



A comparison of dynamic time and spatial correlation methods in time-lapse seismology

Brian Russell
Vice President, CGG GeoSoftware
Calgary, Alberta, Canada

cgg.com





Introduction

- One of the key calibration steps in time-lapse seismology is finding the optimal dynamic time shifts to calibrate the monitor surveys with the base survey.
- Traditionally, this was done using standard cross-correlation methods, and this is still the main technique in many workflows.
- Recently, several new options have been developed for computing the shifts:
 - The Taylor series expansion method
 - Dynamic time warping
 - Vector warping with Gaussian windowing
- This talk will summarize these methods and show their application to a steam flood case study from northern Alberta.





Case Study: GLISP Pilot

AMOCO/AOSTRA Gregoire Lake In-situ Steam Pilot (GLISP)

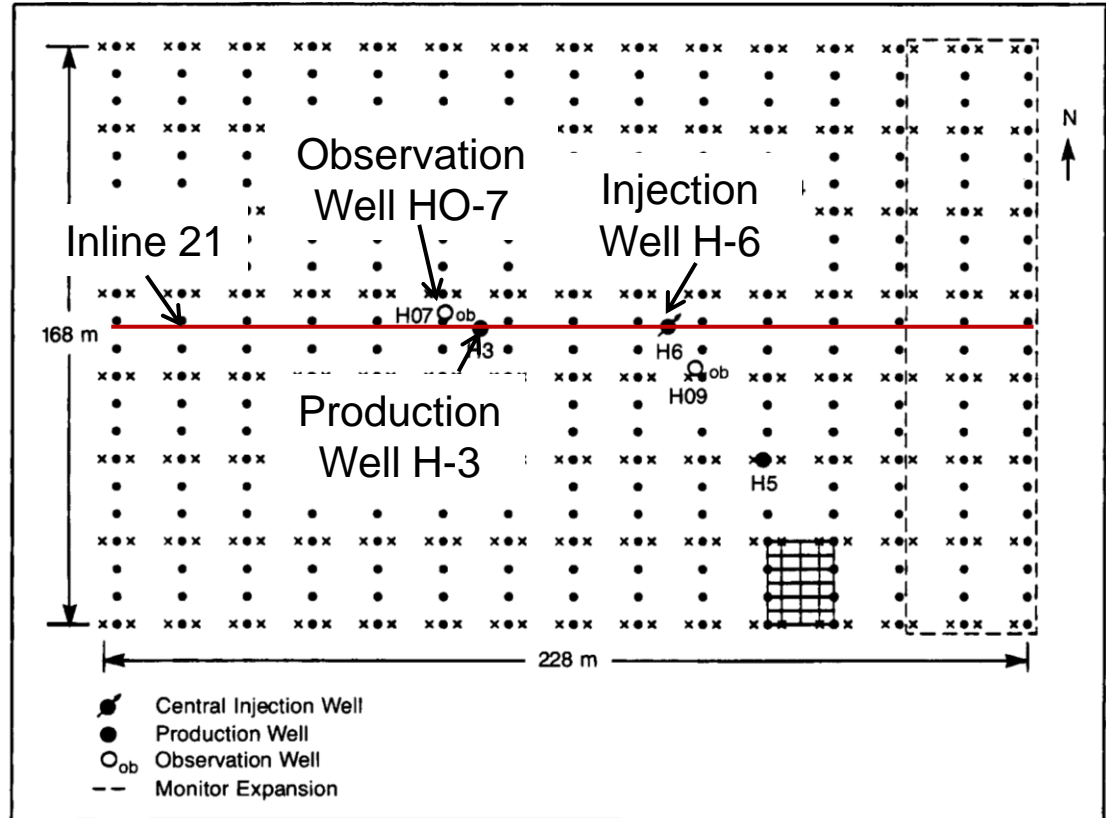
(approx. 40 km south of Ft. McMurray)

- Base survey acquired April 1985
- First Monitor acquired January 1987
- Second Monitor 1988
- Third monitor acquired 1989



Base Map for GLISP Pilot

- A permanent source and receiver array were used.
- Seismic coverage approx. 200 X 200m.
- Bin size 4 X 4 m.
- Frequency bandwidth 20-240 Hz.
- Ten wells were drilled in the pilot area.
- We will look at Inline 21, which intersects wells HO-7, H-3 and H-6.





Recording history of GLISP Pilot

- The Base survey was recorded in 1985.

First time period

- Three wells (H3, H4, H5) were selected for steam injection that continued for 15 days each. The first Monitor was recorded in 1987.

Second time period

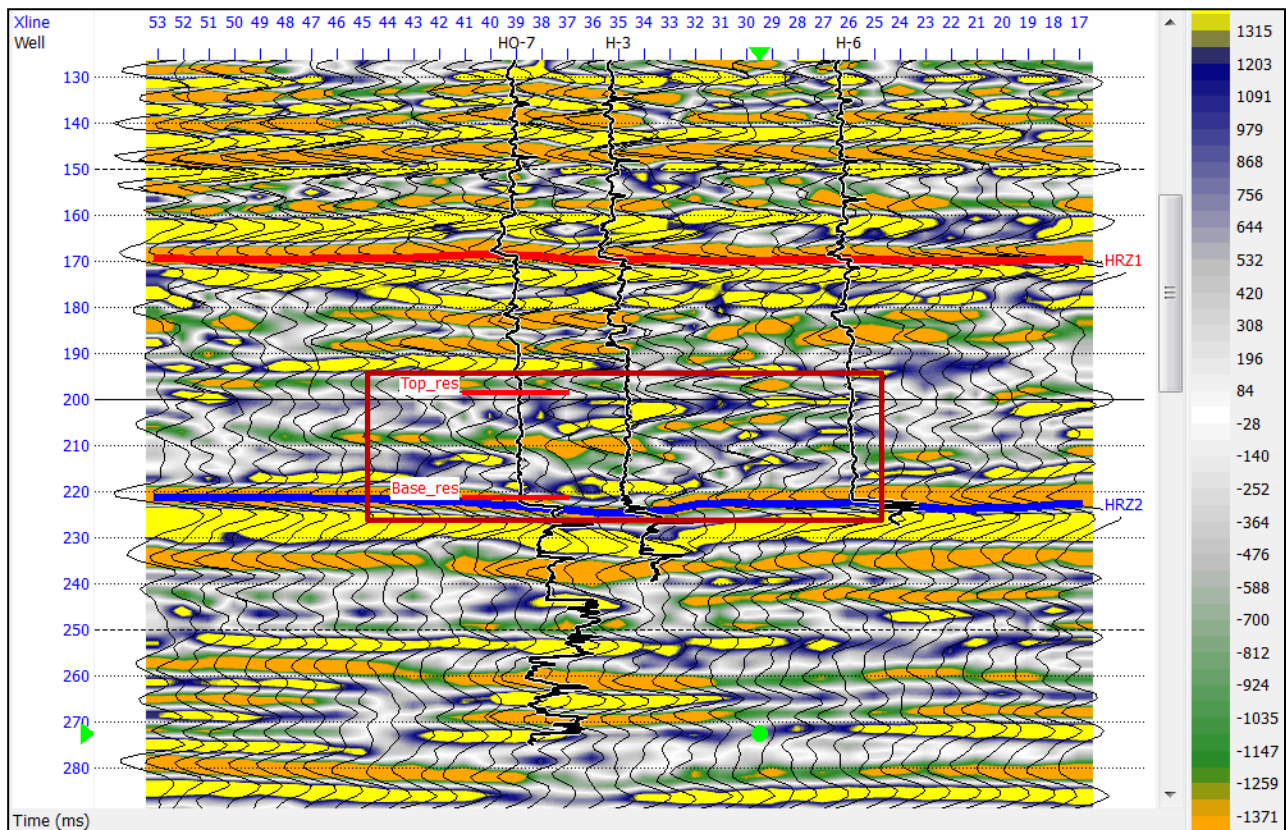
- The 3 active injection wells (H3, H4 H5) were converted to producers.
- An injector well (H6) was selected and steam was injected for a period of 96 days. The second Monitor was recorded in 1988.

Third time period

- Steam was injected into 2 producing wells for a short time period.
- Steam was injected into the main injector well (H6) for a period of 6 months. The third Monitor was recorded in 1989.



Data before processing

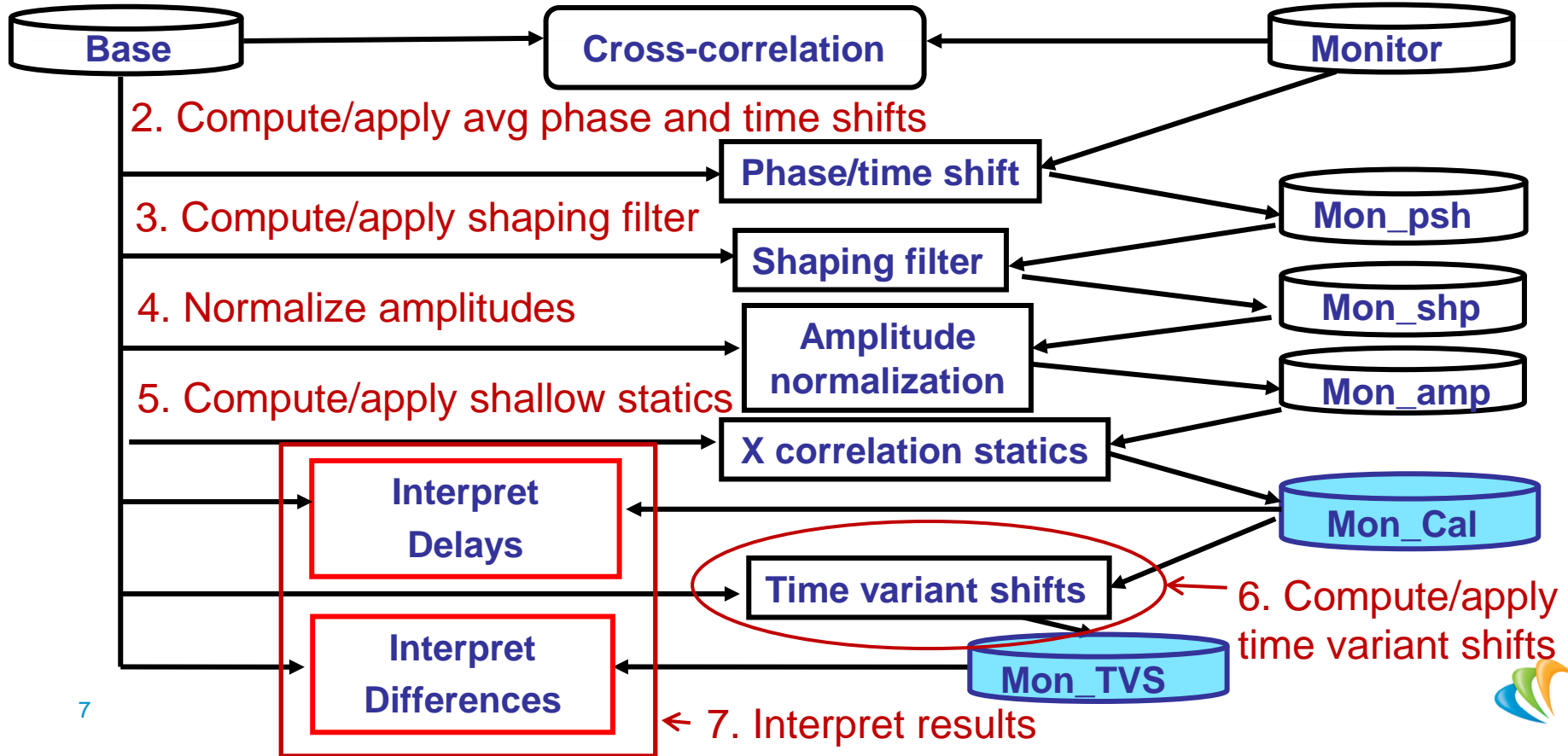


- Here is the amplitude difference between the base survey and first monitor survey before any processing, with the sonic logs inserted.
- The blue horizon is the base of oil sand, and the top and base reservoir are indicated on the log.
- The anomalies do not stand out in that zone.

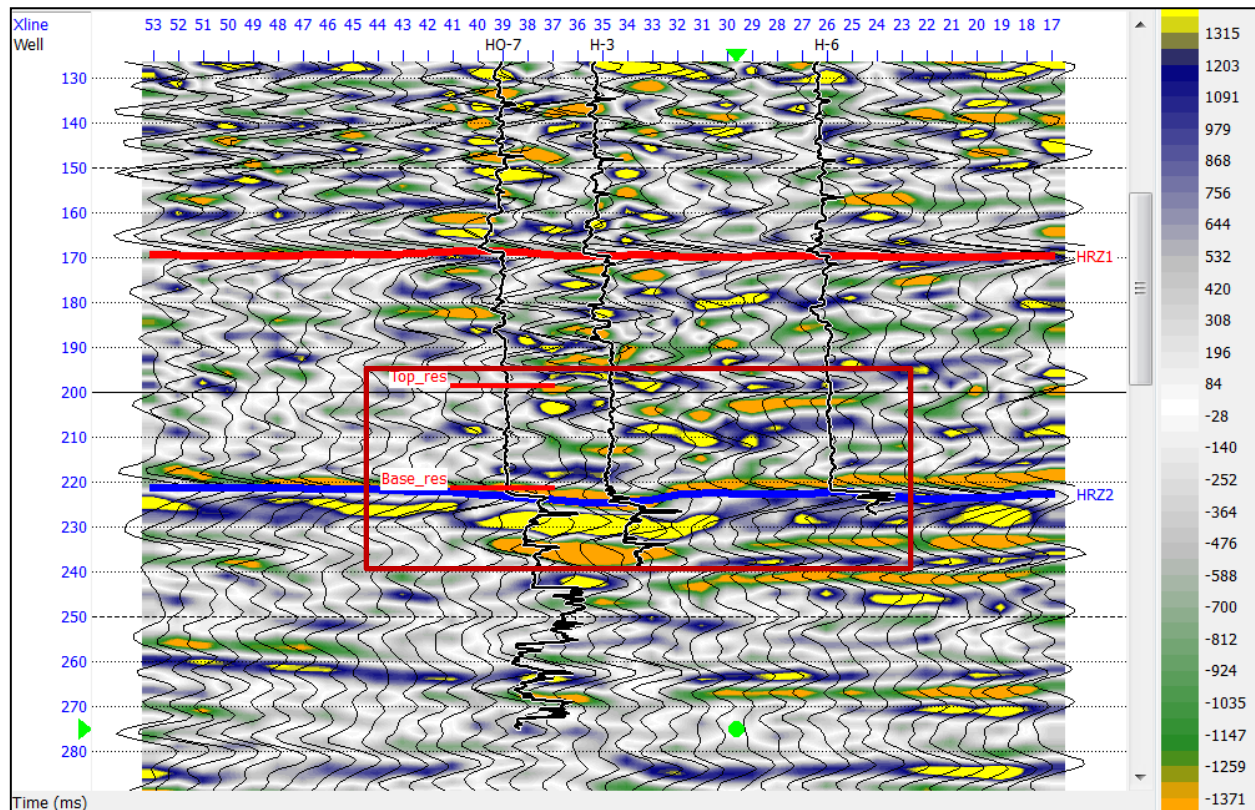


The time-lapse workflow

1. Find overall correlation coeffs and shifts



Base – Monitor 1 difference after step 5



- Here is the amplitude difference between the base survey and first monitor survey before time variant shifting.
- The reservoir zone is now showing some interesting production anomalies.
- But there are still many extraneous artifacts below the base of reservoir.





Time variant time shifts using cross-correlation

- The theory for cross-correlating two vintages of seismic data, $v_1(t)$ and $v_2(t)$, can be written:

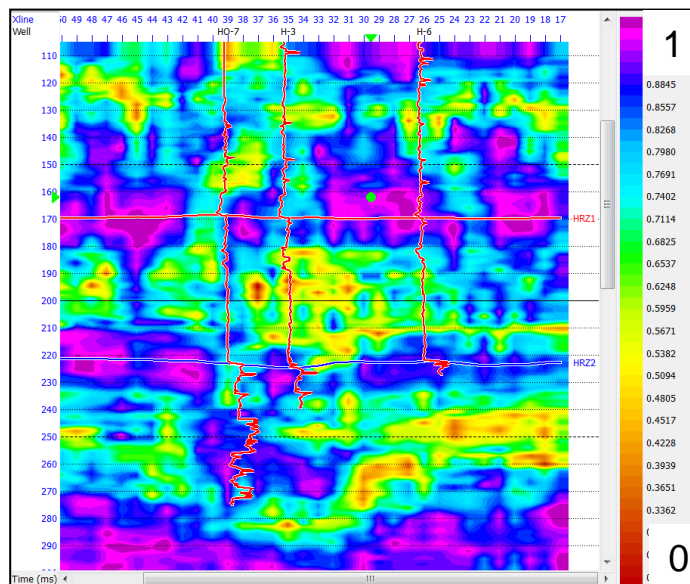
$$c_{v_1v_2}(t, \tau) = \sum_{t=0}^{N-1} v_1(t)v_2(t - \tau), \tau = -\text{max_lag}, \dots, +\text{max_lag}.$$

- In the case of time-variant time shifts, short correlation windows are defined throughout the reservoir zone and the shifts for each window are computed.
- Shifts for samples between the windows are then interpolated.
- The time variant time shifts give the time delay information required for interpretation and also can be removed so that difference amplitudes can be correctly interpreted.
- This is shown in the next few slides.

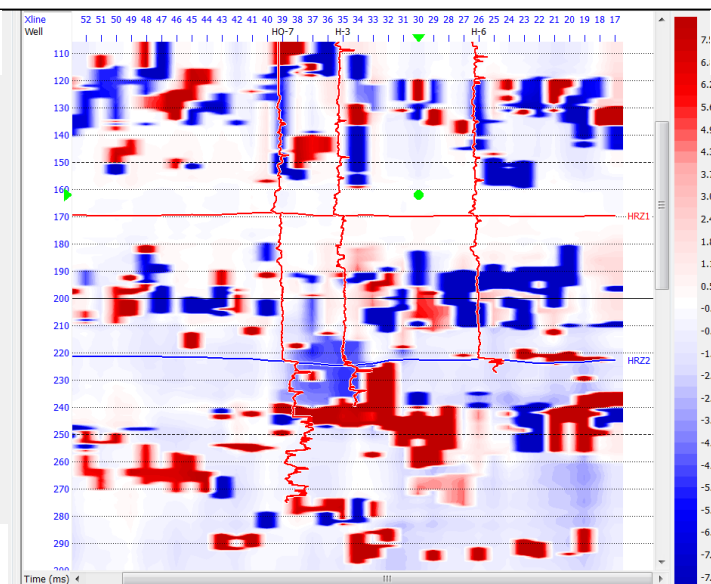


Time variant cross-correlation shifts

- Below are the time variant cross-correlation coefficients and time shifts between the base and monitor 1:



Cross-Correlation Coefficients



Cross-Correlation Time Shifts

+7.5 ms

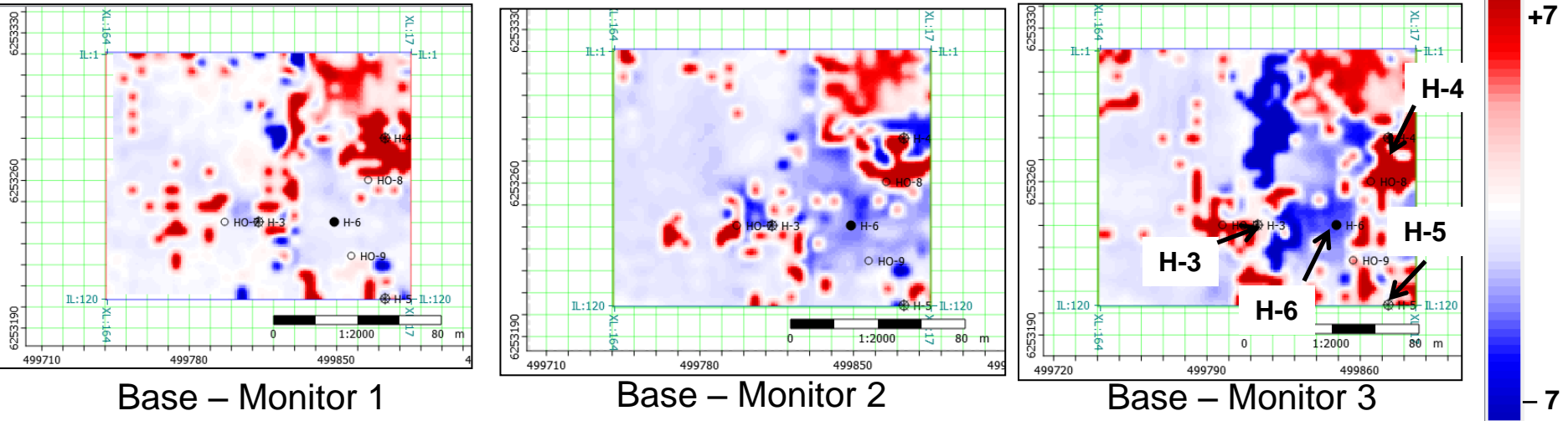
-7.5 ms

- Note that the shifts are quite large and noisy.



Correlation time shifts on time slices

- Here are the correlation time shifts over a constant time slice of 214 ms:

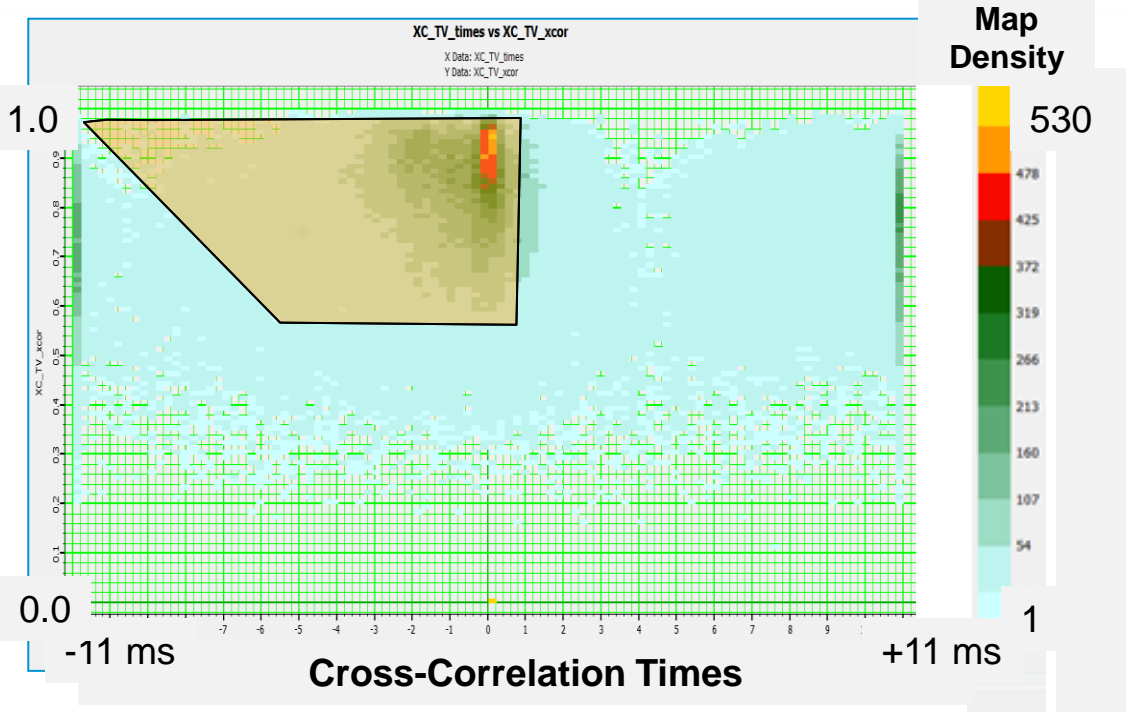


- Note that the time shifts are quite noisy but, as expected, get more negative around the injected steam area.



Conditioning the cross-correlation shifts

Cross-Correlation Coefficients

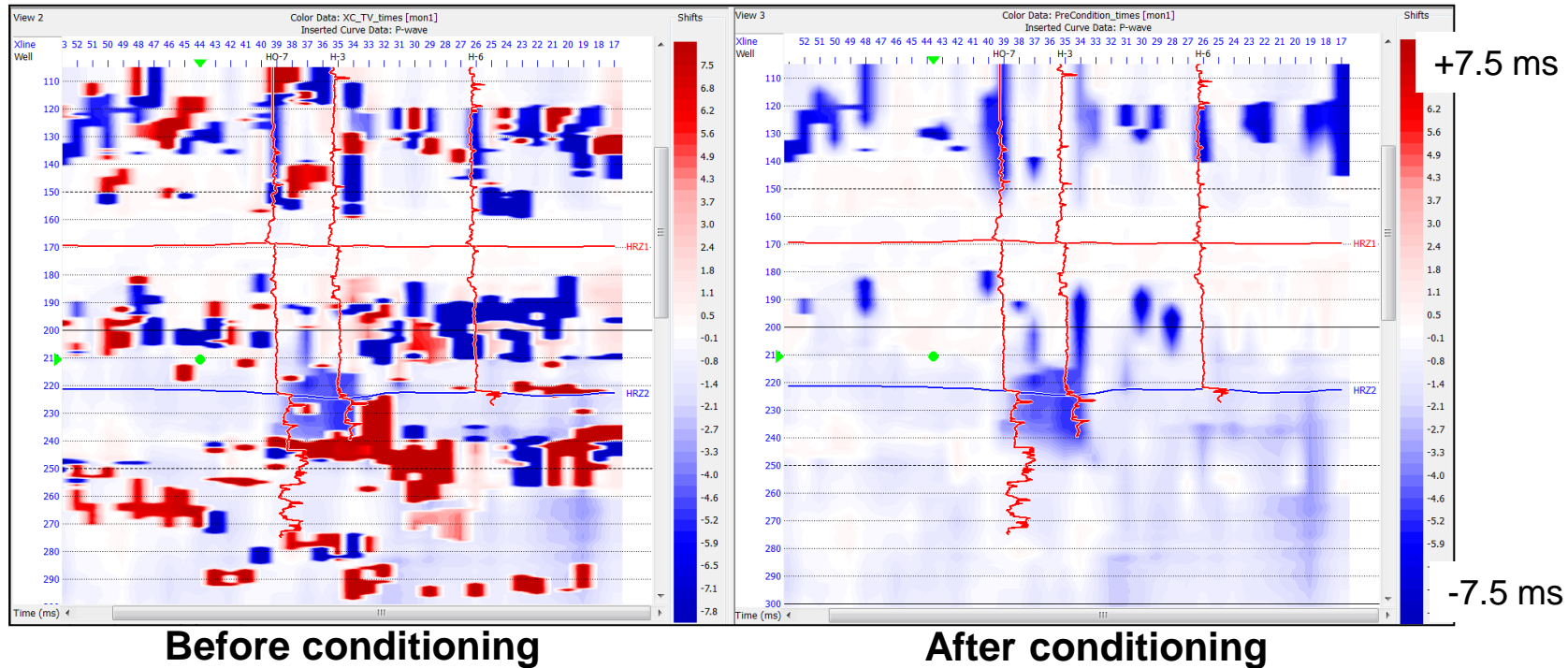


- One way to improve the time shift quality is to keep only those within a range of high correlation and expected time shift.
- Here is a cross-plot of the X-corr times vs X-corr coefficients.
- We will pick a zone that includes only negative time shifts and correlation coefficients > 0.55 .



Comparison of cross-correlation shifts

- Here is the result of excluding shifts outside the zone:



- 13
- Notice the improvement of the picks.

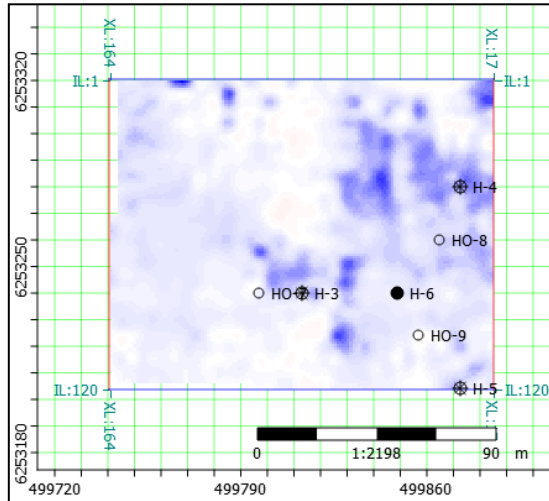




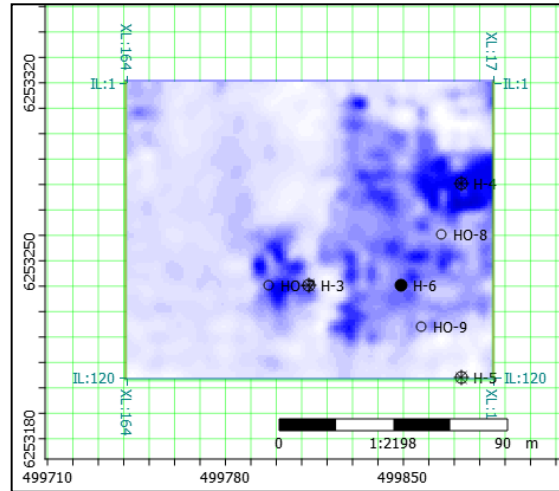
Conditioned Correlation time shifts on time slices

- The conditioned correlation time shifts over a constant time slice of 214 ms:

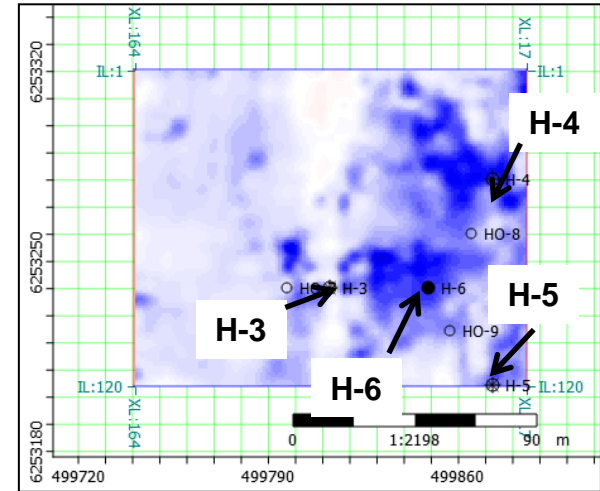
Shift (ms)



Base – Monitor 1



Base – Monitor 2

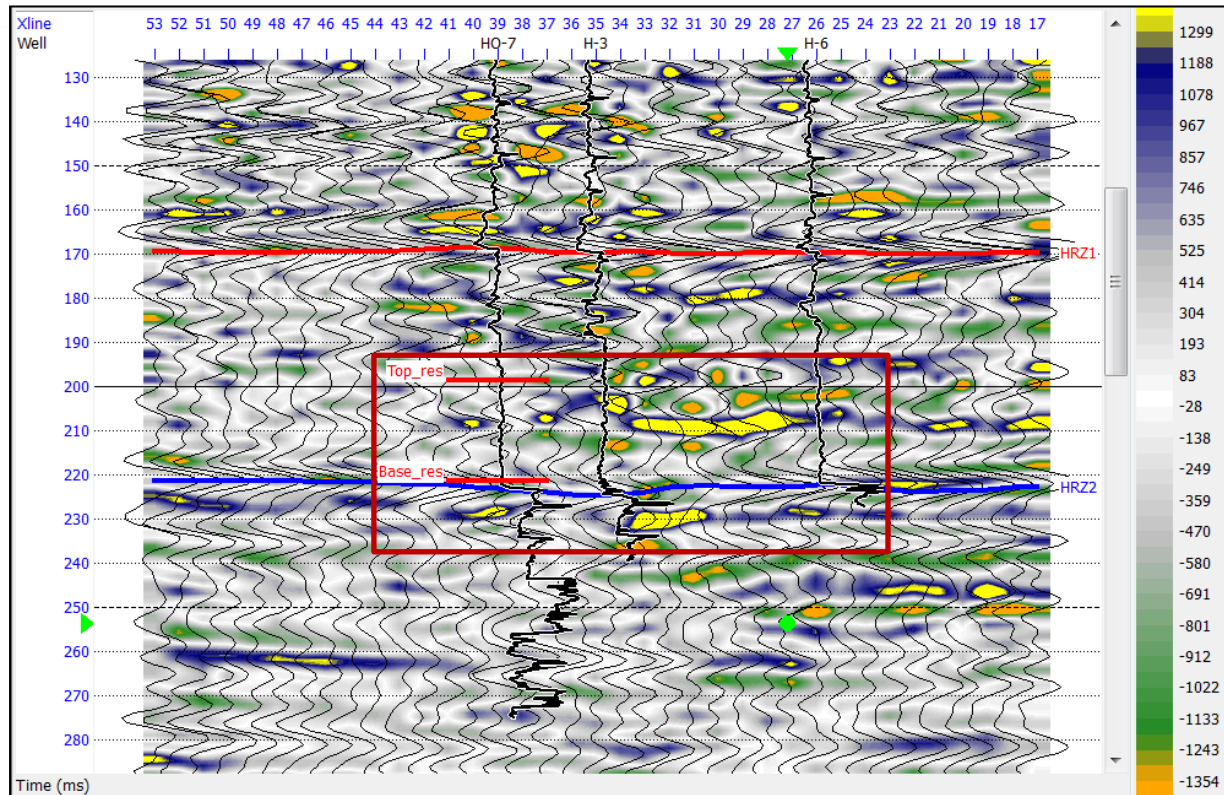


Base – Monitor 3

- Note that the time shifts are much smoother and more negative because of the filter.



Base – Monitor1 diff. after cross-correlation shifts

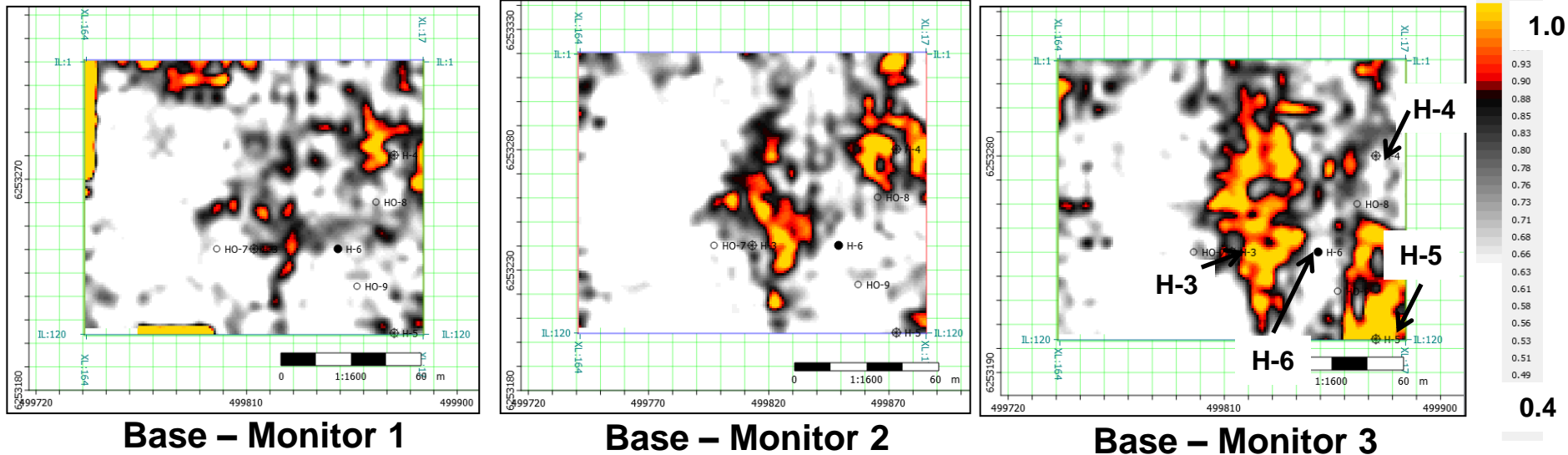


- Here is the amplitude difference between the base and first monitor survey after conditioned time variant shifting.
- Many of the extraneous artifacts below the base of reservoir have now been removed, revealing the production-induced shifts.



NRMS after cross-correlation shifts

- Here is the Normalized Root-Mean-Square (NRMS) amplitude difference between the base and each monitor survey after conditioned time variant shifting:



- NRMS averaging is a common way of normalizing differences between surveys.
- The NRMS averaging was done between Horizons 1 and 2.





Multivintage time-shift estimation by Taylor expansion

- Naeini, Hoeber, Poole and Siahkoohi (2009) propose a multivintage time-shift estimation procedure that was based on earlier work by Hatchell et al. (2007) on 4D geomechanics reservoir monitoring.
- They start by assuming that two vintages of seismic time lapse data that only differ by a time shift of τ_{12} can be written as a Taylor series expansion as follows:

$$v_2(t) = v_1(t + \tau_{12}) \approx v_1(t) + v_1'(t)\tau_{12}, \text{ where } v_1'(t) = \frac{dv_1(t)}{dt}.$$

- Taking the difference between the left and right hand sides of this equation we can minimize it by setting the derivative with respect to the time shift equal to zero, as follows:

$$\frac{df_{12}(\tau_{12})}{d\tau_{12}} = 0, \text{ where } f_{12}(\tau_{12}) = \sum_{\tau=1}^T (v_2(t) - v_1(t) - v_1'(t)\tau_{12})^2$$





Multivintage time-shift estimation by Taylor expansion

- This expression can be extended to multiple vintages and also to the symmetric time shift τ_{21} , which should be the negative of τ_{12} .
- Without going through the detailed calculations this gives us:

$$\tau_{12} = \frac{b_{21} - b_{12}}{a_{21} + a_{12}}, \text{ and } \tau_{21} = \frac{b_{12} - b_{21}}{a_{21} + a_{12}}, \text{ where:}$$

$$a_{12} = \sum_{\tau=1}^T v_1'^2(t), \quad b_{12} = \sum_{\tau=1}^T [(v_1(t) - v_2(t))v_1'(t)], \quad a_{21} = \sum_{\tau=1}^T v_2'^2(t), \quad \text{and } b_{21} = \sum_{\tau=1}^T [(v_2(t) - v_1(t))v_2'(t)].$$

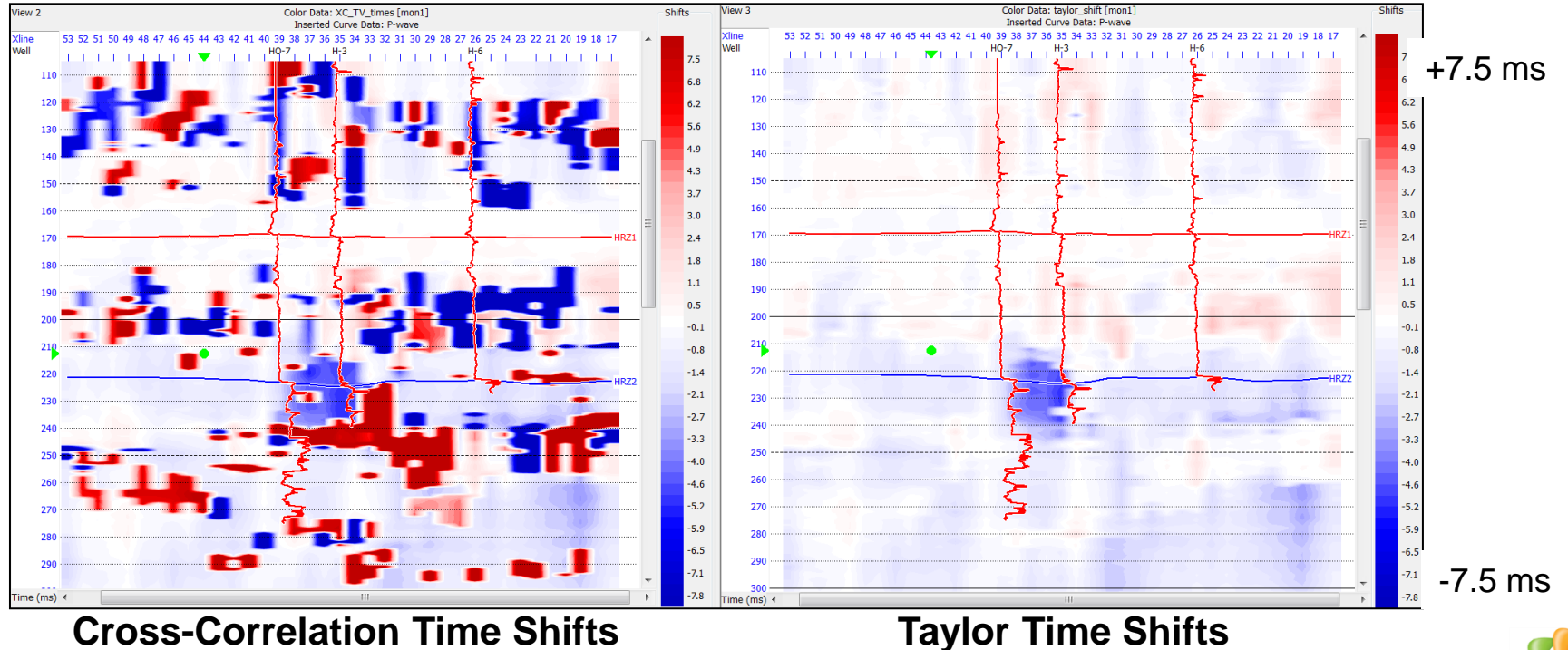
- Note that we can now compute the shifts simply from the traces and their first derivatives.
- As in cross-correlation, the shifts are computed with a sliding window.
- We will now apply the Taylor shift method to the GLISP dataset.





Cross-correlation vs Taylor time shifts

- Here is a comparison between cross-correlation and Taylor time shifts:

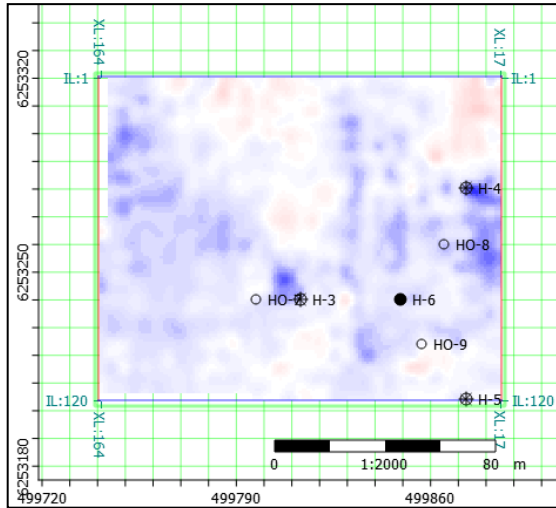


- Note that the Taylor shifts are much less noisy.

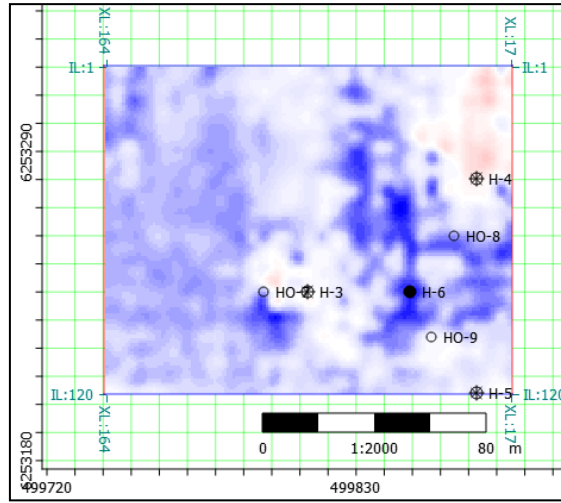
Taylor expansion time shifts on time slices

- The Taylor expansion time shifts over a constant time slice of 214 ms:

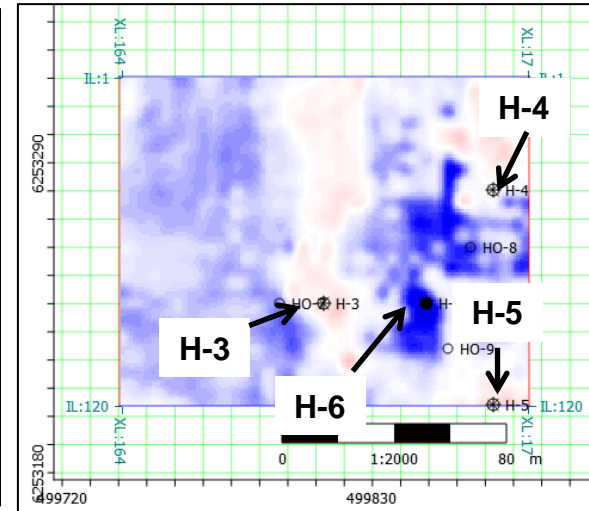
Shift
(ms)



Base – Monitor 1



Base – Monitor 2

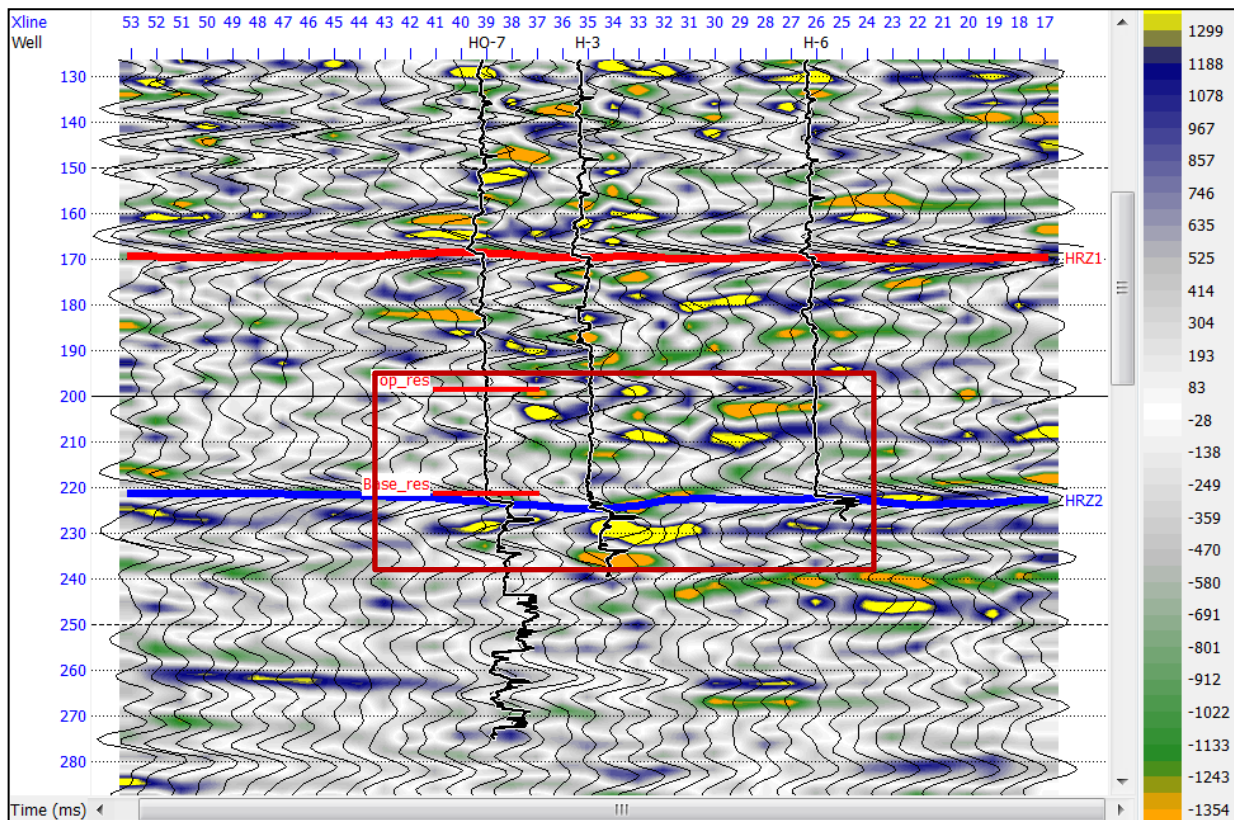


Base – Monitor 3

- Note that the time shifts are dominantly negative without the use of a filter when compared to the cross-correlation approach.



Base – Monitor1 diff. after Taylor shifts

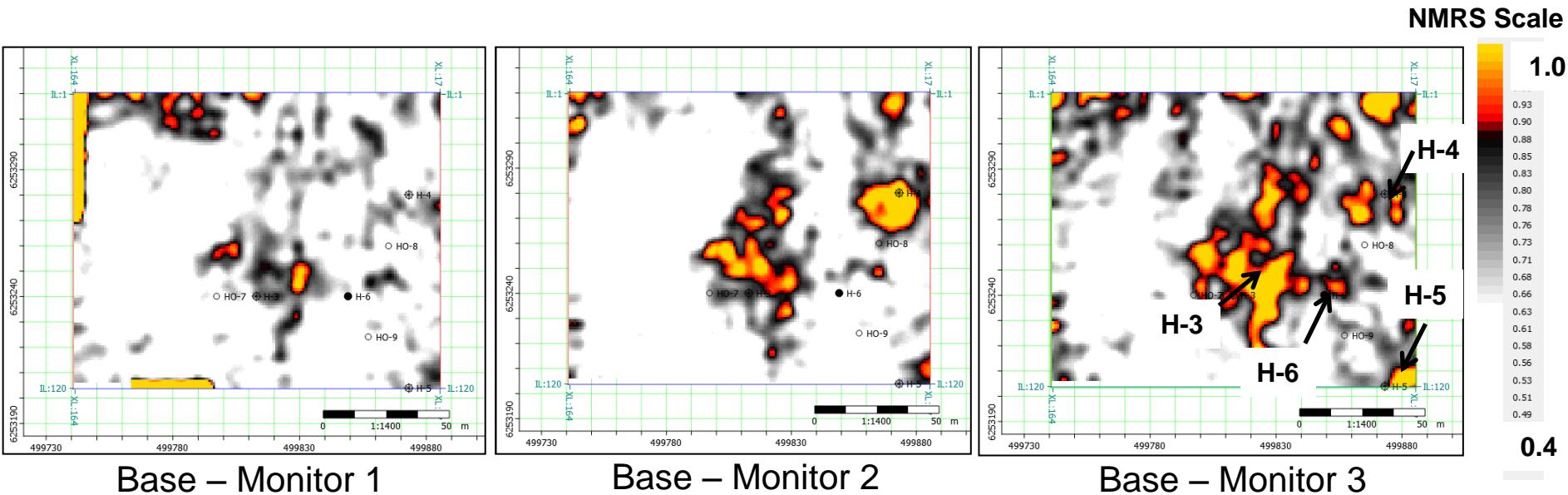


- Here is the amplitude difference between the base and first monitor survey after the Taylor shifts.
- As with the cross-correlation method, many of the extraneous artefacts below the base of reservoir have now been removed, revealing the production-induced shifts.



NRMS after Taylor time shifts

- Here is the Normalized Root-Mean-Square (NRMS) amplitude difference between the base and each monitor survey after application of Taylor time shifts:



- The NRMS averaging was done between Horizons 1 and 2.



Dynamic time warping

- Dynamic time warping (DTW) was first developed for voice recognition by Sakoe and Chiba (1978) in their paper “Dynamic programming algorithm optimization for spoken word recognition”.
- Their algorithm was used to stretch and to squeeze speech to match the stored voice pattern in phone conversations.
- Dave Hale from adopted the algorithm for seismic processing (“Dynamic warping of seismic images”, Geophysics, 2013).
- The algorithm is useful for lining up seismic images from different time-lapse vintages, specifically to determine the time variant time shifts.
- As Hale (2013) pointed out, this method is more accurate than the cross-correlation method when the shifts vary rapidly.



Dynamic time warping theory

- Let us now look at the problem from a mathematical point of view.
- For a single vintage, dynamic time warping finds all the shifts simultaneously by minimizing the sum of error for all possible lags, or:

$$\tau(t) = \min \left[\sum_{l=0}^{N-1} e(t, l(t)) \right], \quad t = 0, \dots, N - 1, \text{ where}$$

$$e(t, l(t)) = (v_1(t) - v_1(t + l(t)))^2, \text{ and } l(t) \text{ is an integer lag.}$$

- One other important aspect of DTW is that it is constrained so that the lag between successive samples cannot exceed + or - 1, or

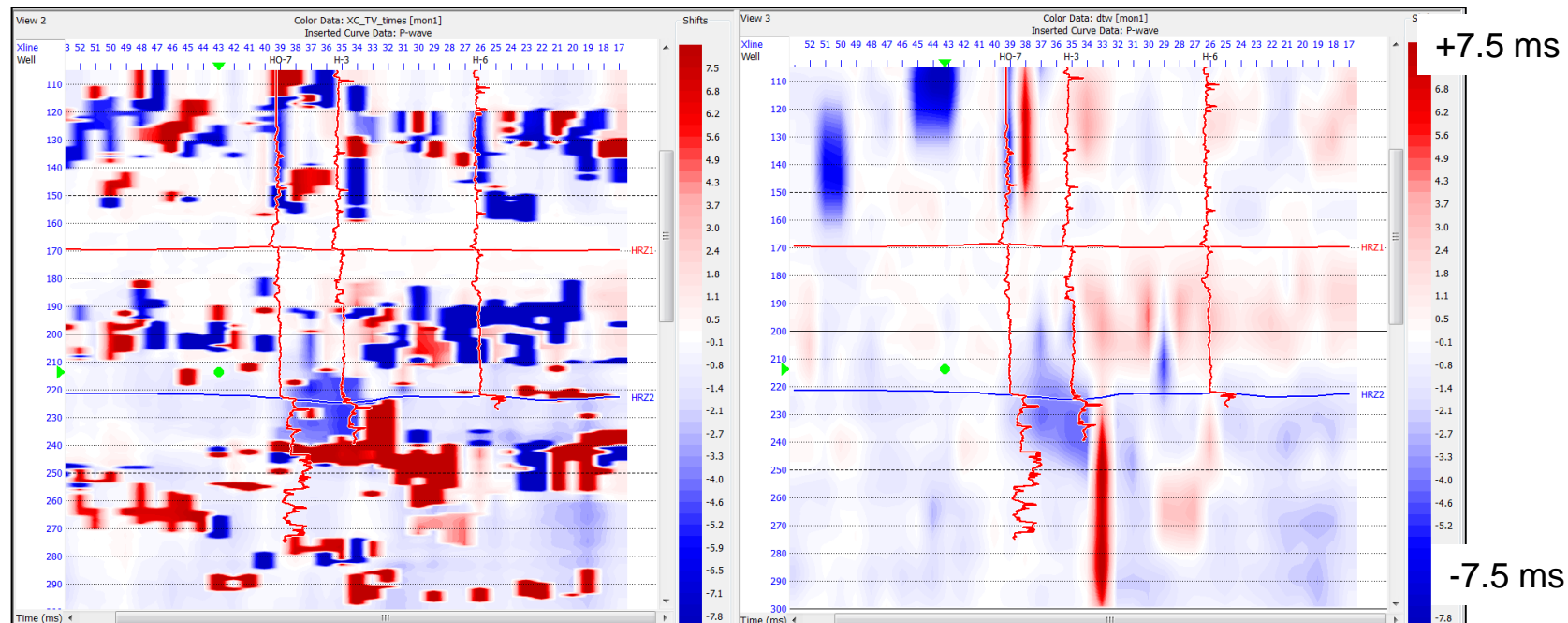
$$|\tau(t) - \tau(t - 1)| \leq 1$$





Cross-correlation vs dynamic time warping shifts

- A comparison of cross-correlation versus dynamic time warping shifts:



Cross-Correlation Time Shifts

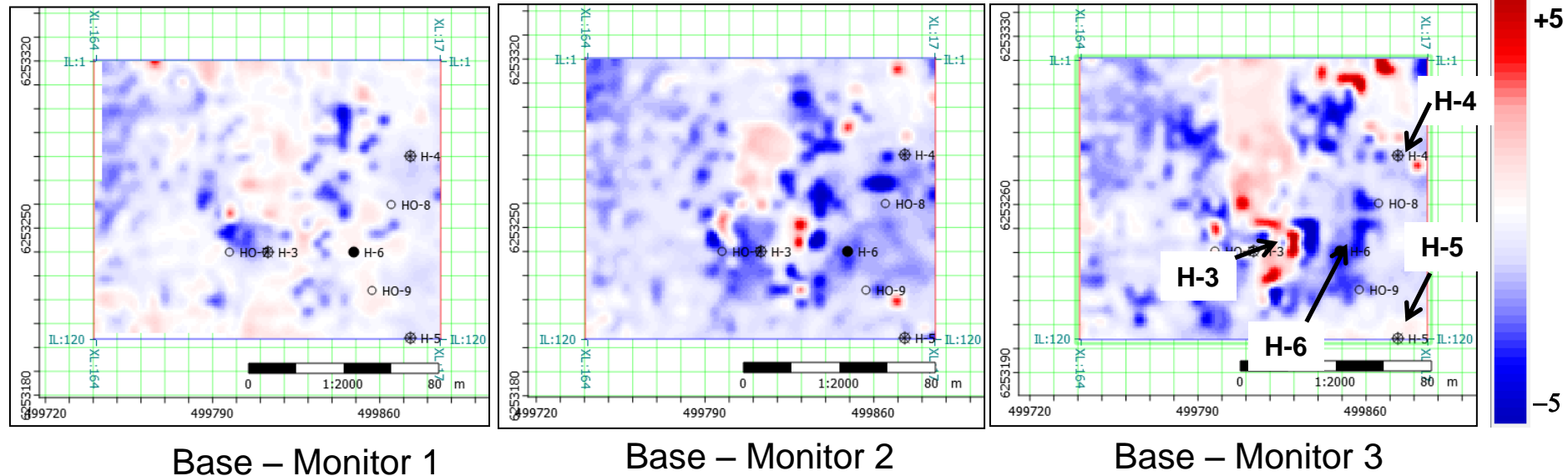
Dynamic Time Warping Shifts

- Note that the DTW shifts are much less noisy.



Dynamic time warping shifts on time slices

- The dynamic time warping shifts over a constant time slice of 214 ms:

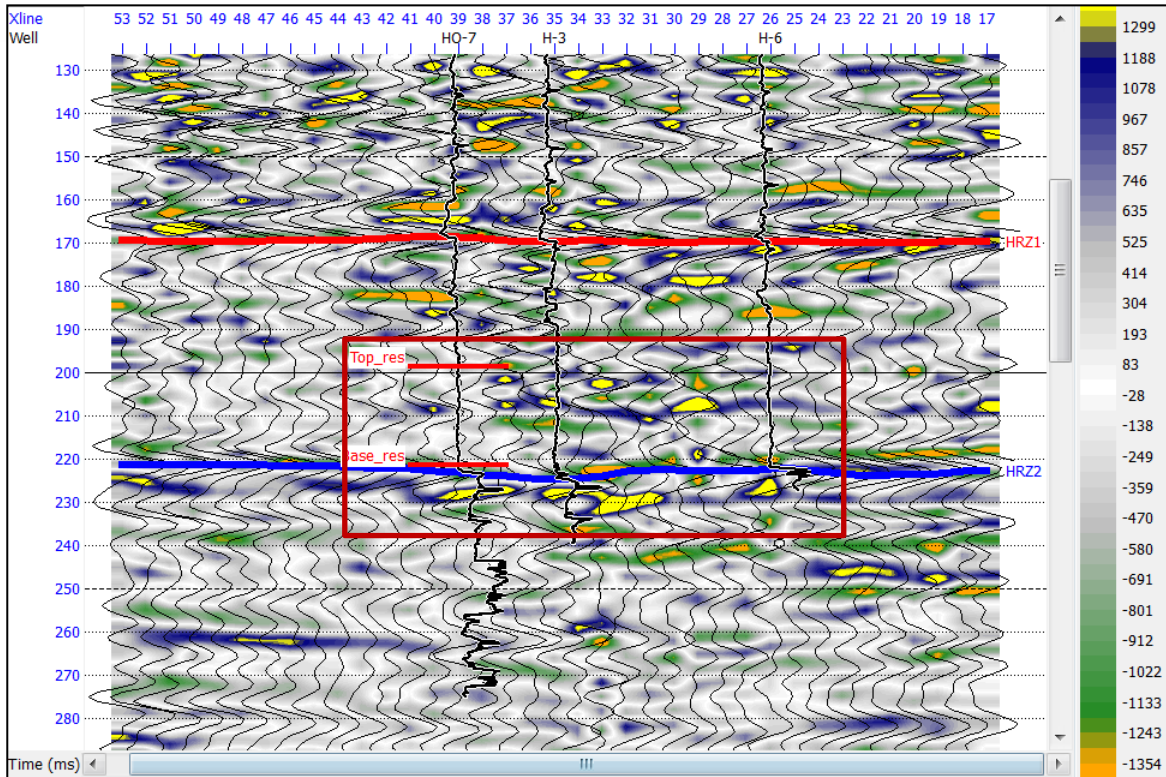


- Note that the time shifts are less smooth than the Taylor shifts but still predominantly negative, indicating lower velocity due to injection.





Base-Monitor1 diff. after DTW shifts

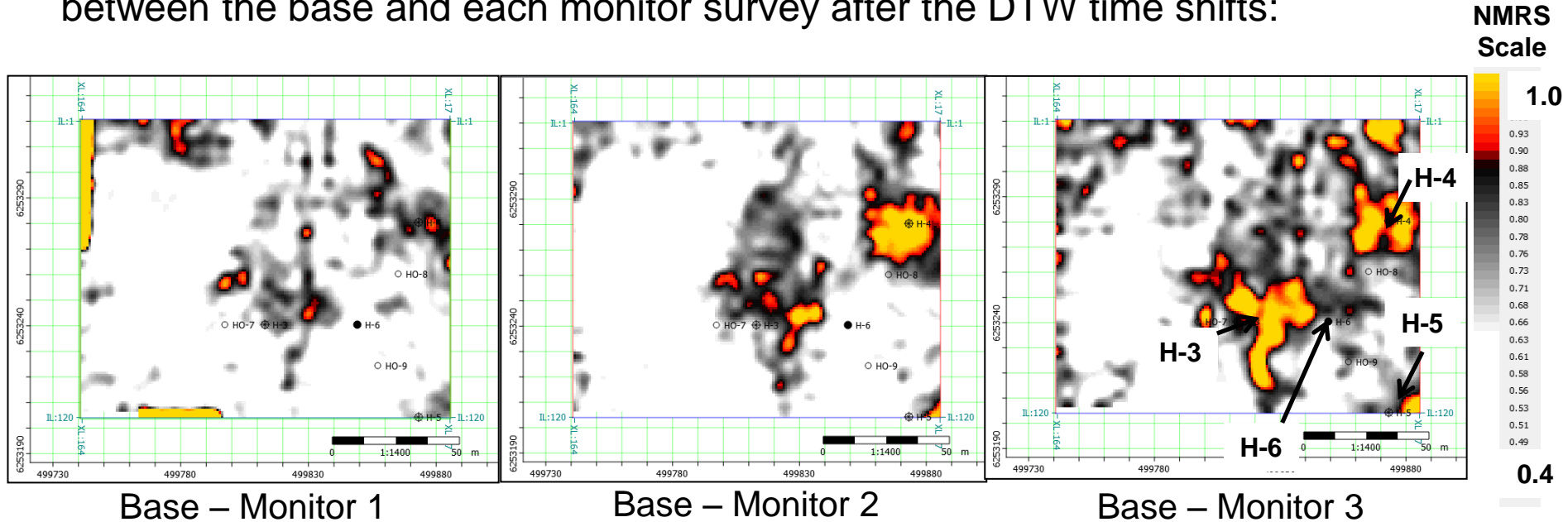


- Here is the amplitude difference between the base and first monitor survey after the DTW shifts.
- Again, many of the extraneous artefacts below the base of reservoir have now been removed, revealing the production-induced shifts.



NRMS after dynamic time warping time shifts

- Here is the Normalized Root-Mean-Square (NRMS) amplitude difference between the base and each monitor survey after the DTW time shifts:



- The NRMS averaging was done between Horizons 1 and 2.



Apparent displacement vectors

- Until now, our dynamic shift calculations have been in the vertical direction.
- However, we know that injection of heat or fluids into the reservoir will also affect the horizontal stresses and create inline and crossline shifts (Guilbot and Smith, 2002).
- In 2009, Dave Hale published a paper in Geophysics entitled “A method for estimating apparent displacement vectors from time-lapse seismic images”, which proposed a way to compute all three shifts.
- Hale’s work extended earlier work by Hatchell (Hatchell and Bourne, 2005, Cox and Hatchell, 2008), Nickel (Nickel and Sønneland, 1999 and Nickel et al., 2003), and Hall (Hall et al., 2002, and Hall, 2006).
- Since this method is an extension of the correlation equation shown earlier, the next slide will show this extension to the vector case.



Displacement vector theory

- The basic problem is now to find the following vector shifts:

$$v_2(\mathbf{j}) = v_1(\mathbf{j} + \mathbf{u}(\mathbf{j})), \text{ where}$$

$\mathbf{j} = (j_1, j_2, j_3)$ is a vector of vertical, inline and crossline directions,
and $\mathbf{u}(\mathbf{j}) = (u_1(\mathbf{j}), u_2(\mathbf{j}), u_3(\mathbf{j}))$ is a vector of displacements.

- In the displacement vector computation, Hale (2009) uses cross-correlation, but now extends it to three dimensions and applies a Gaussian weighting function:

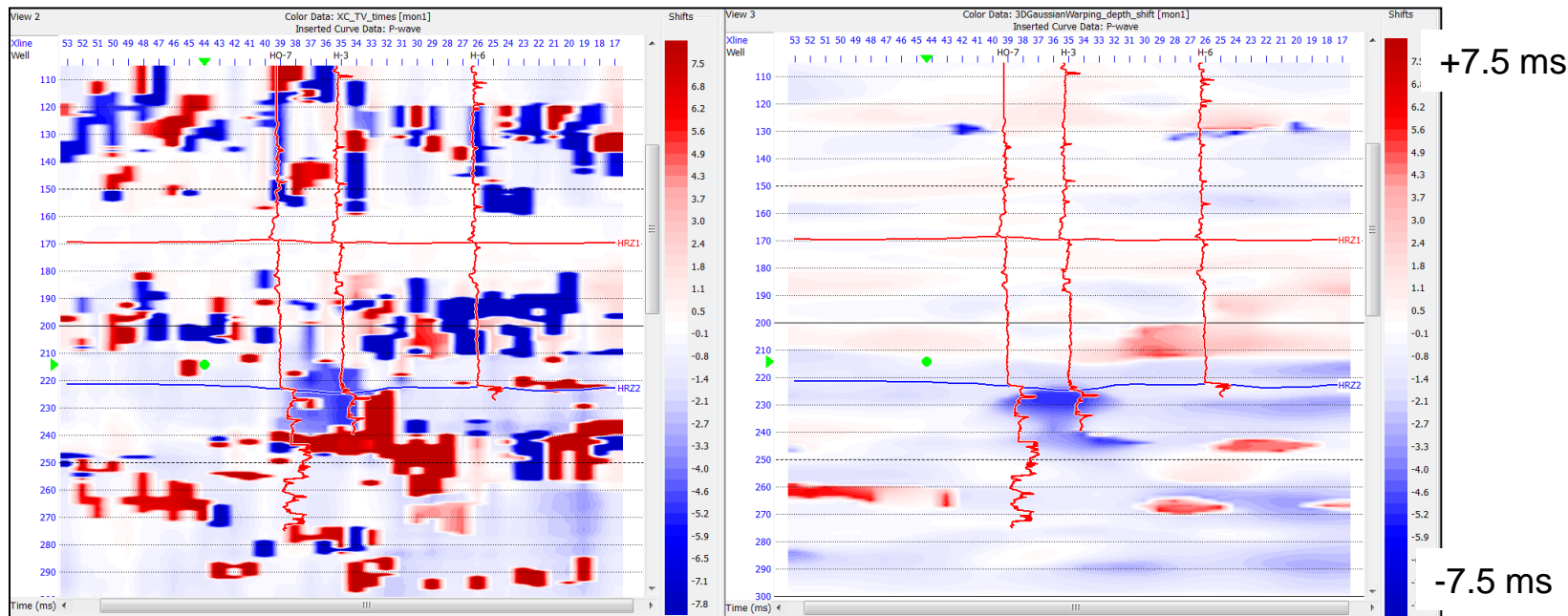
$$c_{v_1 v_2}(\mathbf{k}, \mathbf{l}) = \sum_{\mathbf{j}} v_1(\mathbf{j}) v_1(\mathbf{j} + \mathbf{l}) \times w(\mathbf{k} - \mathbf{j}), \text{ where}$$

$w(\mathbf{k}) = \exp\left[\frac{-\mathbf{k} \times \mathbf{k}}{2\sigma^2}\right]$ is a Gaussian weighting function of radius σ .



Cross-correlation vs Gaussian correlation time shifts

- Cross-correlation vs Gaussian correlation (or displacement vector) time shifts:



Cross-Correlation Time Shifts

Gaussian correlation time shifts

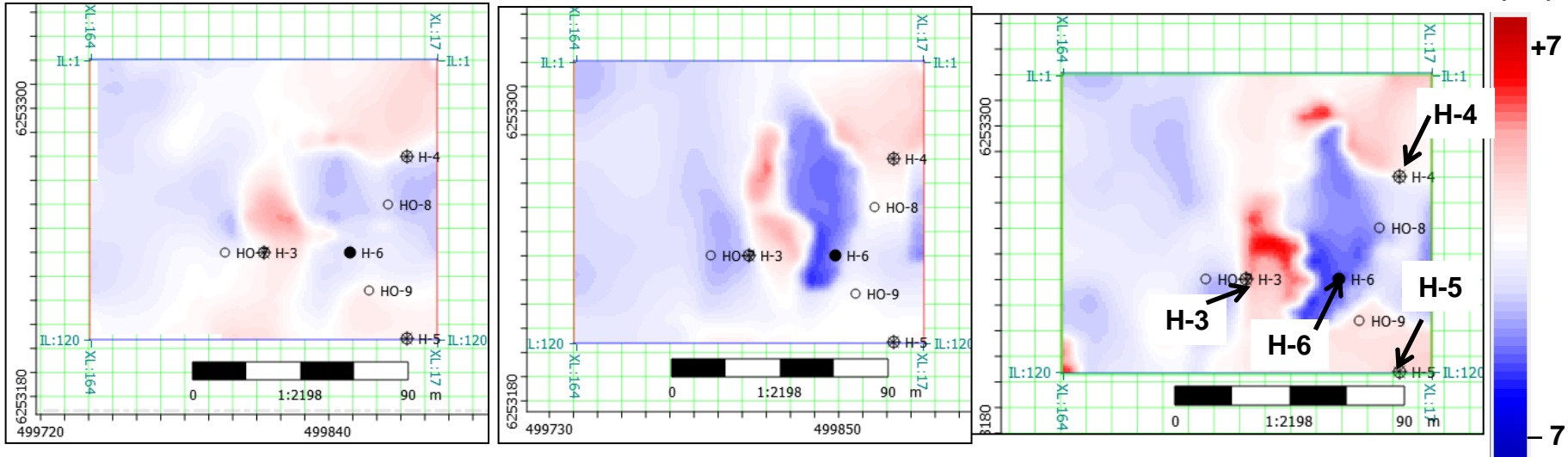
- Note that the shifts are much less noisy than regular cross-correlation.





Gaussian correlation time shifts on time slices

- The Gaussian correlation time shifts over a constant time slice of 214 ms:



Base – Monitor 1

Base – Monitor 2

Base – Monitor 3

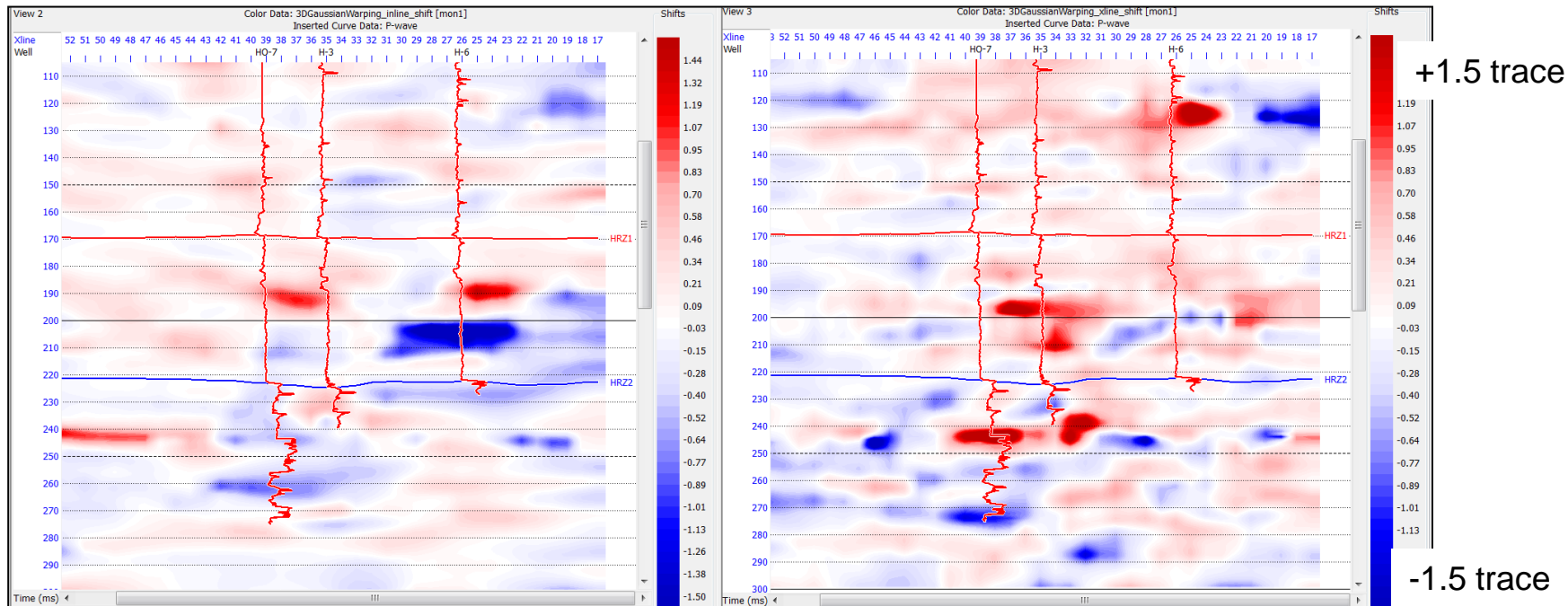
- Note that the time shifts are most negative around well H-6.





Displacement vector in-line and cross-line shifts

- We also get two other volumes of shifts from the displacement vector calculation, the inline shifts and crossline shifts, shown below:



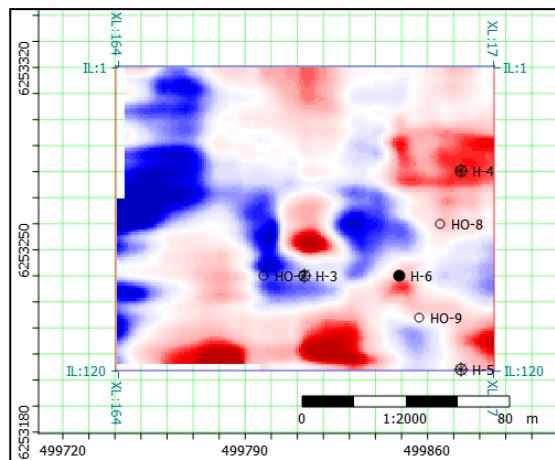
Inline displacement vector shifts

Crossline displacement vector shifts

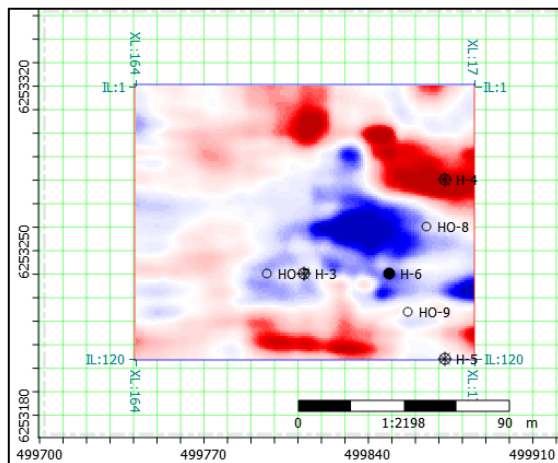


Gaussian correlation inline shifts on time slices

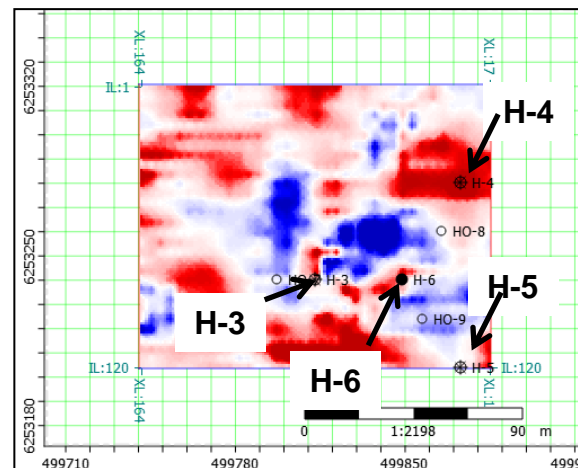
- The Gaussian correlation inline shifts over a constant time slice of 214 ms:



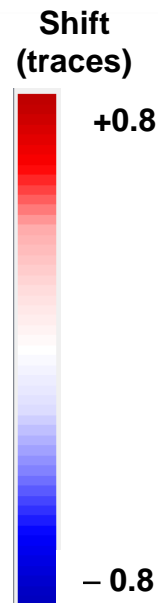
Base – Monitor 1



Base – Monitor 2



Base – Monitor 3



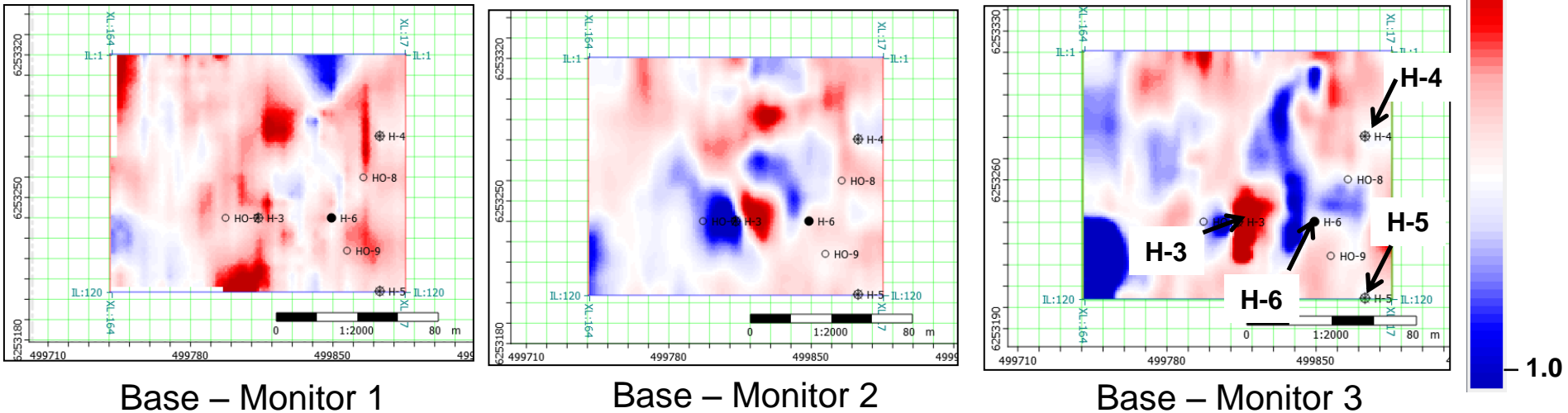
- Note the negative shifts around injector well H-6 and positive shifts around injectors/producers H-4 and H5.





Gaussian correlation crossline shifts on time slices

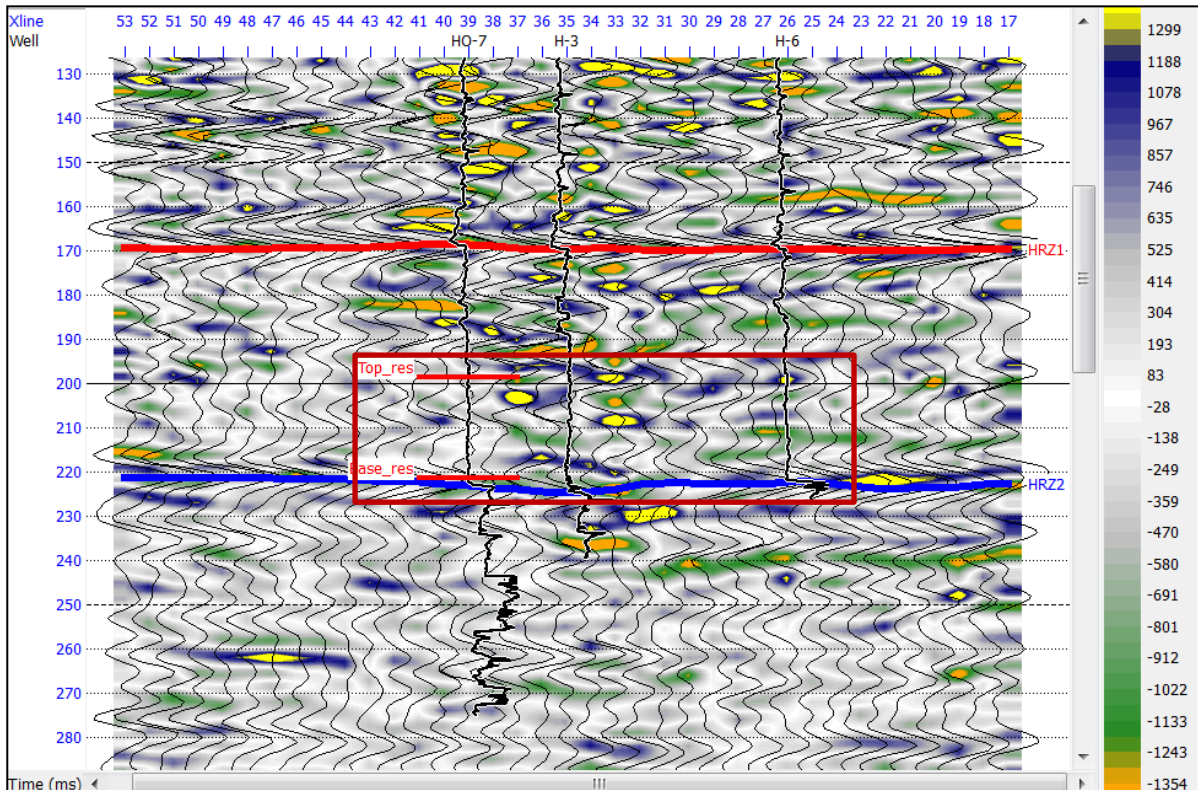
- The Gaussian correlation crossline shifts over a constant time slice of 214 ms:



- Note the gradual change from positive to negative shifts at injector wells H-6, H-4 and H5.



Base-Monitor1 diff. after displacement vector shifts



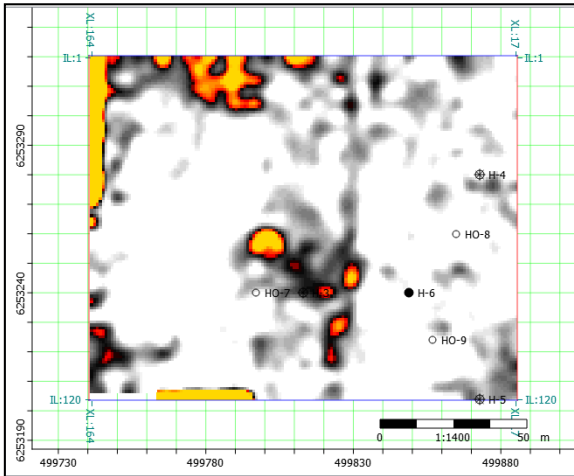
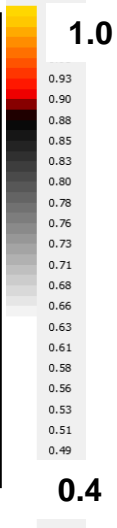
- Here is the amplitude difference between the base and first monitor survey after full displacement vector shifting.
- Again, many of the extraneous artefacts below the base of reservoir have now been removed, revealing the production-induced shifts.



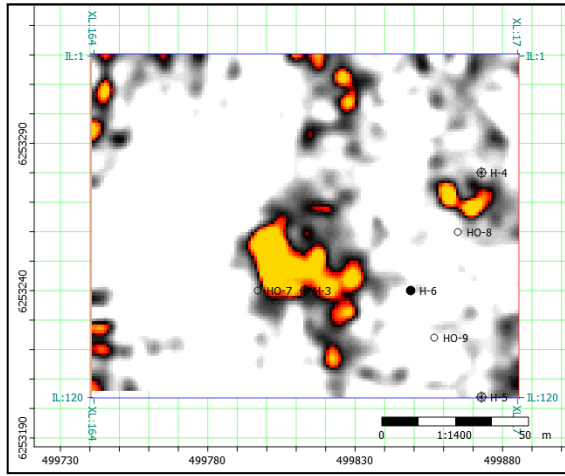
NRMS after Gaussian correlation application

- The Normalized Root-Mean-Square (NRMS) amplitude difference between the base and each monitor after Gaussian correlation time and lateral shift application:

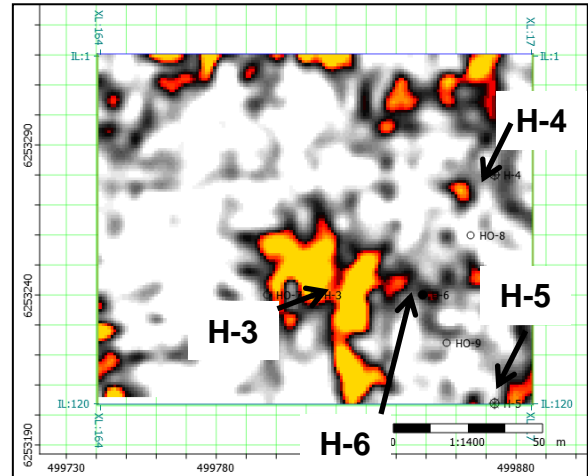
NRMS Scale



Base – Monitor 1



Base – Monitor 2



Base – Monitor 3

- The NRMS averaging was done between Horizons 1 and 2.





Recording history of GLISP Pilot Revisited

- The Base survey was recorded in 1985.

First time period

- Three wells (H3, H4, H5) were selected for steam injection that continued for 15 days each. The first Monitor was recorded in 1987.

Second time period

- The 3 active injection wells (H3, H4 H5) were converted to producers.
- An injector well (H6) was selected and steam was injected for a period of 96 days. The second Monitor was recorded in 1988.

Third time period

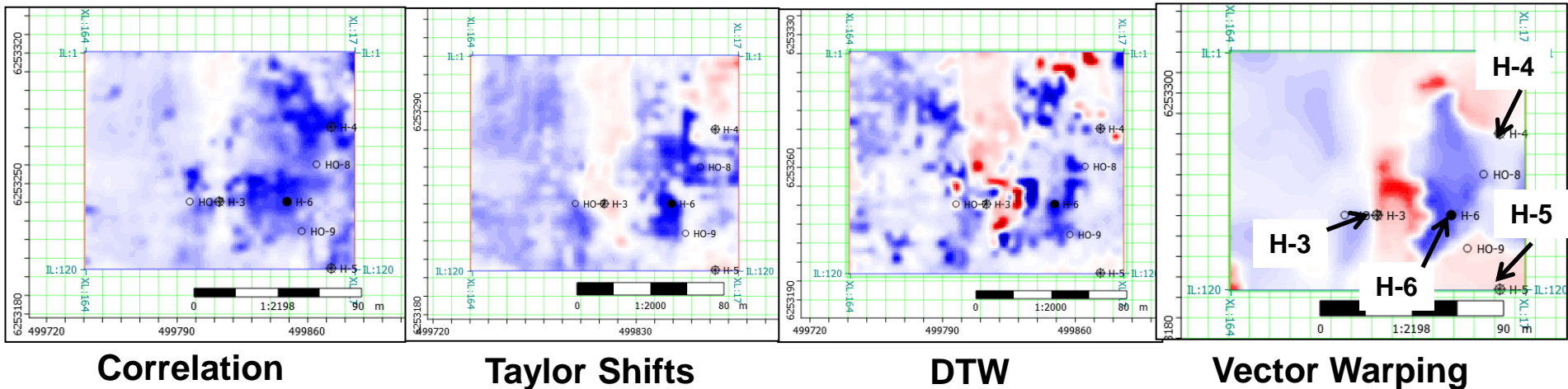
- Steam was injected into 2 producing wells for a short time period.
- Steam was injected into the main injector well (H6) for a period of 6 months. The third Monitor was recorded in 1989.





Summary of time shift results for Base – Monitor3

- The Gaussian correlation time shifts over a constant time slice of 214 ms:

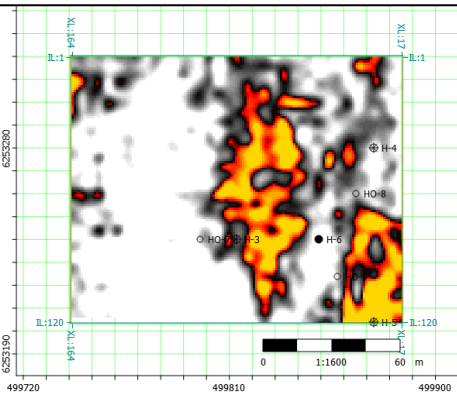


- Noting that H-6 was the main injector in the second two time periods, and that H-3, H-4 and H-5 had been converted to producers after time period 1, the Taylor, DTW and Gaussian Correlation results are more consistent than the conditioned correlation.

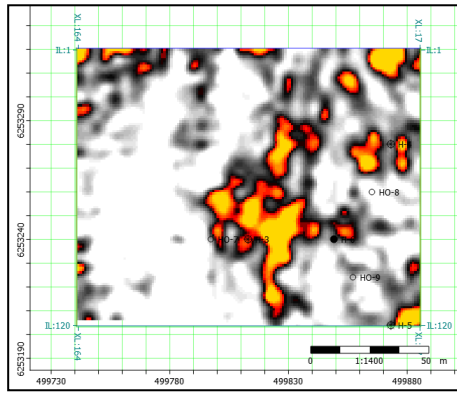


NRMS amplitude difference comparison

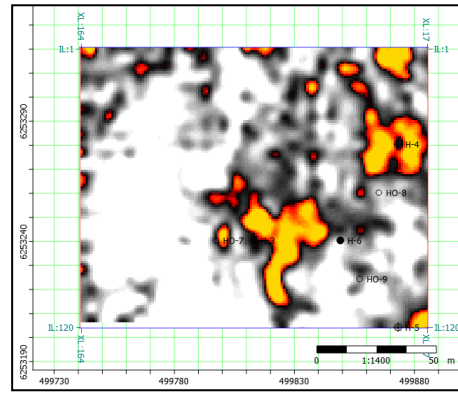
- Here is a comparison of the NRMS amplitude difference between Horizons 1 and 2 for the Base – Monitor 3 results after our four main algorithms:



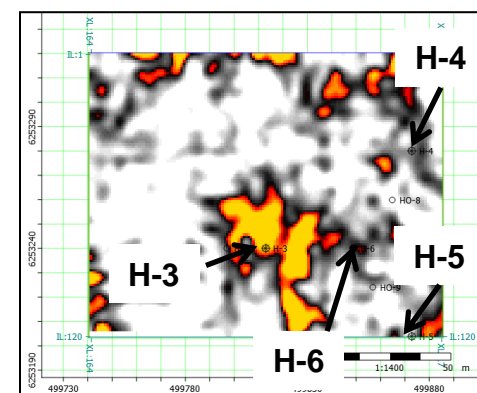
Correlation



Taylor Expansion



DTW



Vector Warping

- Noting that H-6 was the main injector in the second two time periods, and that H-3, H-4 and H-5 had been converted to producers after time period 1, the Taylor, DTW and Gaussian Correlation results are more consistent than the Conditioned Correlation.





Conclusions

- In this talk I compared four options for the computation of time variant time shifting between a Base and 3 Monitor Surveys in the GLISP project:
 - Conditioned cross-correlation
 - The Taylor series expansion method
 - Dynamic time warping
 - Dynamic vector warping with Gaussian windowing.
- Of the four methods, the Taylor expansion shifts, Dynamic Time Warping and Gaussian Correlation Vector warping appear to give more reasonable results than the original conditioned cross-correlation method.
- Gaussian Correlation Vector warping also produces inline and crossline shift information in addition to time shift information.





Acknowledgements

- I would like to thank the following current and former colleagues at HampsonRussell:
 - Keith Hirsche who conceived the idea of Pro4D and ran our 4D consortium for many years until his retirement.
 - Francis Ma for being the initial chief developer for Pro4D and for implementing the Taylor Expansion method,
 - Tim Yue for implementing the Dynamic Time Warping algorithm, and
 - Tiancheng Song for implementing the Gaussian Weighted Vector Warping method.

