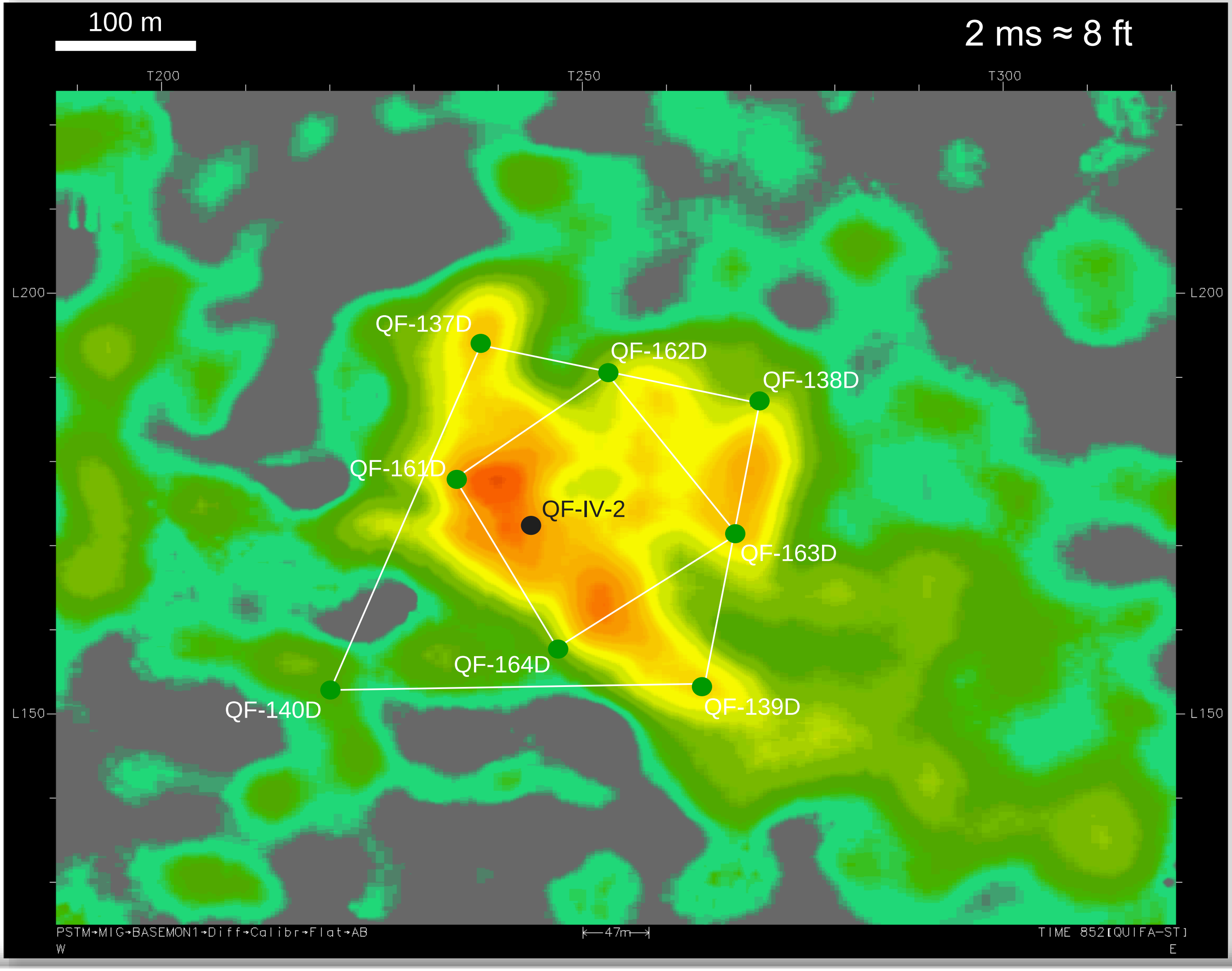
“Horizon slice” from difference volume (amplitudes): monitor 1 – baseline



Volume flattened at top of basal sands

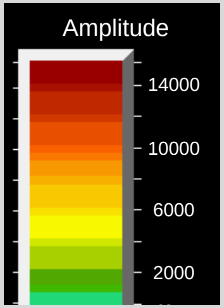
HS taken at formation top

“Horizon slice” from difference volume (amplitudes): monitor 1 – baseline



Volume flattened at top of basal sands

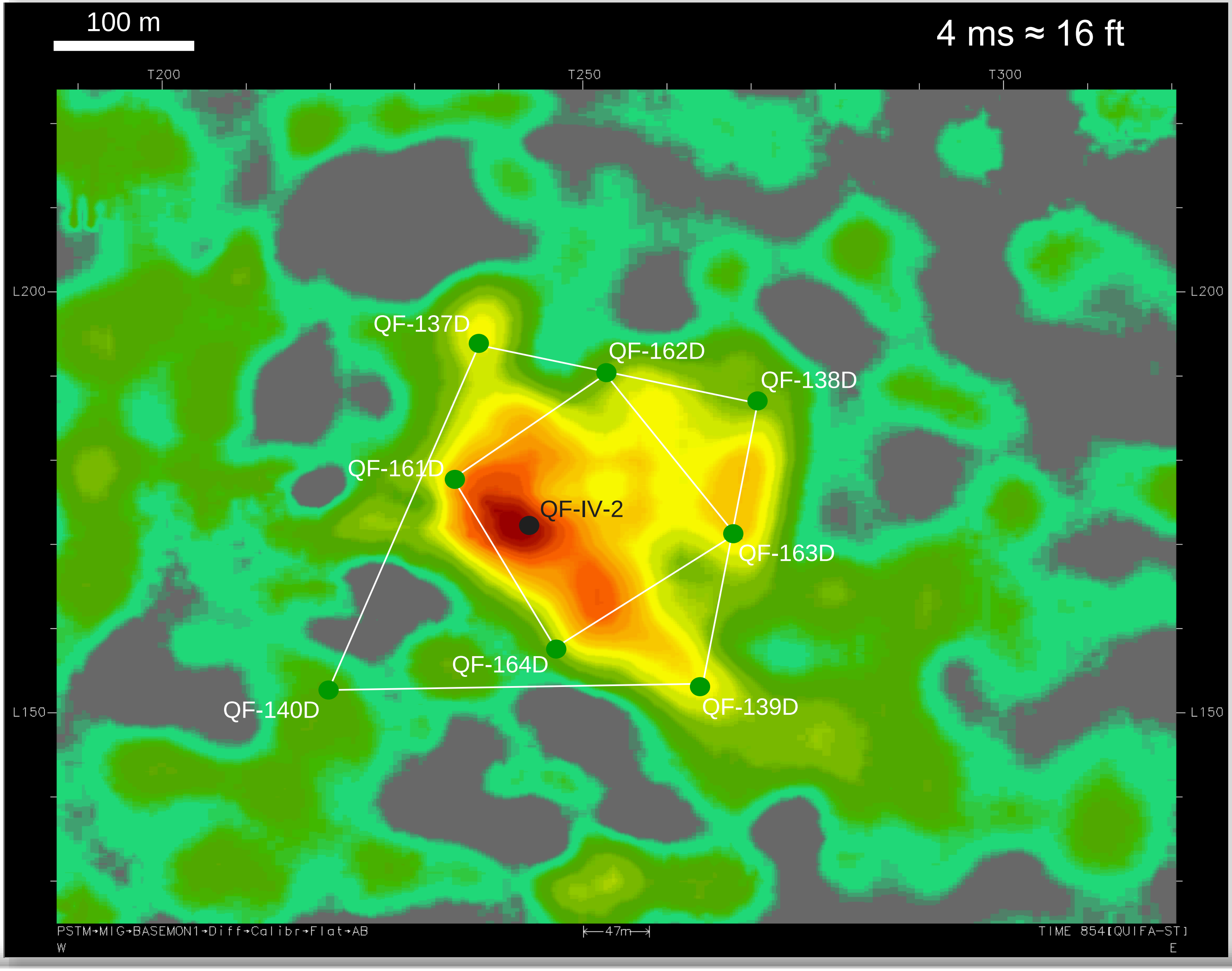
HS taken 2 ms below formation top



High

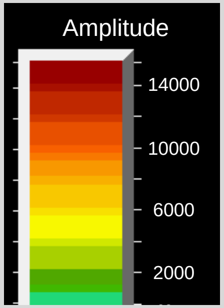
Low

"Horizon slice" from difference volume (amplitudes): monitor 1 – baseline



Volume flattened at top of basal sands

HS taken 4 ms below formation top



High

Low

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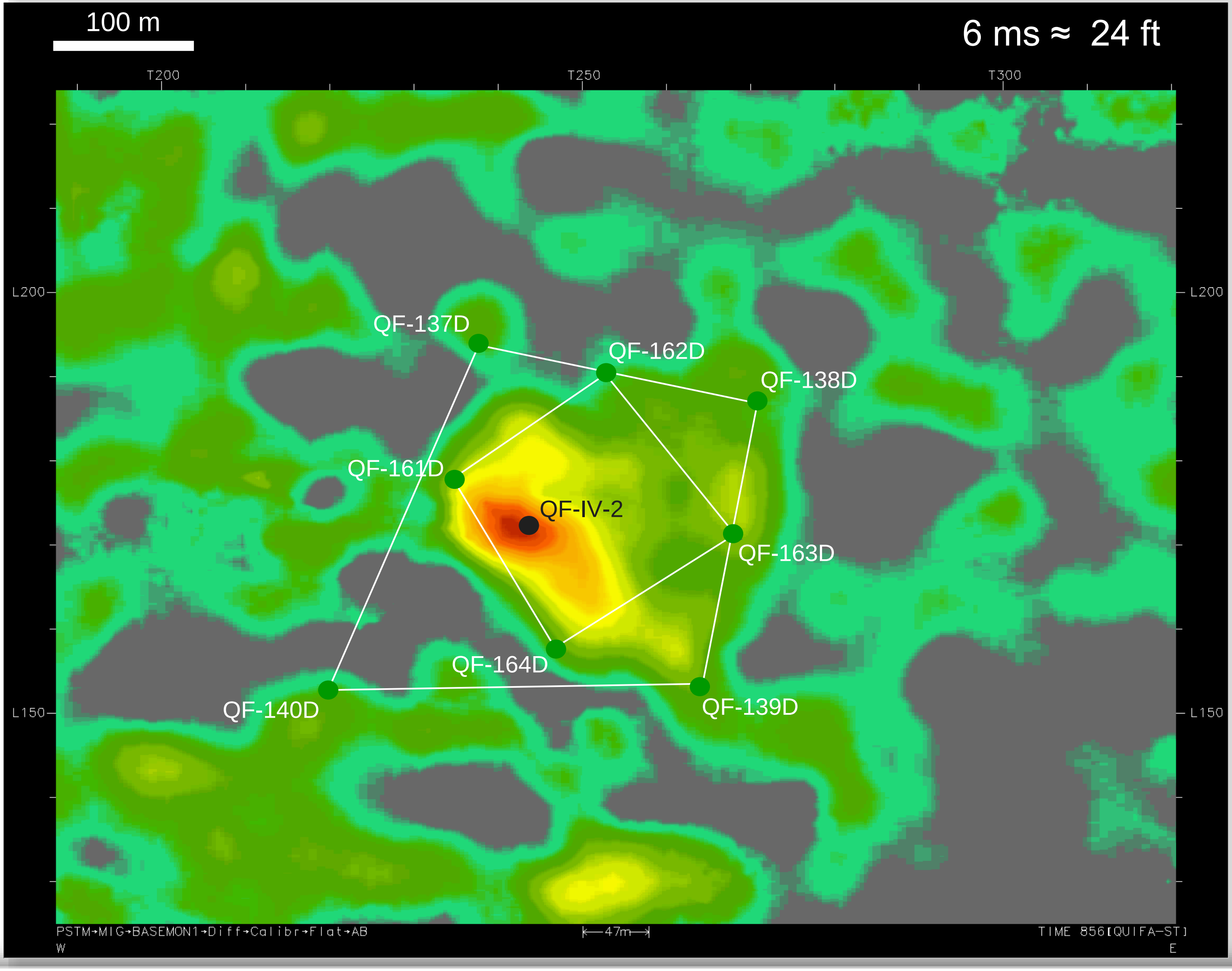
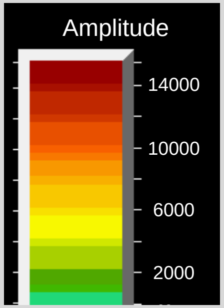
"Horizon slice" from difference volume (amplitudes): monitor 1 – baseline



Volume flattened at top of basal sands

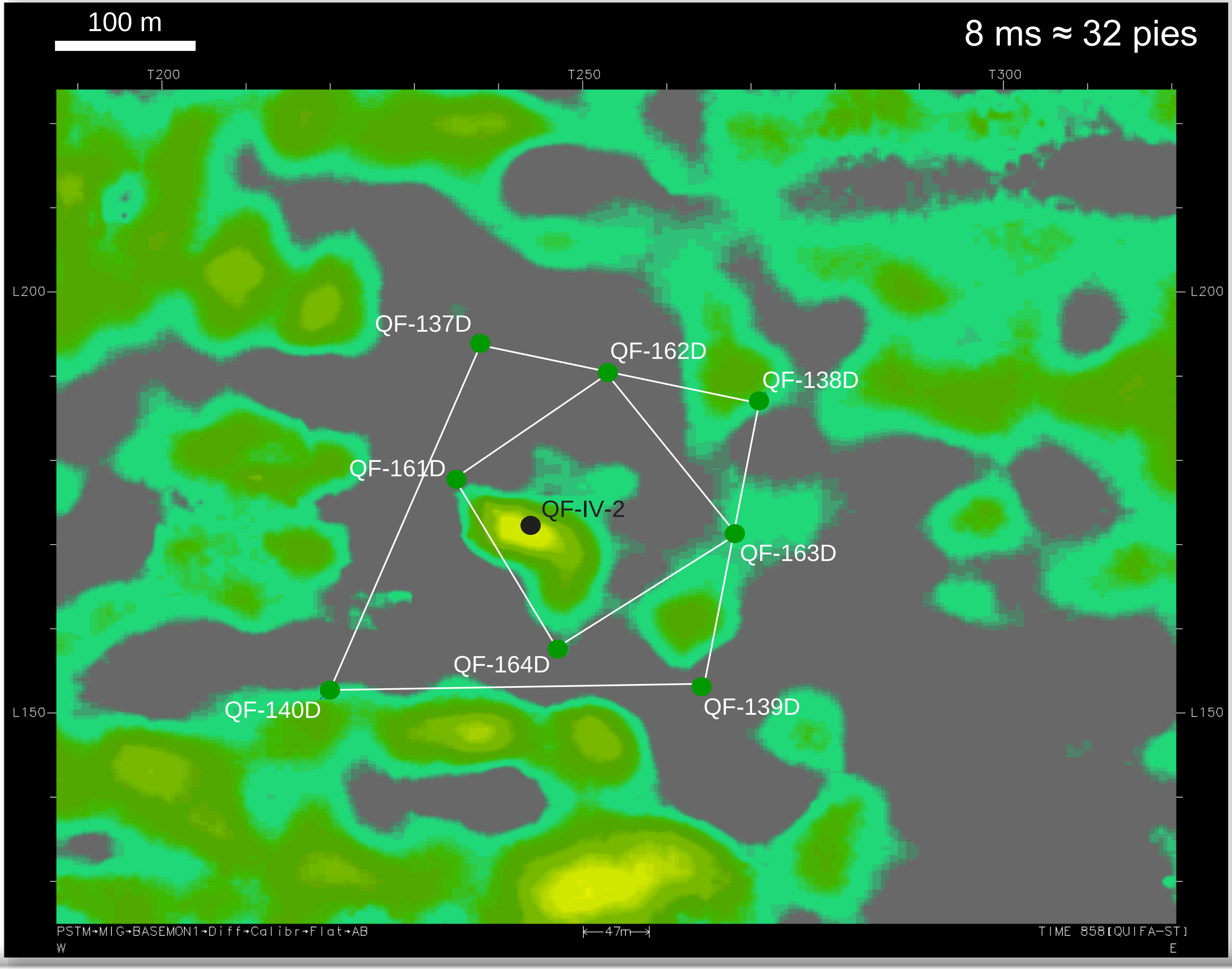
HS taken 6 ms below formation top



High

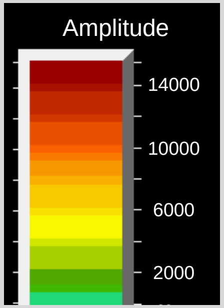
Low

"Horizon slice" from difference volume (amplitudes): monitor 1 – baseline



Volume flattened at top of basal sands

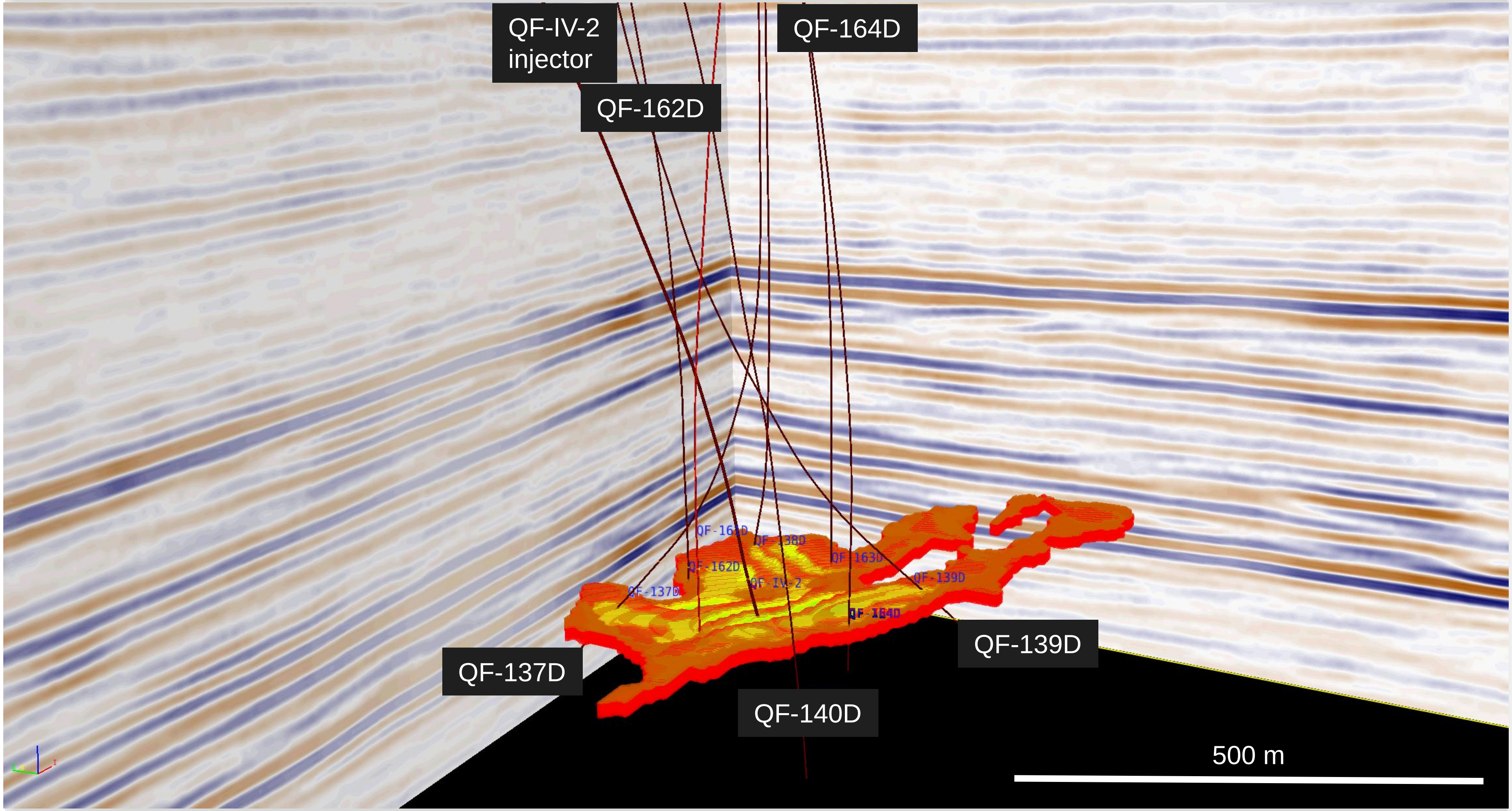
HS taken 8 ms below formation top



High

Low

3D amplitude anomaly (Geobody)



Geobody of amplitude anomaly (Difference)

Seismic monitoring. Interpretation.

What do the seismic anomalies represent?

- Changes in the elastic properties of the rock and fluids.

- Fluids seem to account for most of the observed effects. Changes in rock matrix seem to be “small” or not significant enough to alter the elastic modulii within the seismic resolution.

- Fluid effects come from air injection, combustion gasses, steam generation.

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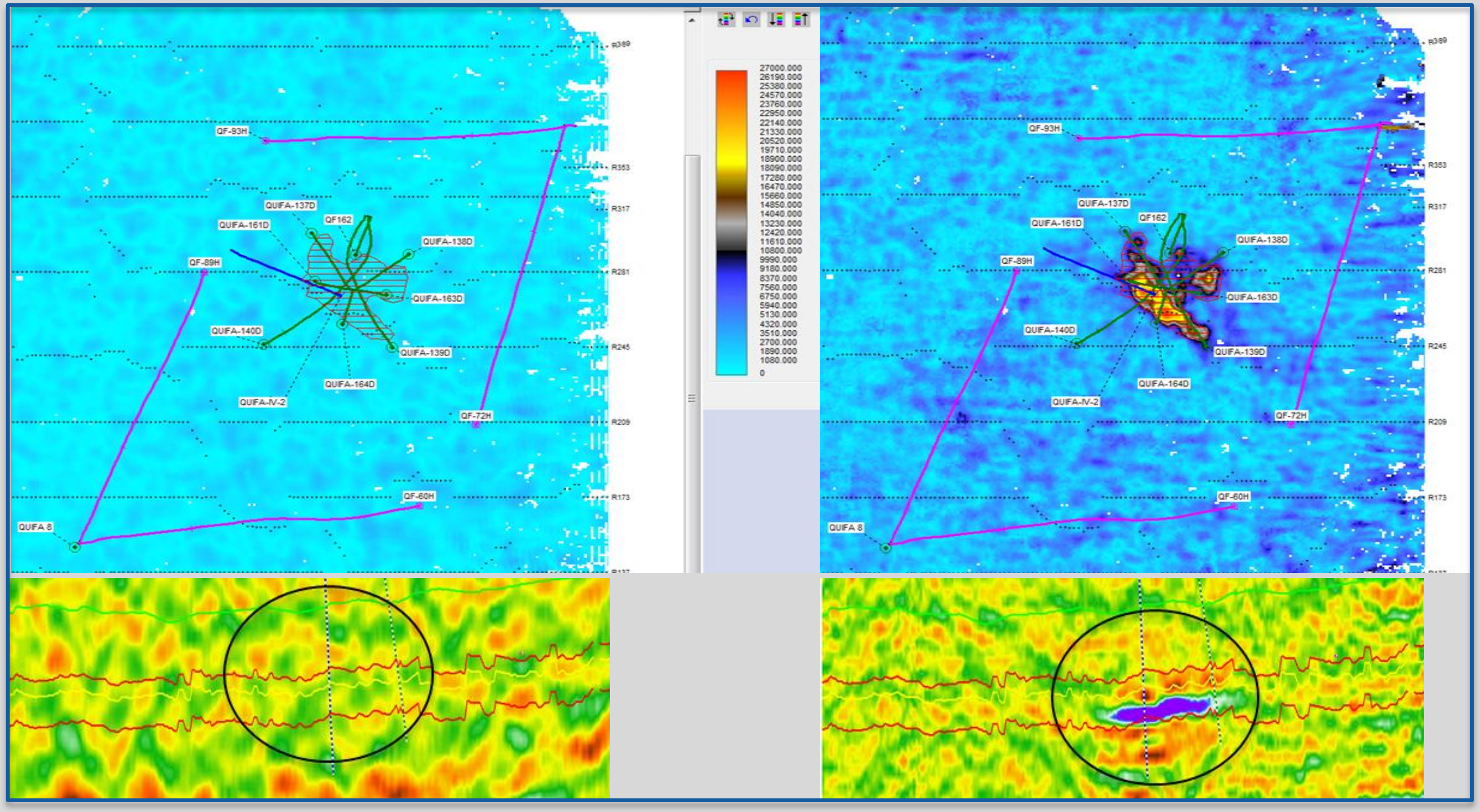
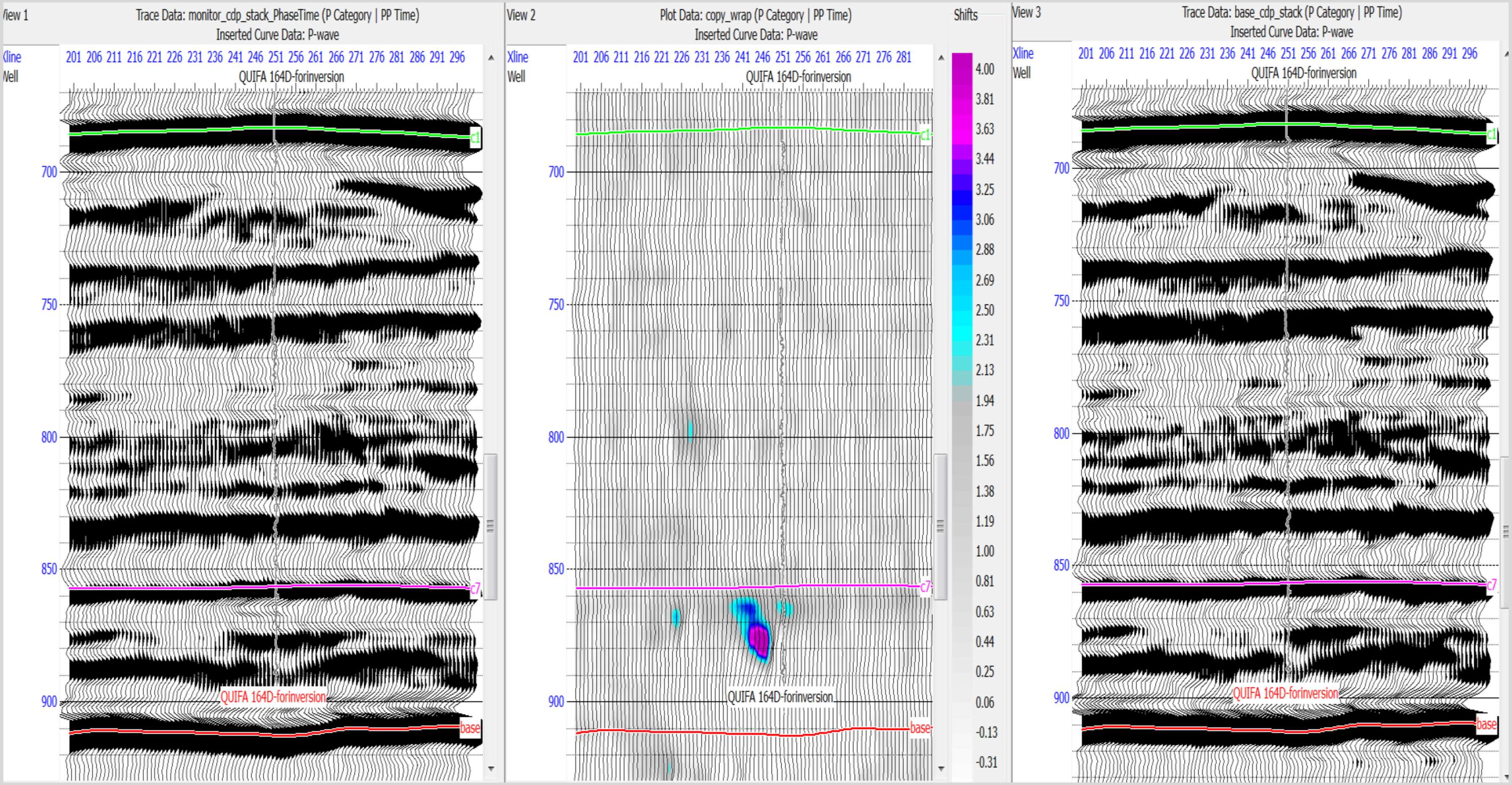
Amplitude difference (Monitor 1-Base) PS, PP



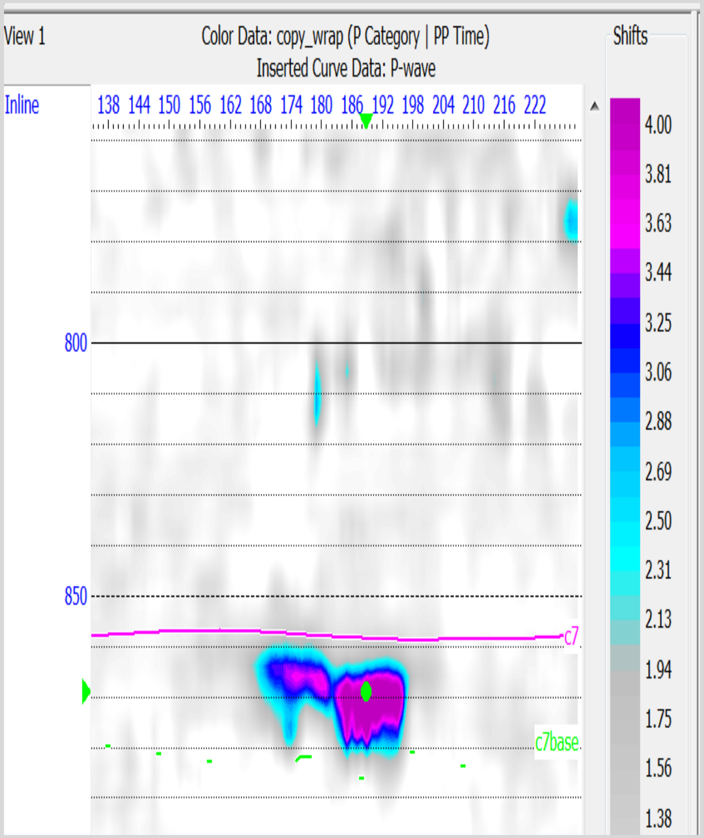
PS PP

Delay-time effect

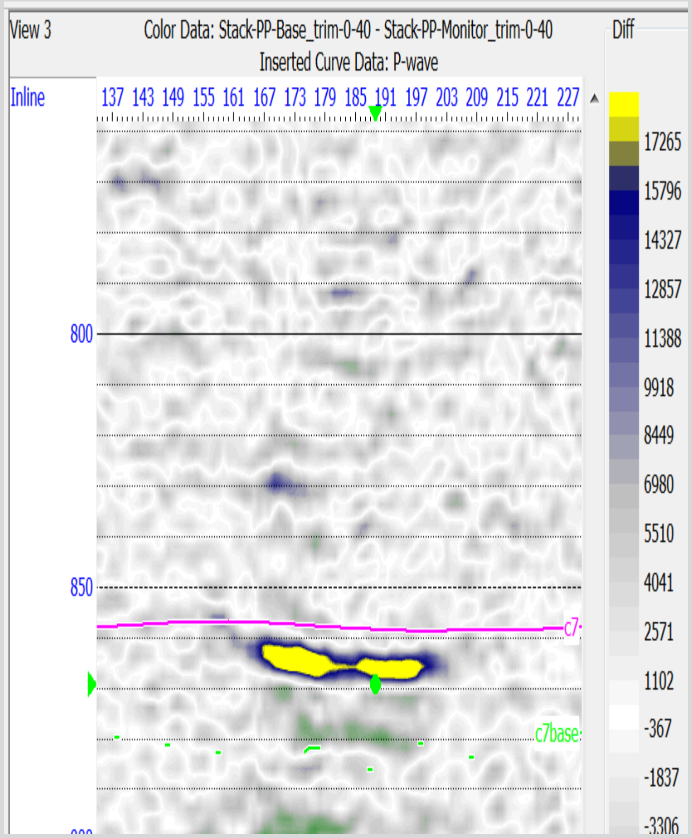


Monitor Delay Base

Time and amplitude differences: Monitor 1-base



Time difference (Delay)



Amplitude difference

Conclusions

- Surface 4D seismic is an effective tool for monitoring the effects of in-situ combustion of Quifa heavy oil reservoir.
- The most evident changes in the seismic parameters are in amplitudes and delay times.
- Comparison between anomalies in PP and PS may help discriminate effects due to changes in the rock matrix vs. changes due to fluids.

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