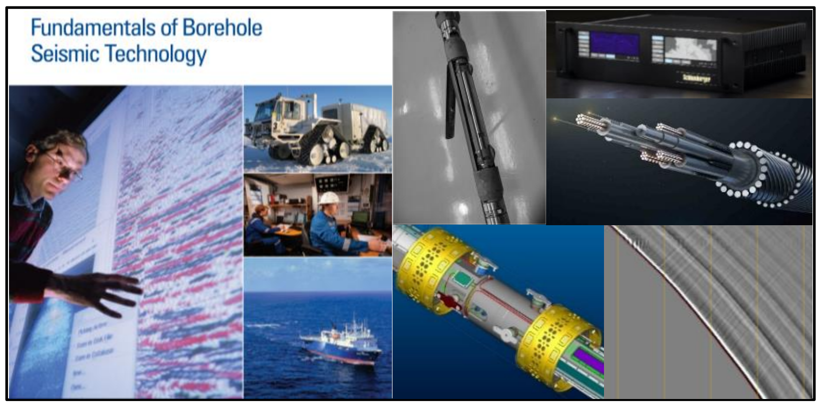
NORWEGIAN PETROLEUM DIRECTORATE
50 years

FORCE

NPD FORCE Geophysical Methods Group

Data processing technology & case studies

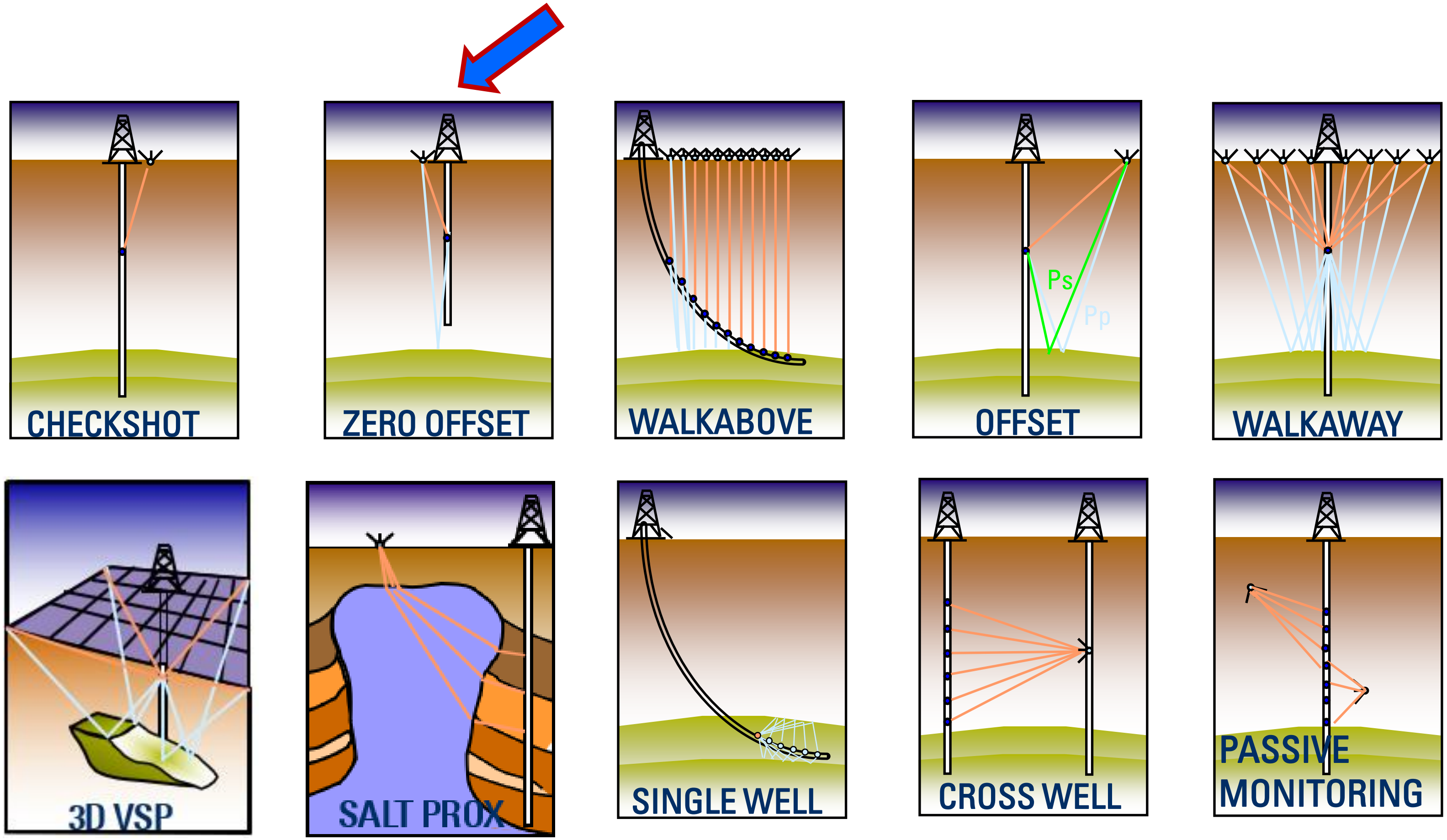


By: Rogelio Rufino (A&I Lead Borehole Geophysicist)

Schlumberger

Stavanger, 04-Oct-2022

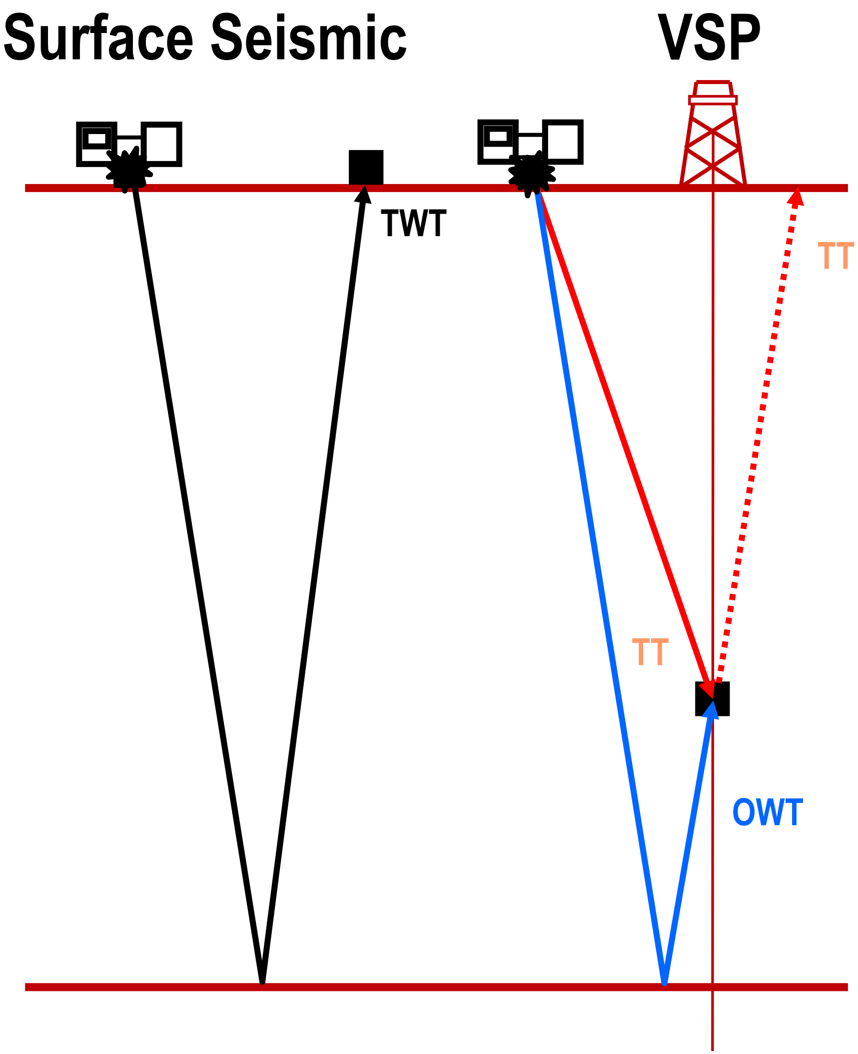
Borehole Seismic Survey Types

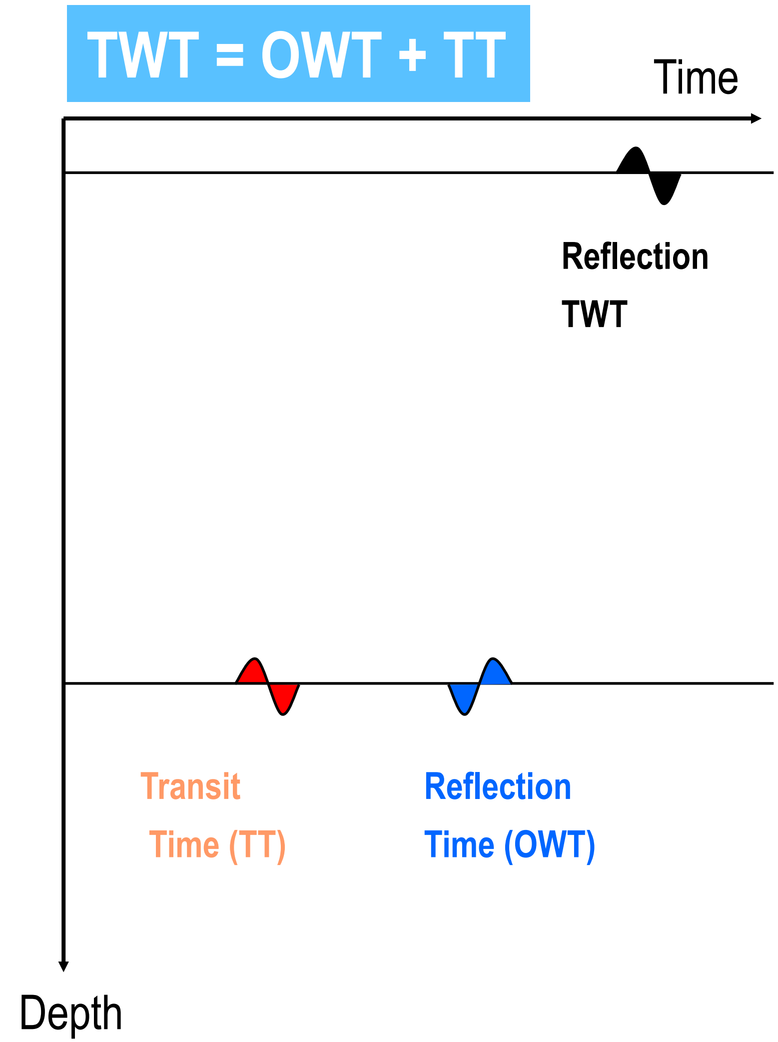


Basic VSP Processing and Concepts

Transit Time Calculation

One-Way Time vs. Two Way Time





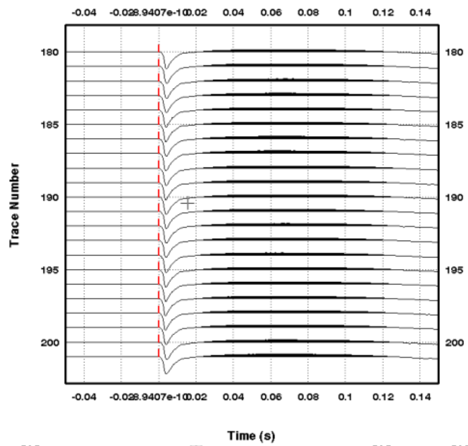
Transit Time Calculation, T-Z Function

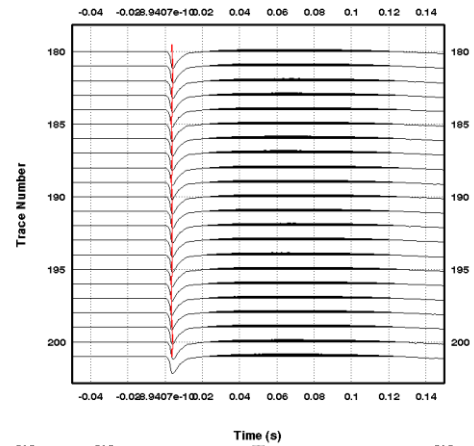
- Surface hydrophone time picks (Inflection Point or Trough)
- Downhole data stack and first arrival time picks (Inflection Point or Trough)
- Well deviation survey
- Source Offset and Azimuth
- Gun and sensor depth
- Replacement velocity

Transit Time Picks

Surface hydrophone

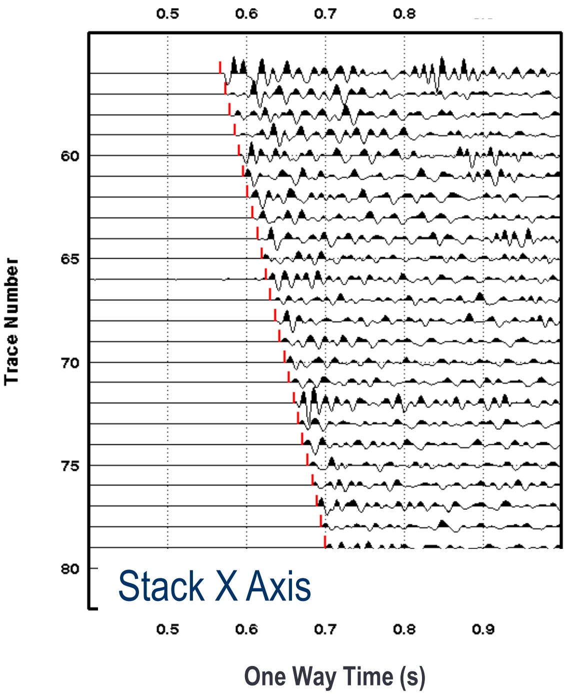
Time pick inflection point

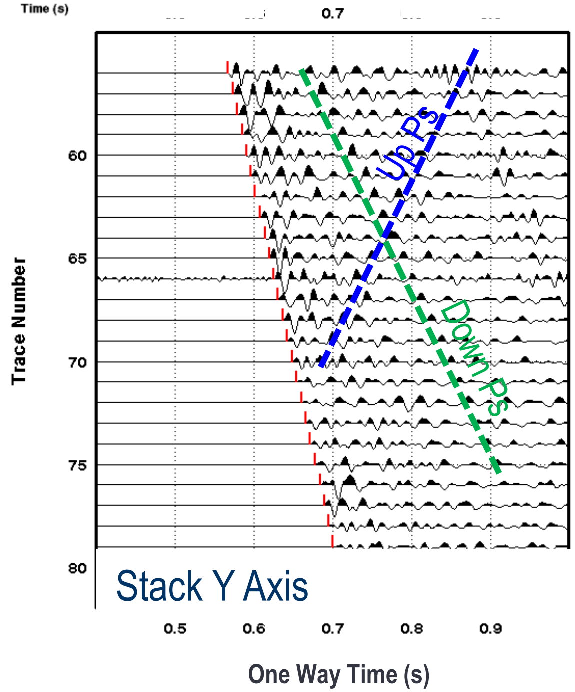


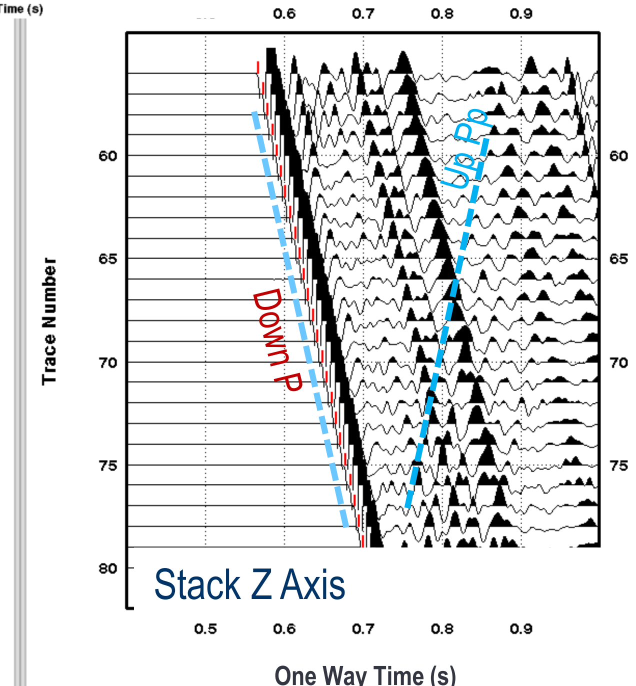


Surface hydrophone

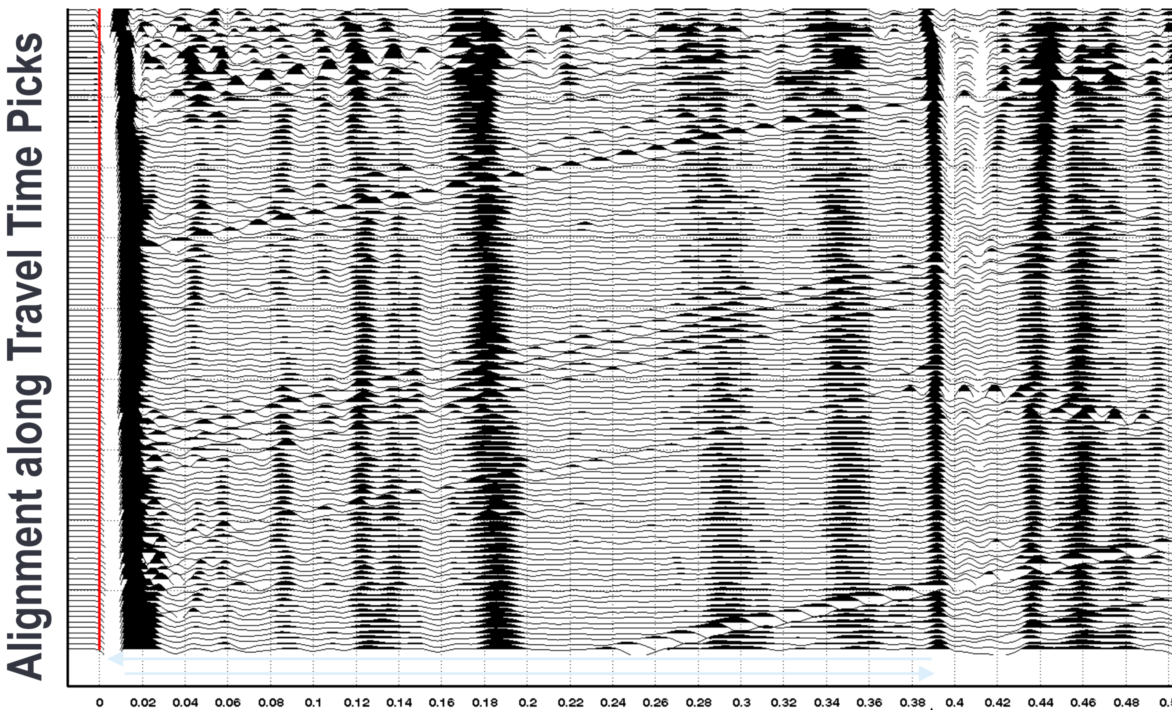
Time pick Trough

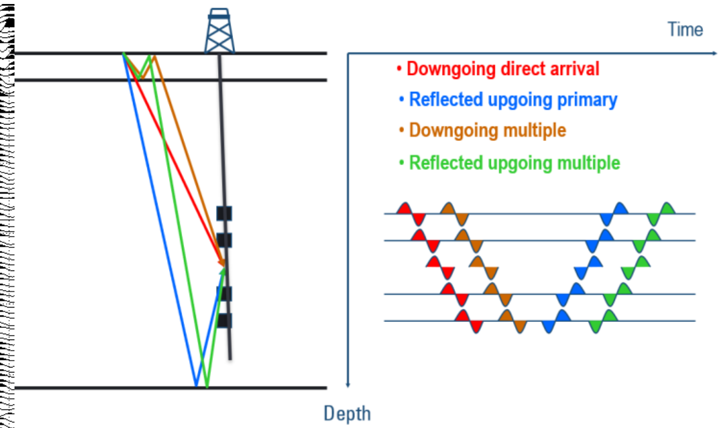


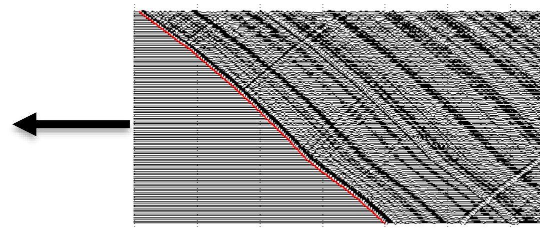




Average Sea Velocity Estimation





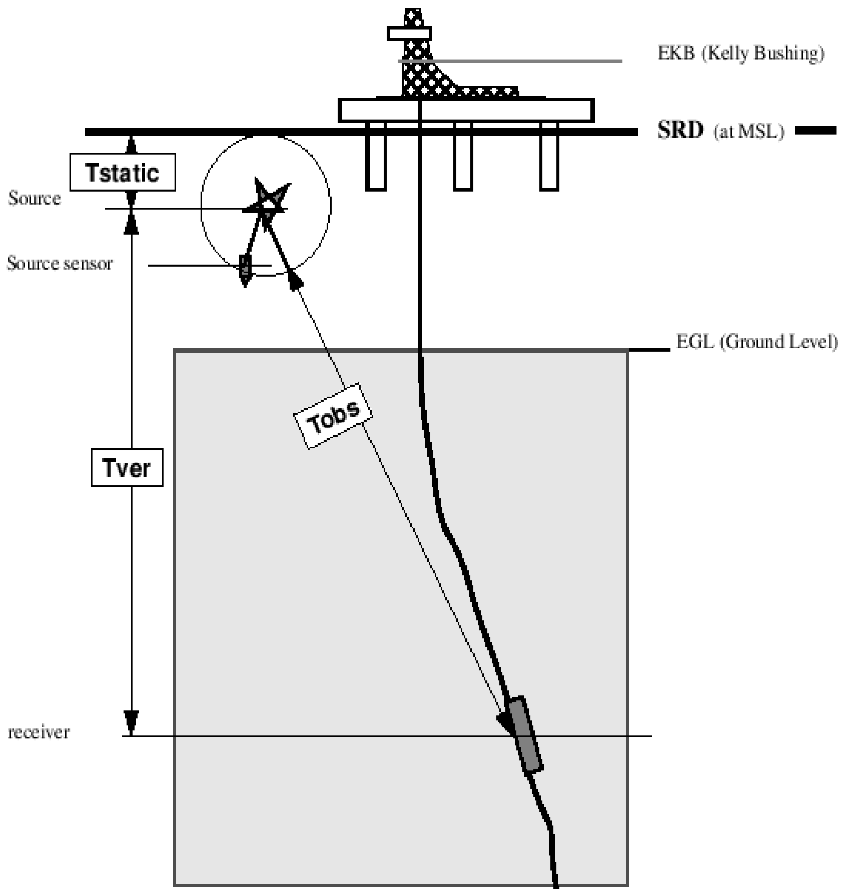


Seafloor: -288m

Seafloor multiple (0.3892s) after first break

Velocity = 288m / 0.3892s = 740.5 m/s x 2 (Two Way Path) = **1481 m/s**

Transit Time Calculation and Velocities



Air-Gun depth - correction

G-depth: 5m / 1480 = **0.003378s TStatic**

Client & Well Information

- **Company** :
- **Well** :
- **Logging Date** :

Survey Information

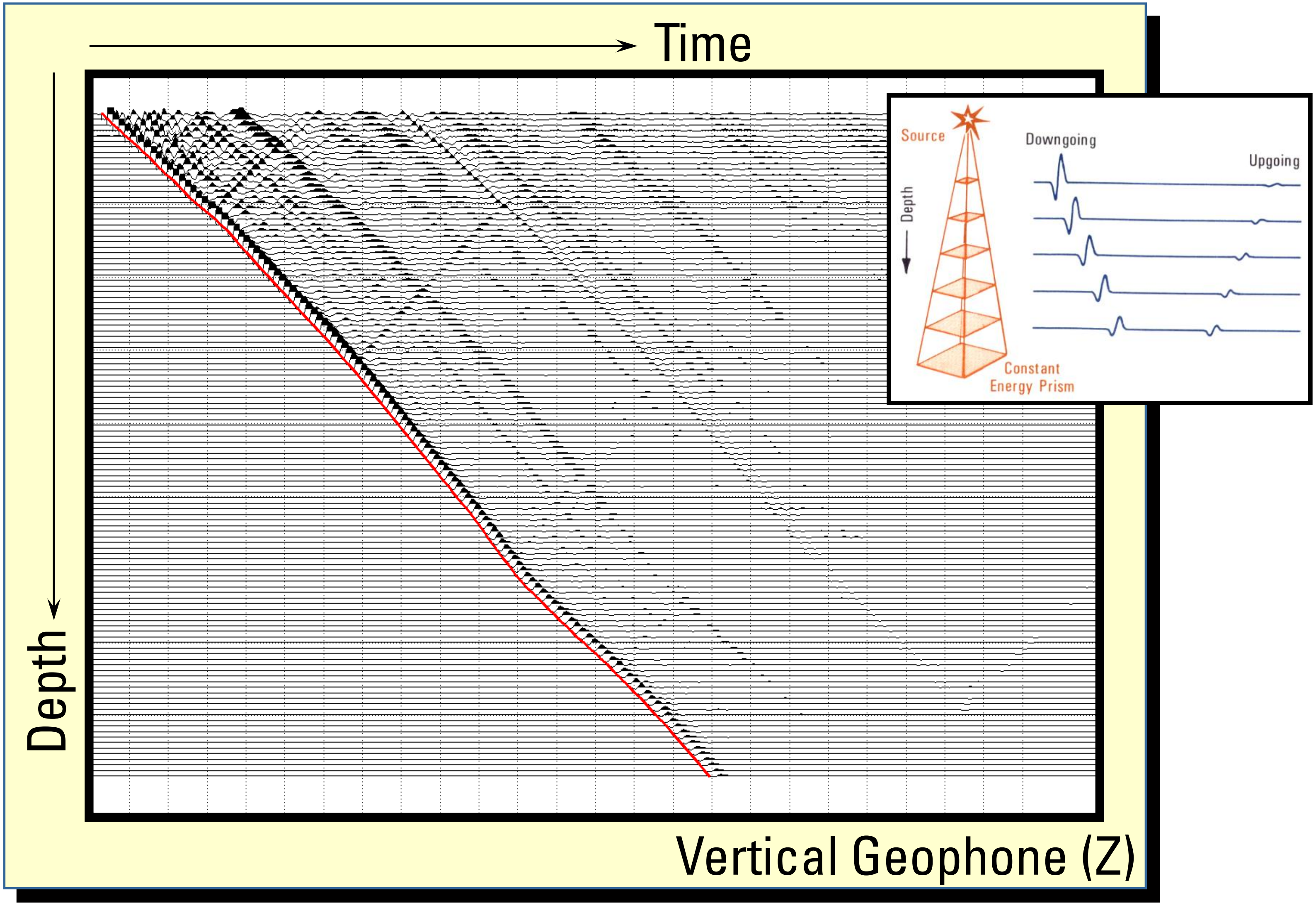
- **KB Elevation** :
- **DF Elevation** :
- **SRD** :
- **Sea Bed** :
- **Source Depth** :
- **Source Offset** :
- **Source Azimuth** :
- **Run** :
- **Replacement Velocity** :

Reference : **MSL**

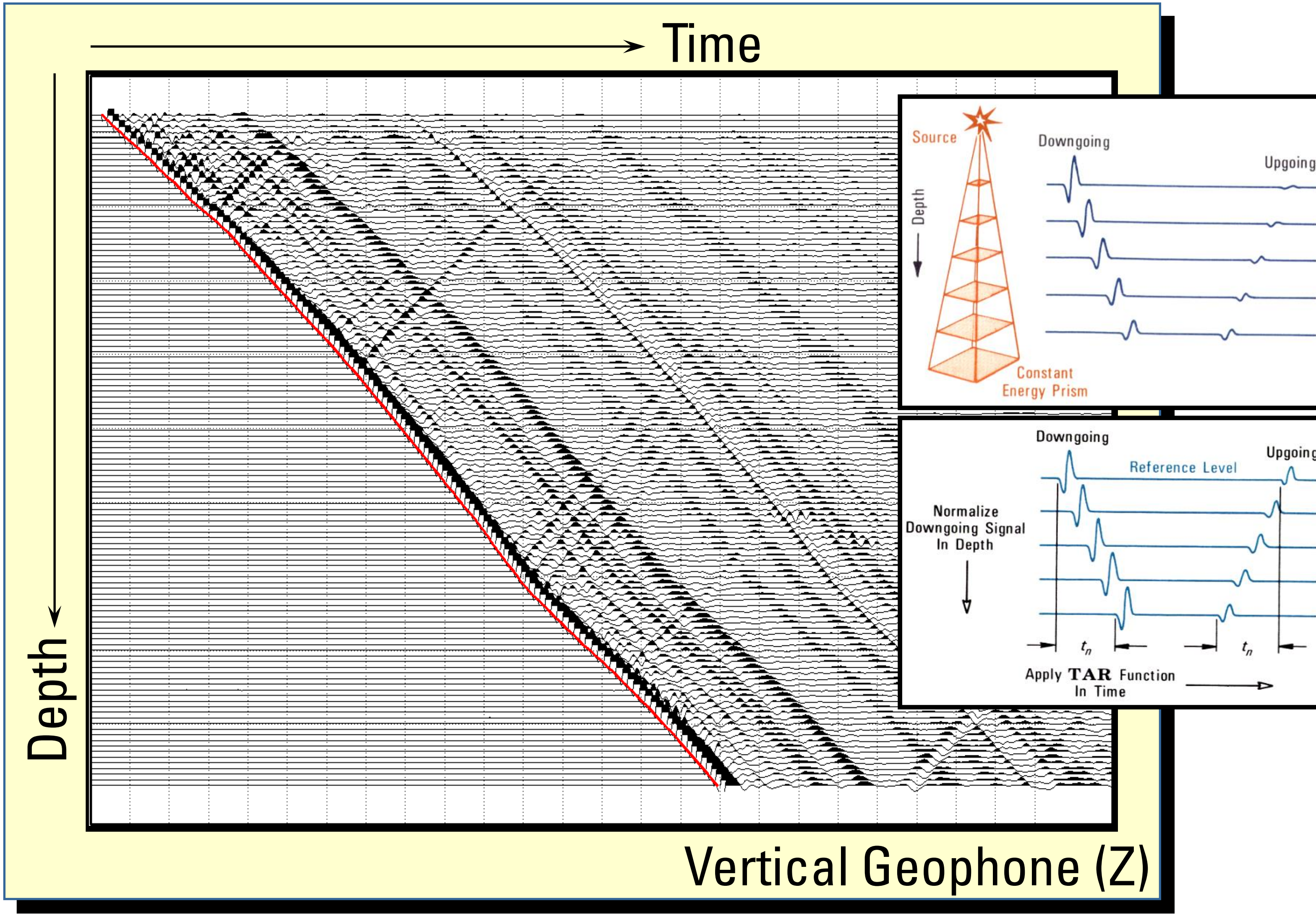
Level Number	Vertical Depth From SRD (m)	Measured Depth From DF (m)	Depth Interval (m)	Observed Time From Source (s)	Vertical OWT From SRD (s)	Time Difference (s)	Interval Velocity (m/s)	Average Velocity (m/s)	RMS Velocity (m/s)
1	0.0				0.0000				
							1441		
2	260.8	290.8		0.1847	0.1810			1441	1441
			15.2			0.0079	1924		
3	276.0	306.0		0.1921	0.1889			1461	1464
			15.2			0.0080	1903		
4	291.3	321.3		0.1997	0.1969			1479	1485
			15.2			0.0080	1909		
5	306.5	336.5		0.2073	0.2049			1496	1504
			15.2			0.0078	1944		
6	321.7	351.7		0.2148	0.2127			1512	1522
			15.2			0.0072	2130		
7	336.9	367.0		0.2215	0.2199			1532	1546
			15.2			0.0086	1765		
8	352.2	382.2		0.2299	0.2285			1541	1554
			15.2			0.0076	1995		
9	367.4	397.4		0.2372	0.2361			1556	1571
			15.2			0.0083	1835		
10	382.7	412.7		0.2453	0.2444			1565	1580
			15.2			0.0076	1996		
11	397.9	427.9		0.2526	0.2521			1578	1594

Schlumberger-Confidential

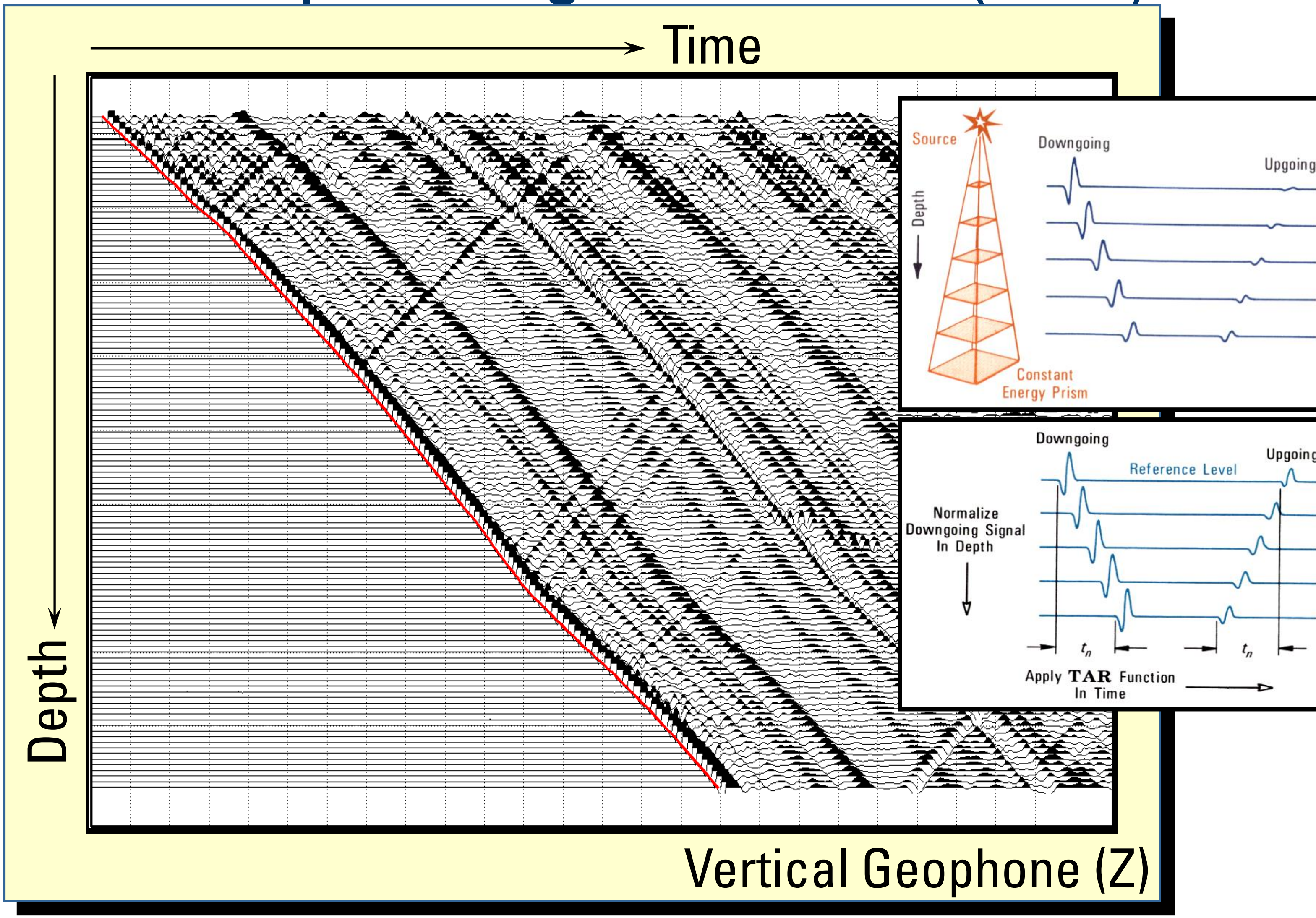
Median Stack Results



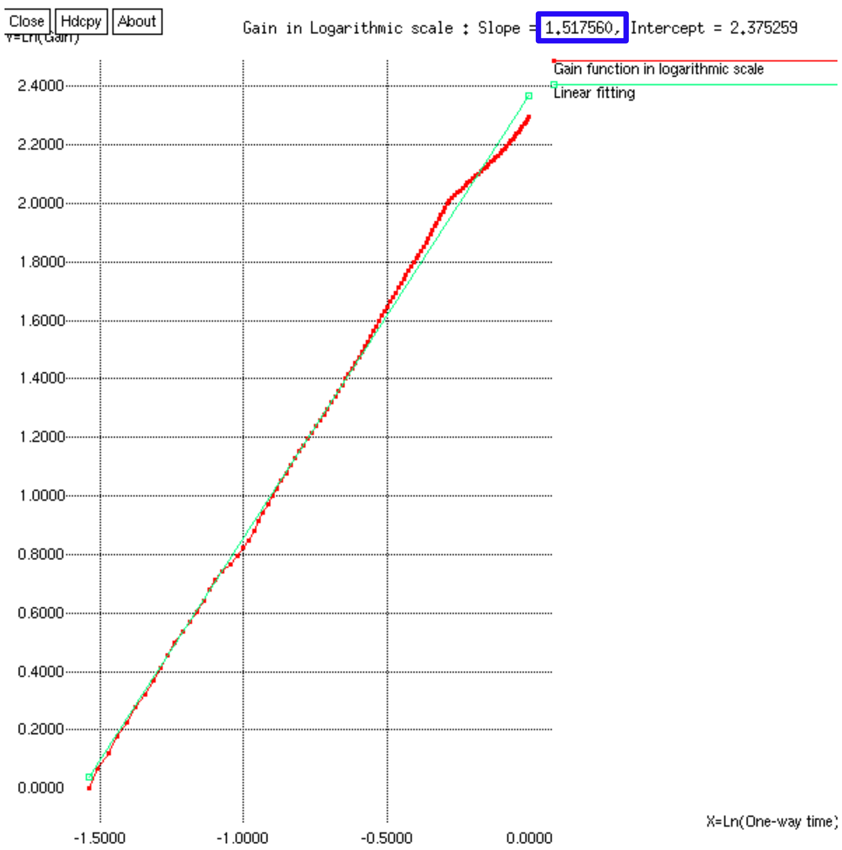
Normalization



Geometrical Spreading Correction (TAR)



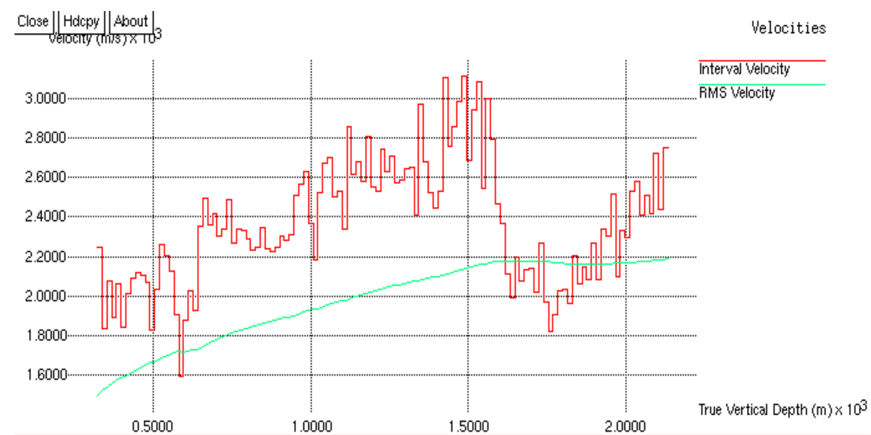
Geometrical Spreading (GS)



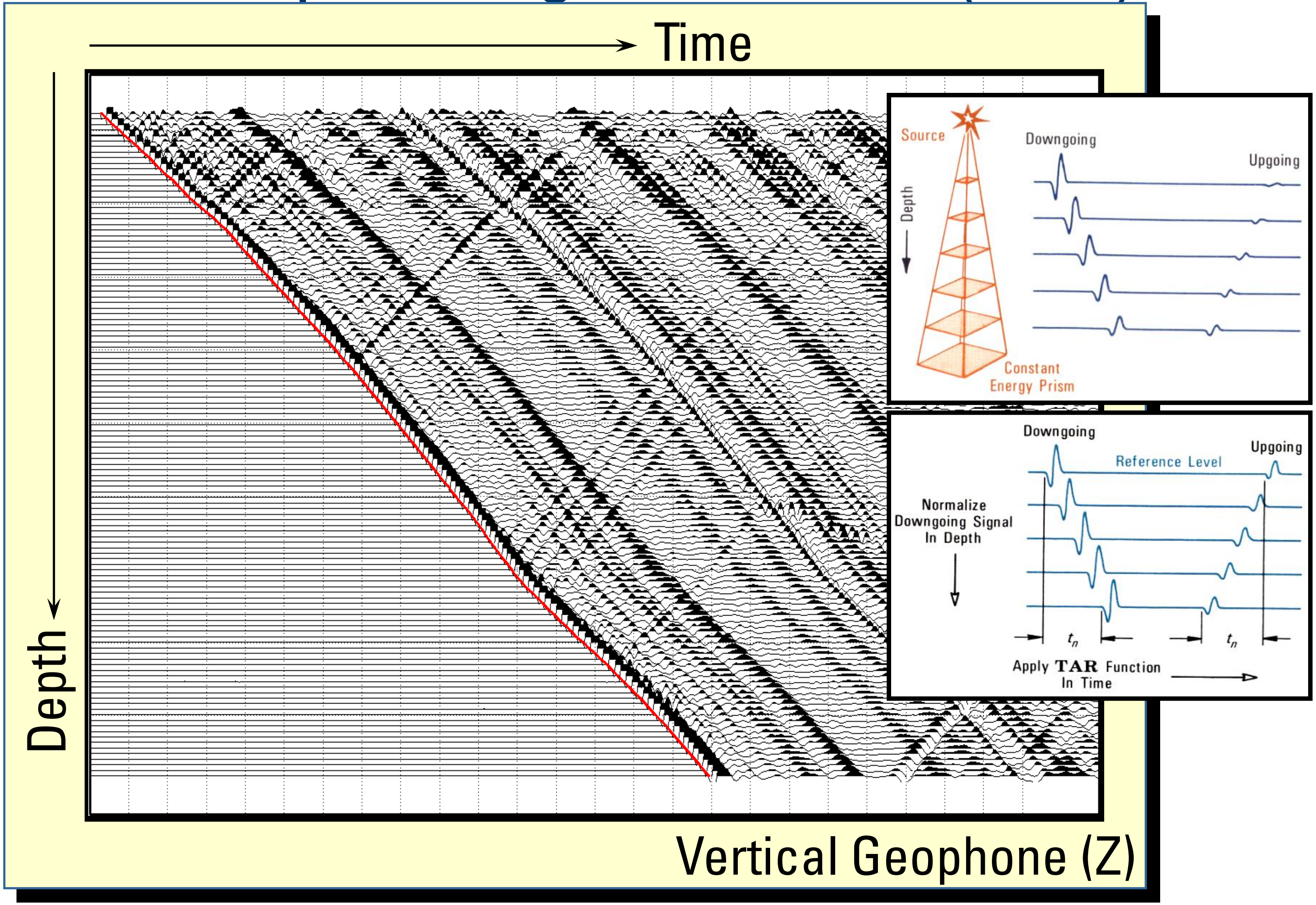
The Gain exponent (x) is estimated using the V_{RMS} calculated from the VSP vertical time-depth curves assuming:

$G = V^2_{RMS}T \Rightarrow \ln G = \ln\alpha + x\ln T$.

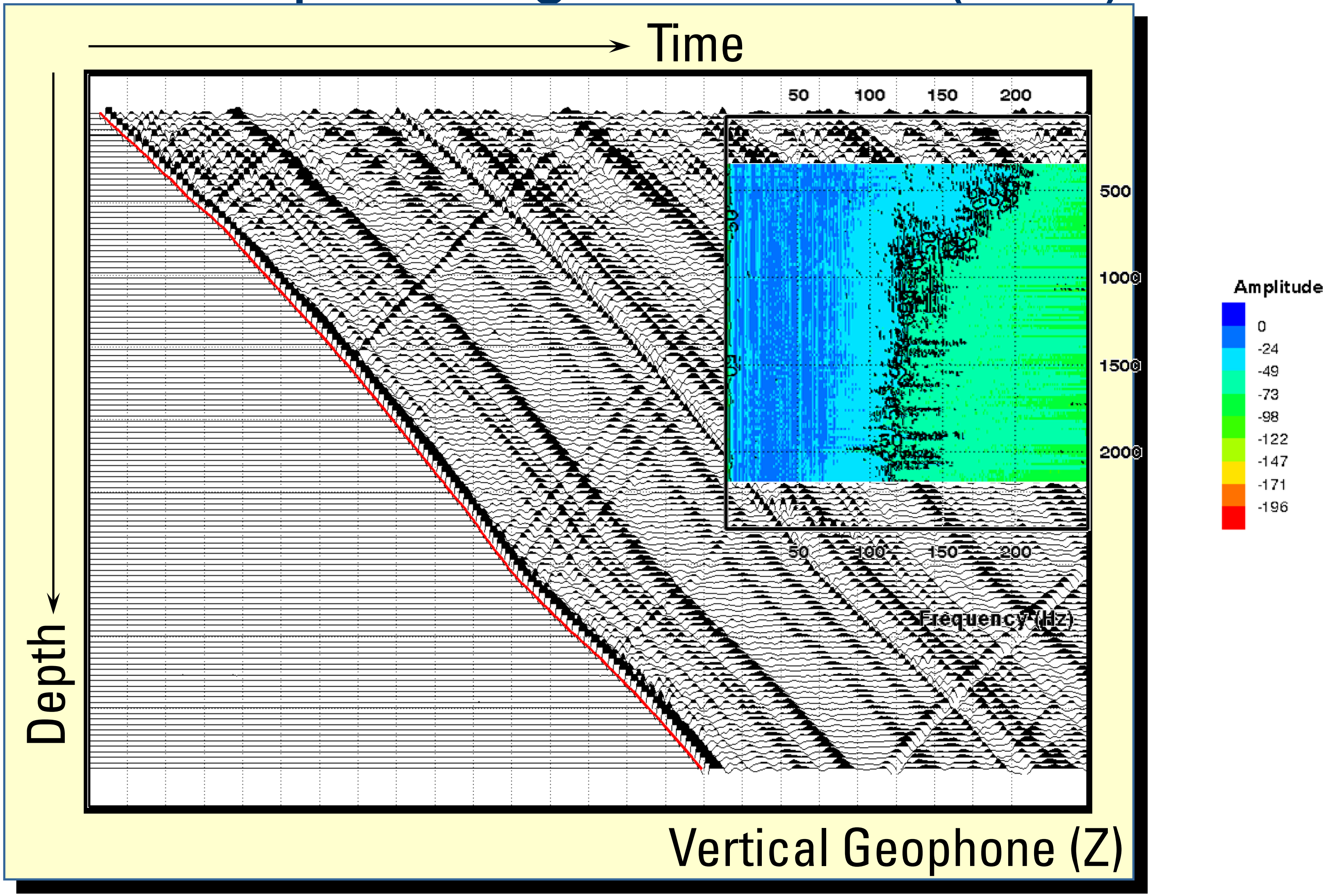
The gain exponent x is the slope of a best-fit linear estimate on a logarithmic T versus G plot. An average gain-exponent of **1.51** was estimated for the ZOVSP survey using this method.



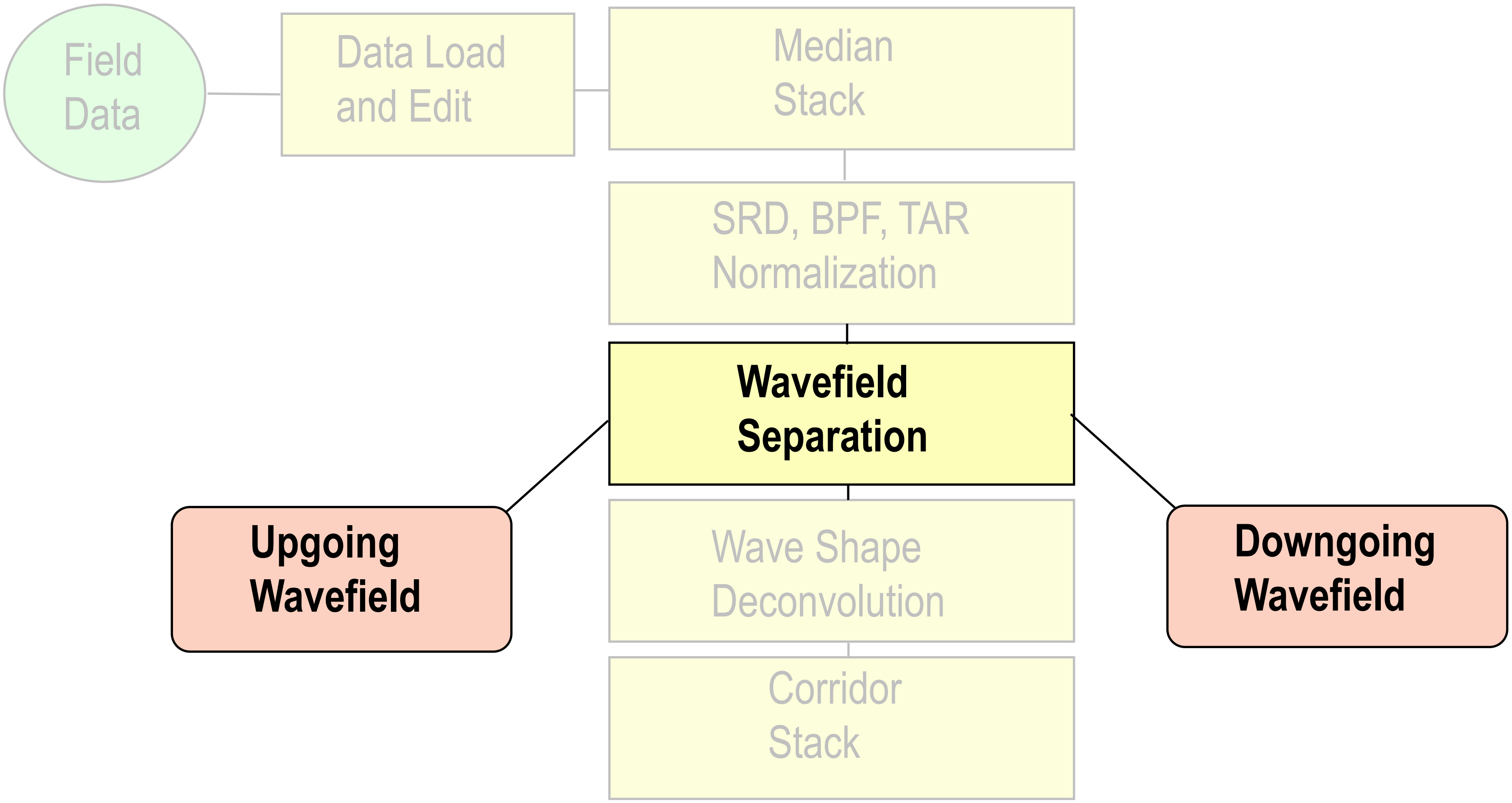
Geometrical Spreading Correction (TAR)



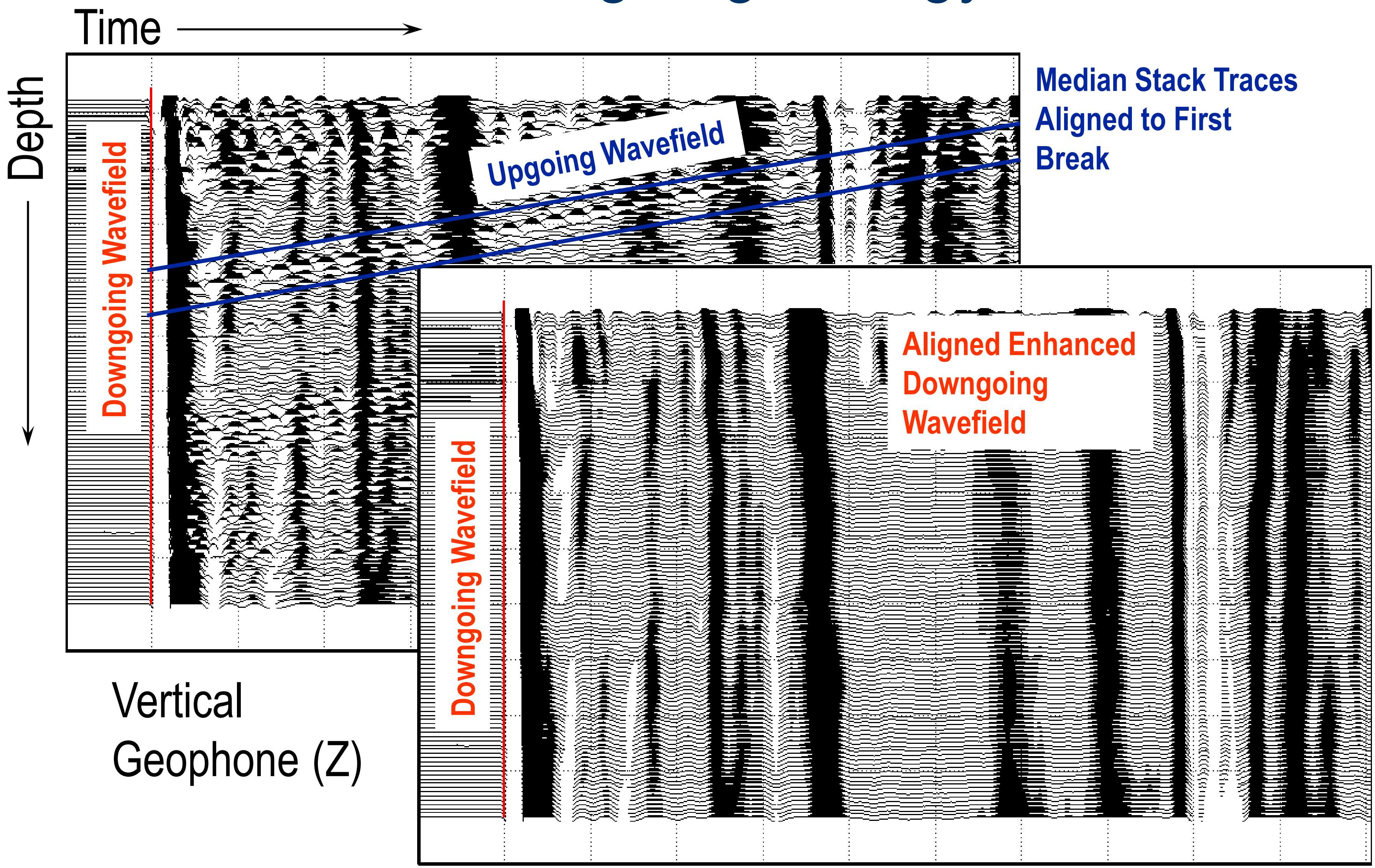
Geometrical Spreading Correction (TAR)



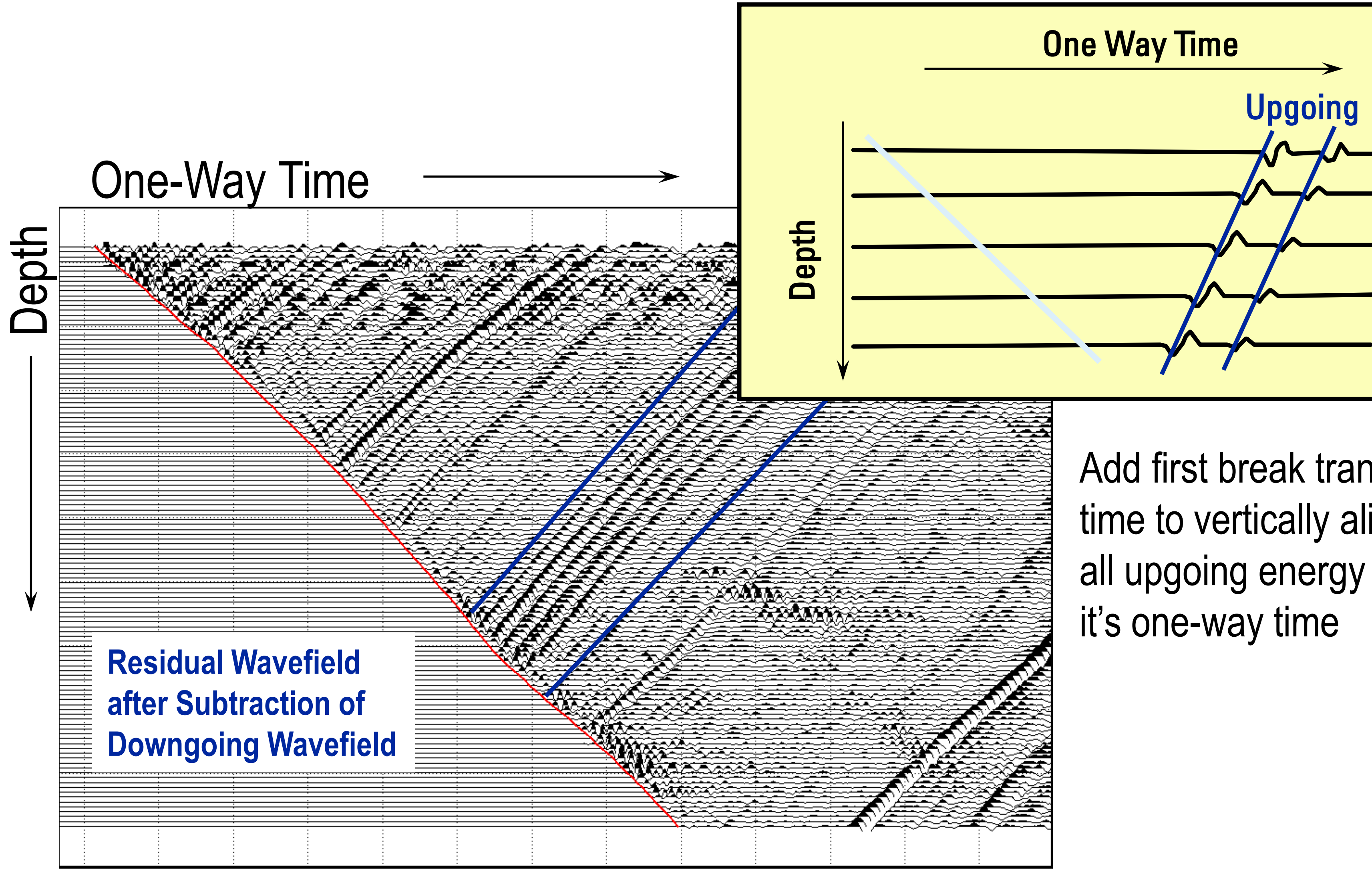
VSP Processing – Wavefield Separation



Estimation of Downgoing Energy

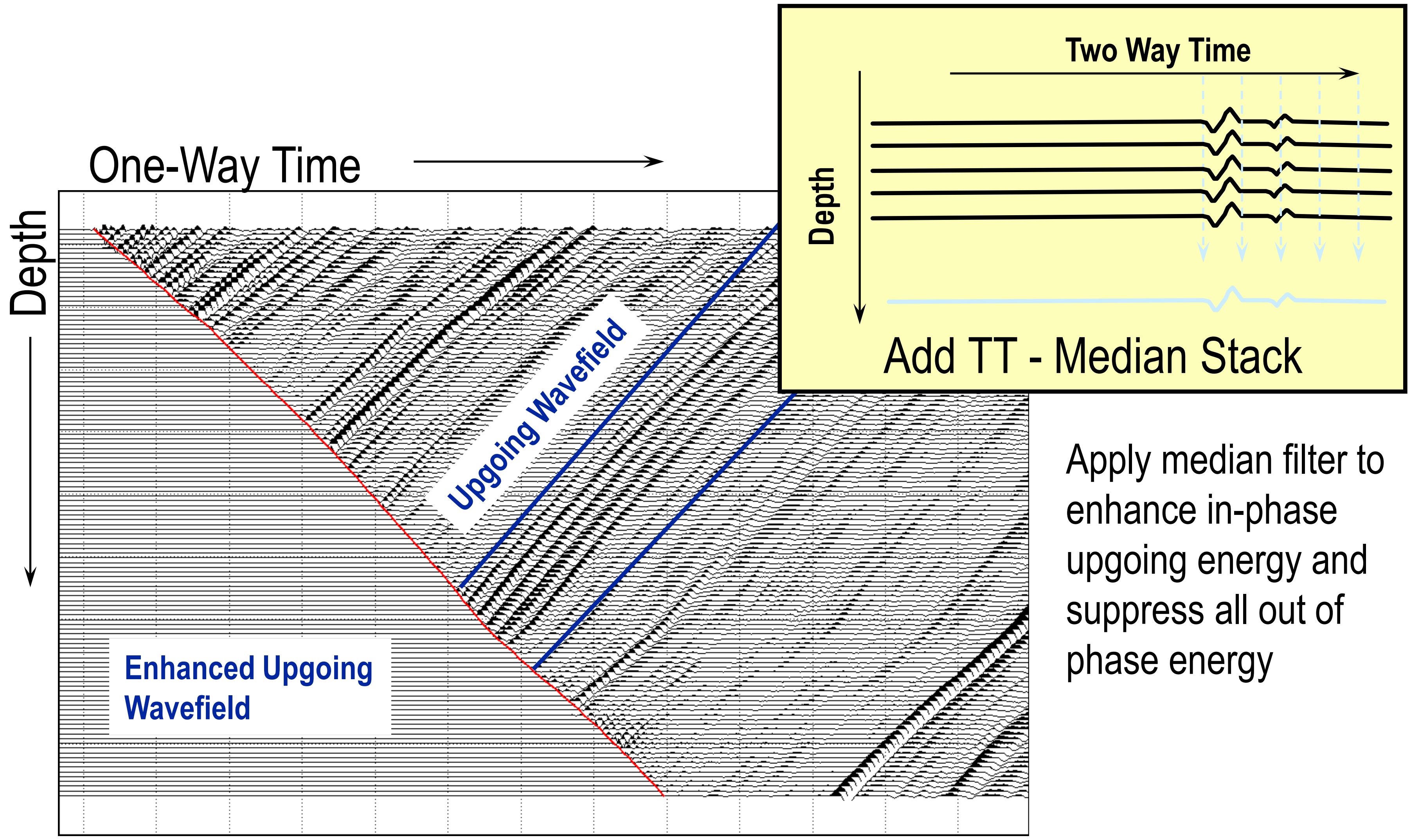


Enhance Upgoing Energy (1st Residual)



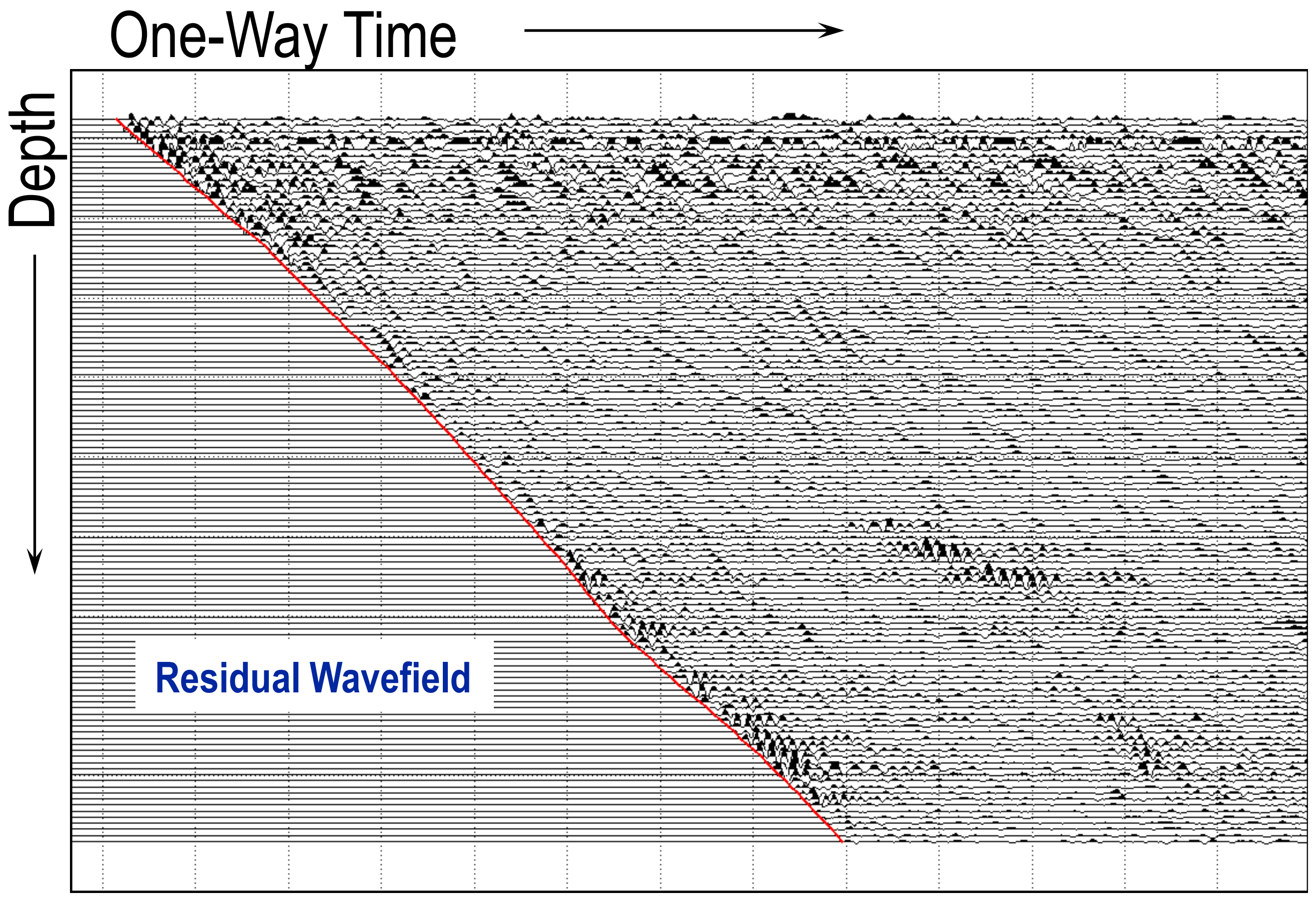
Add first break transit time to vertically align all upgoing energy at it's one-way time

Enhance Upgoing Energy



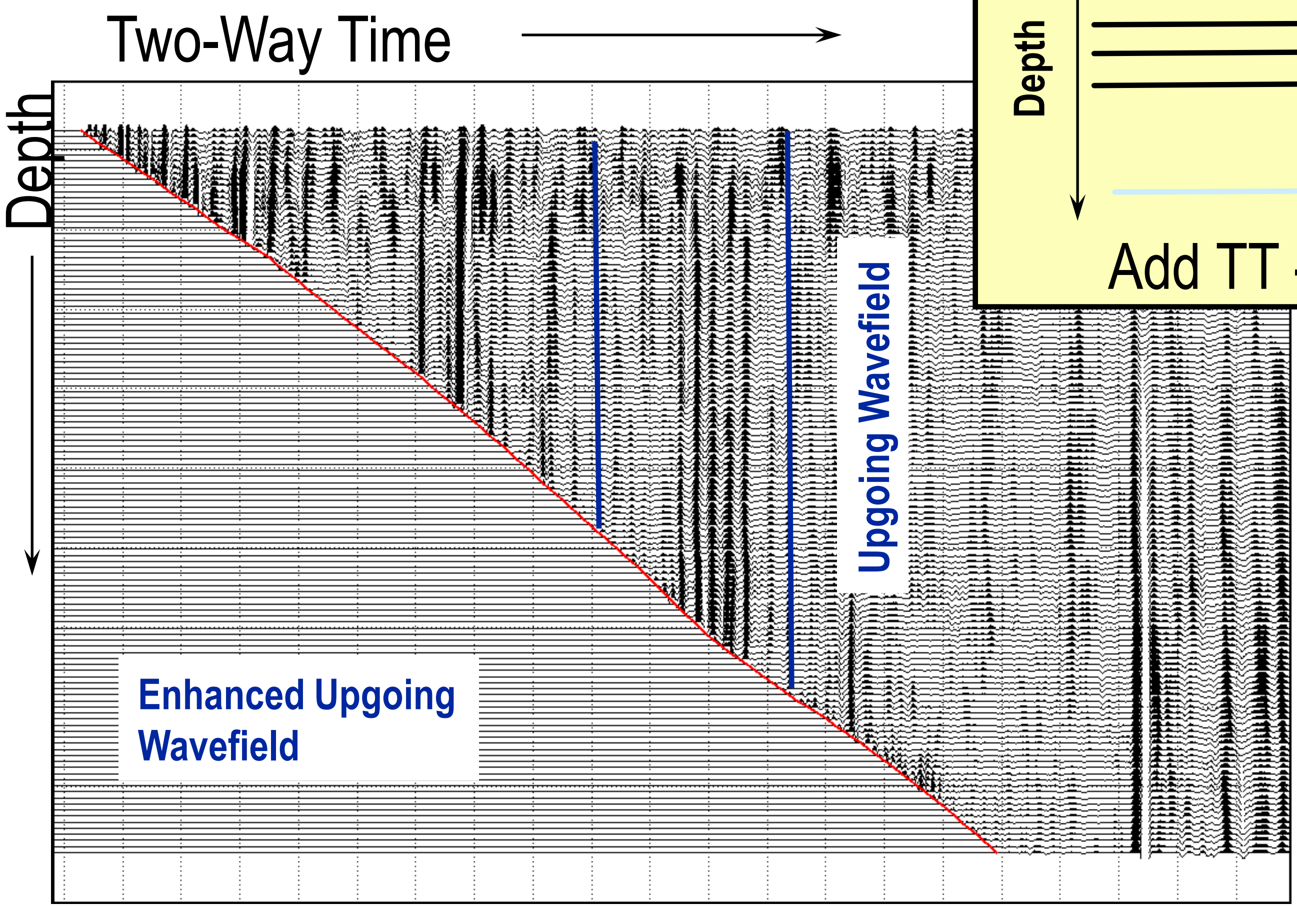
Apply median filter to enhance in-phase upgoing energy and suppress all out of phase energy

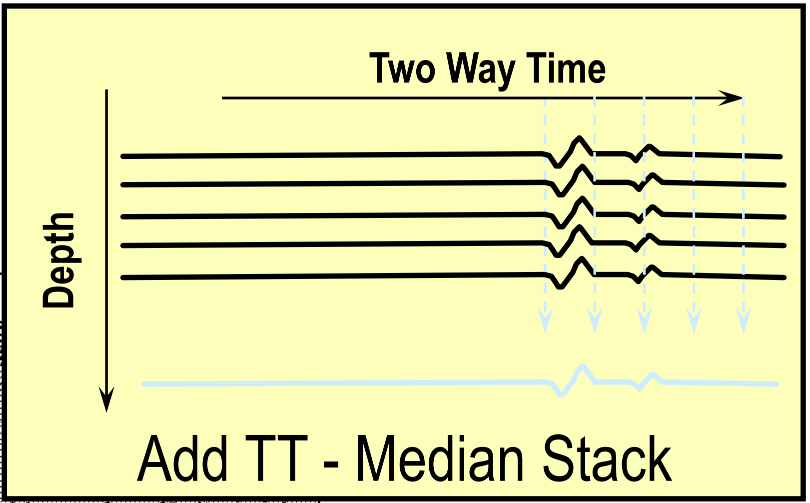
Enhance Upgoing Energy (2nd residual)



Residual wavefield contains : Random noise, events of out plane, shear waves, tube waves, etc.) – It is important to QC the residual to avoid taking relevant reflected signal when moveouts are complex.

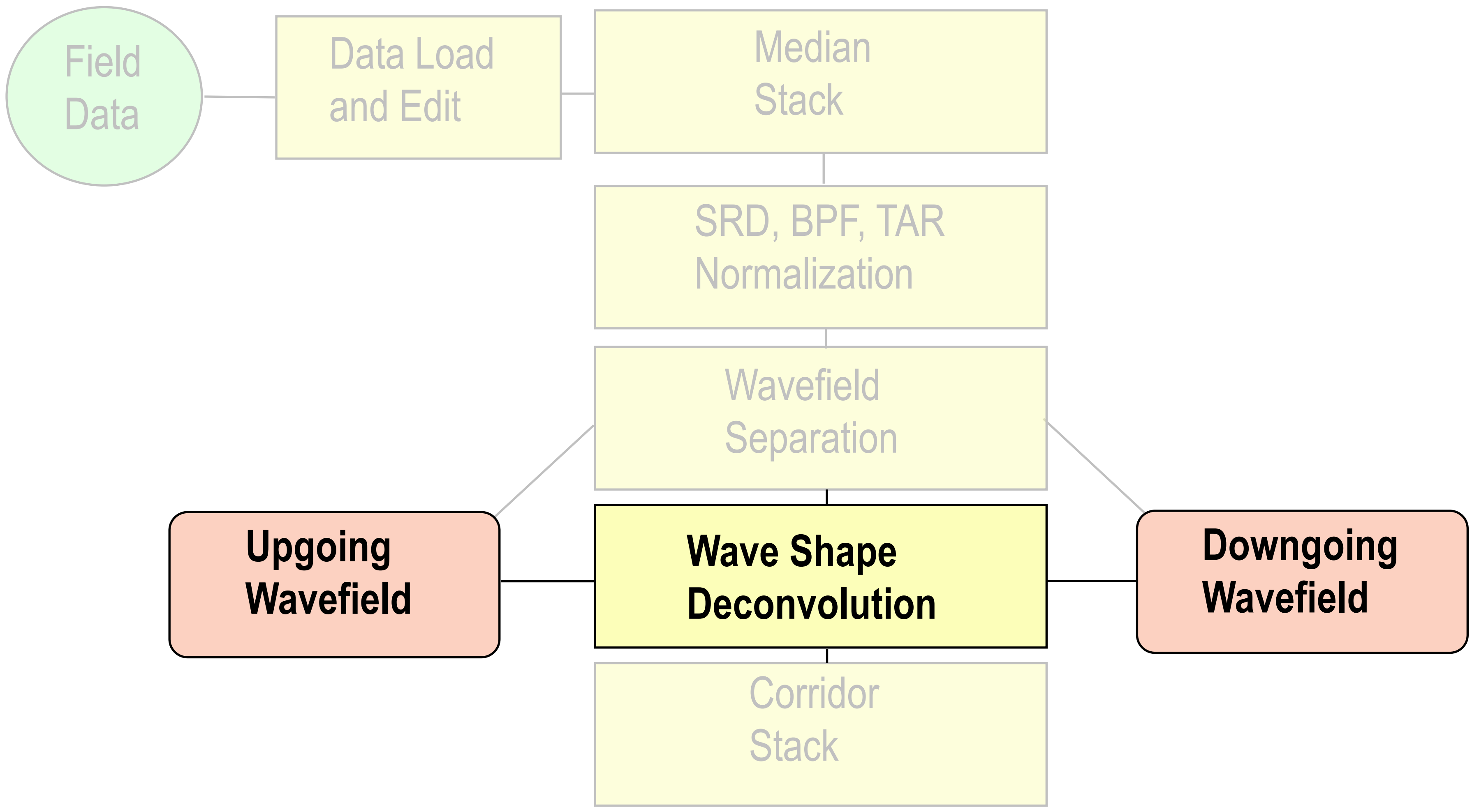
Enhance Upgoing Energy





Apply median filter to enhance in-phase upgoing energy and suppress all out of phase energy, add first break transit time to vertically align all upgoing energy at it's two-way time.

VSP Processing - Deconvolution

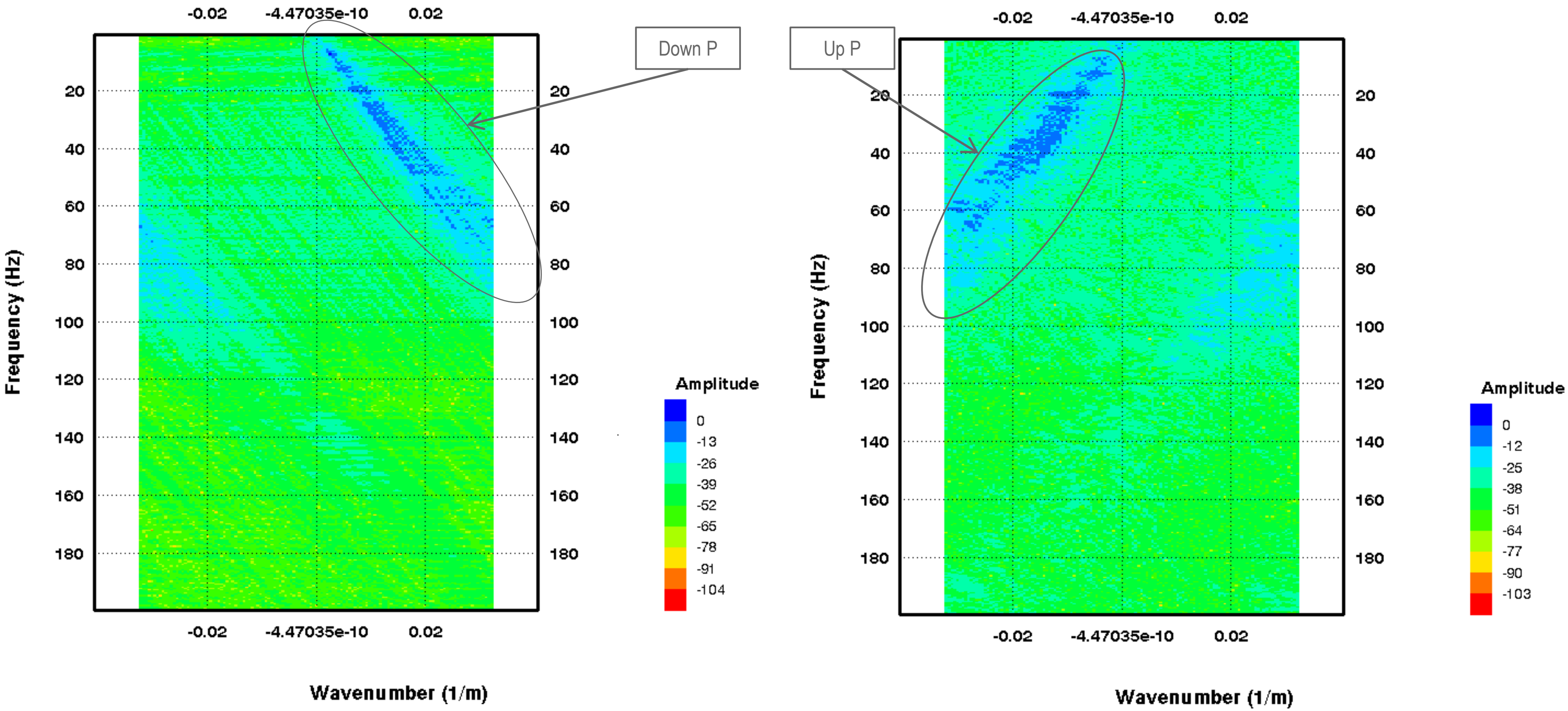


Deconvolution

The function of deconvolution is to precisely improve the resolution capabilities of the upgoing wavetrain:
It removes the near surface multiples & the bubble effects
It optimizes the resolution characteristics of the source signature

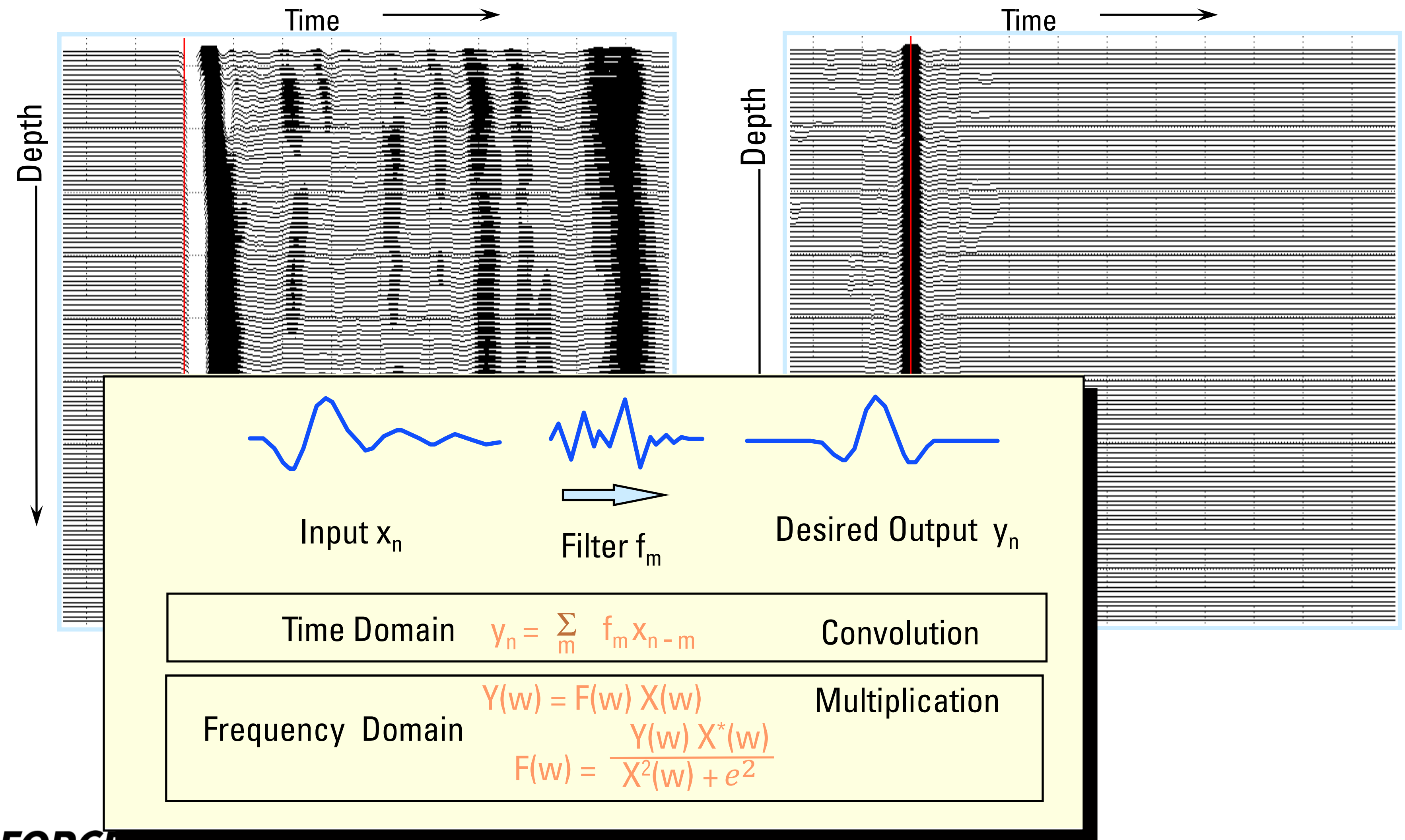
Deconvolution filters are computed on the downgoing wavetrain and applied to both the downgoing and upgoing waves

Wavefield Spectral Analysis

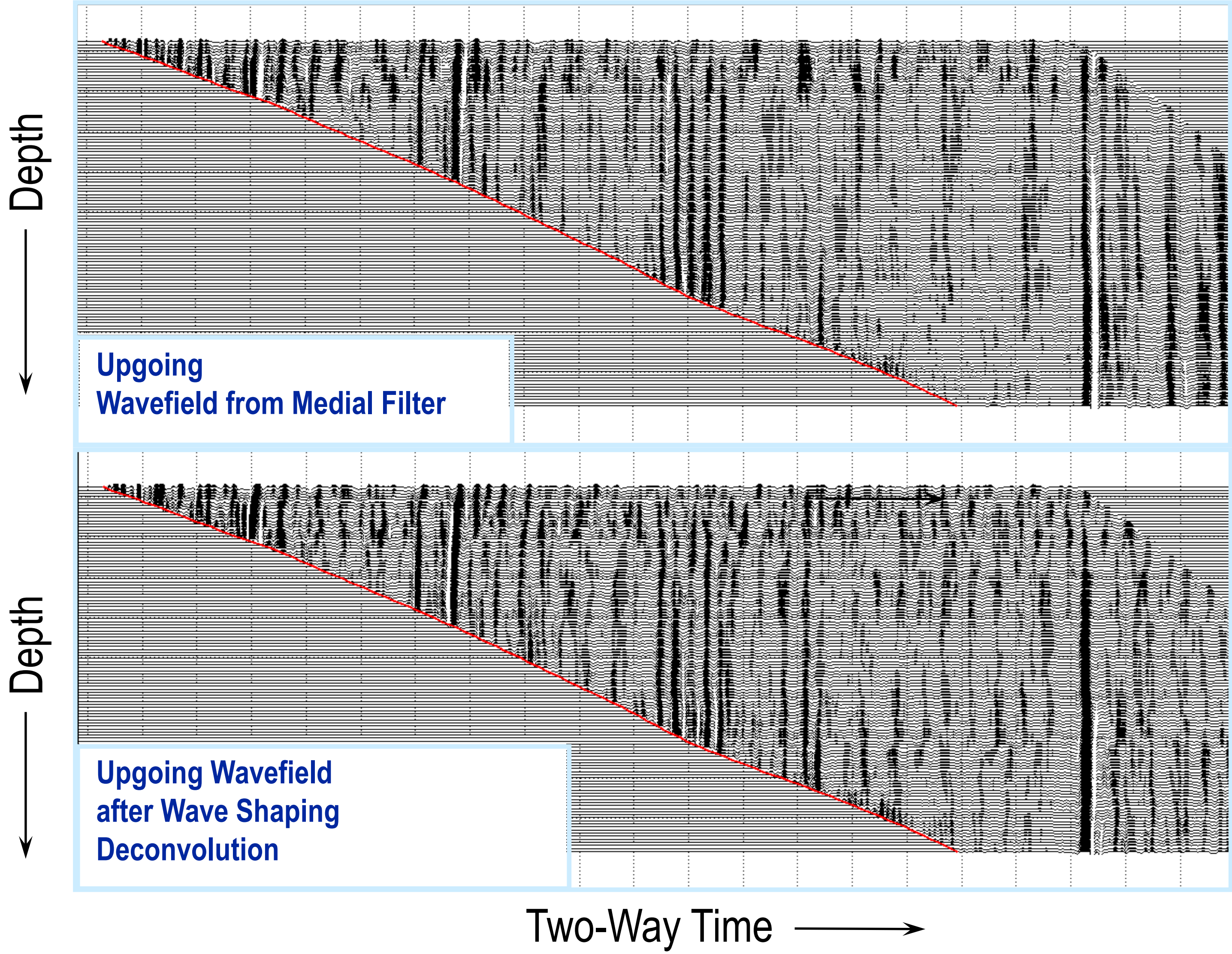


The FK spectra for the downgoing P and upgoing P wavefields both shows that the separation has been done properly. The maximum frequency bandwidth used for waveshaping deconvolution will be 5-120Hz but the corridor stack will also be delivered with lower frequency bandwidths.

Wave Shaping Deconvolution on downgoing wavefield



Wave Shaping Deconvolution on upgoing wavefield



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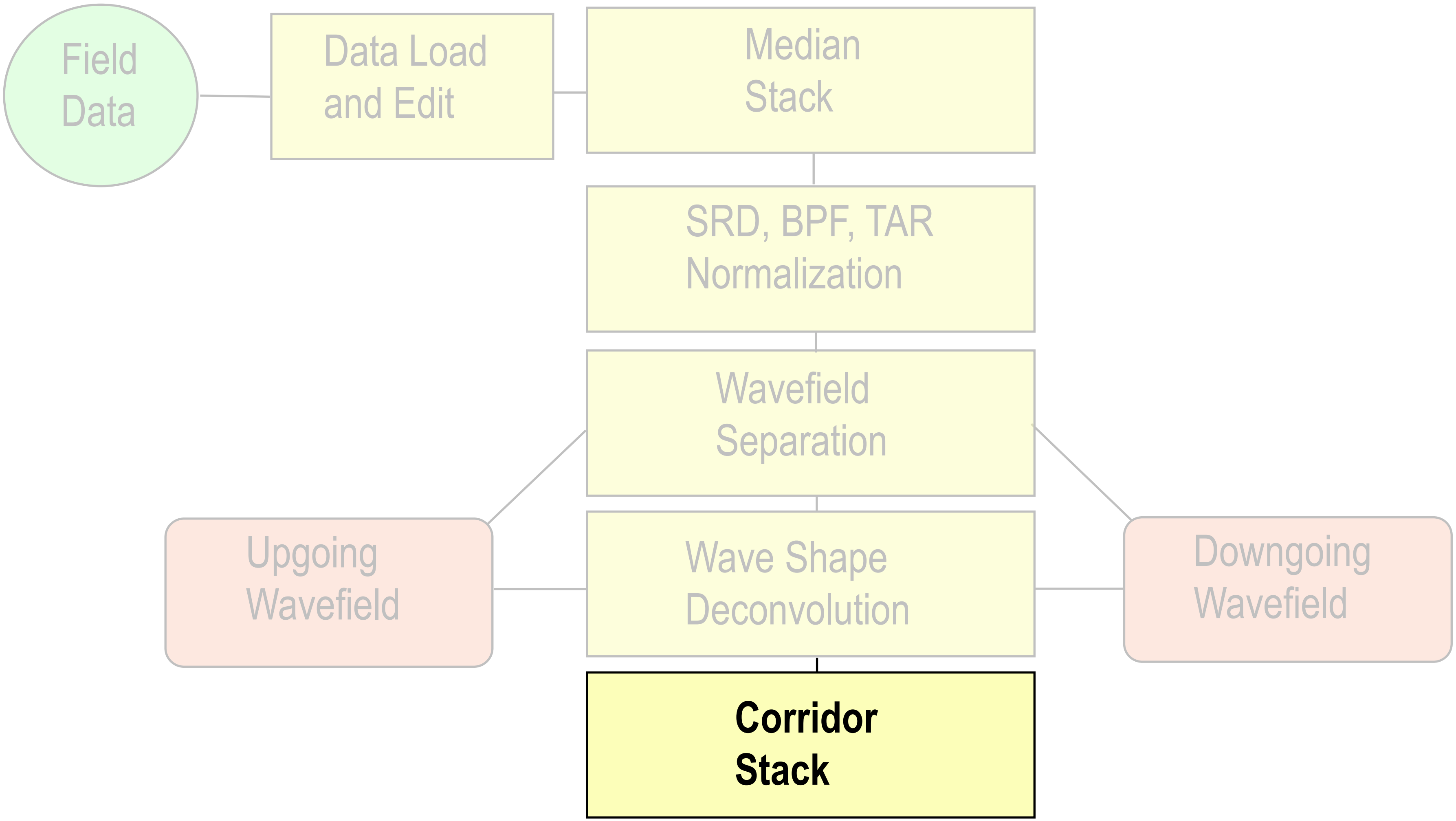
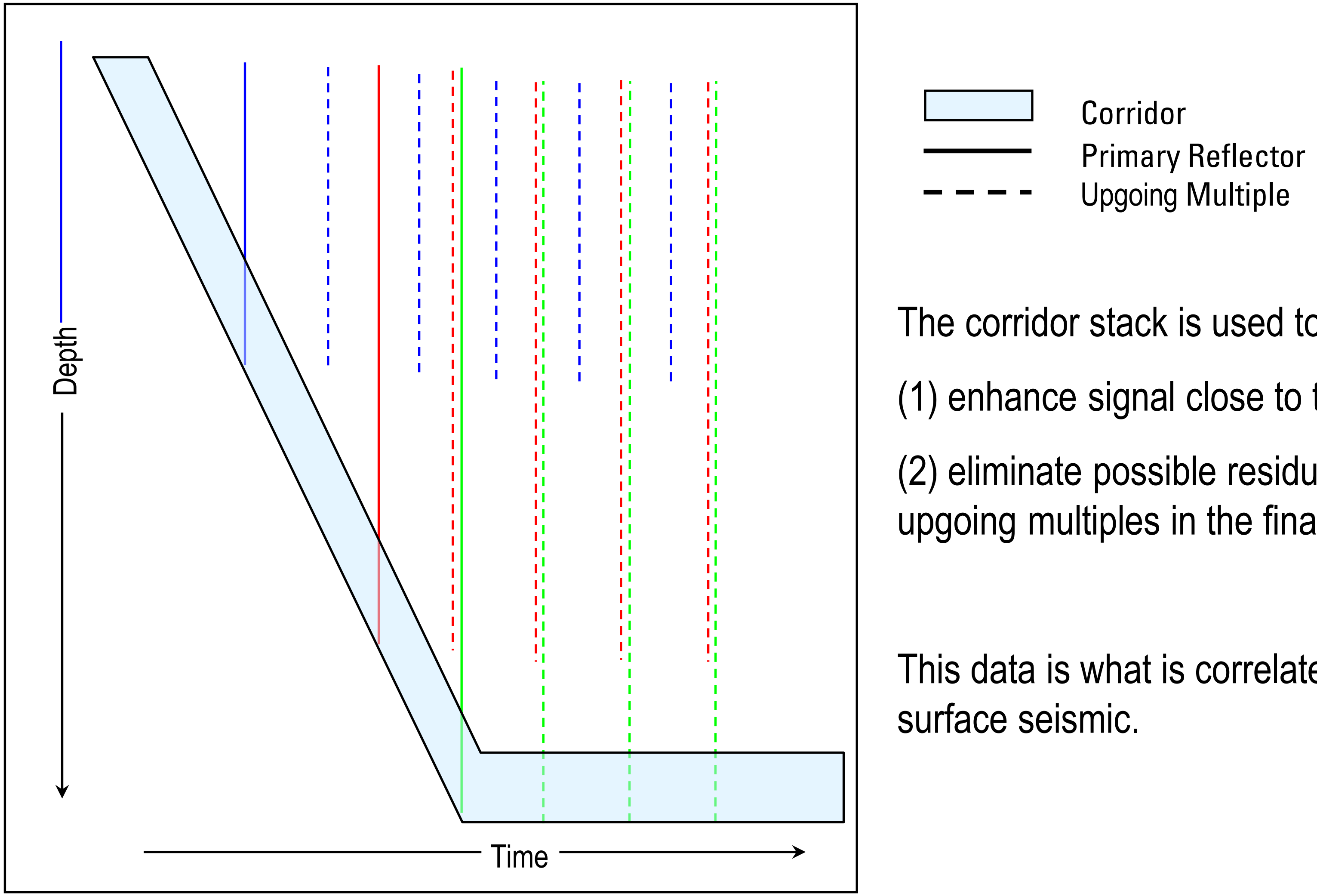
Fundamentals of Borehole Seismic Technology *(Kelsall, Rufino & Guerra, 2022)*

VSP Processing – Corridor Stack



Corridor Stack



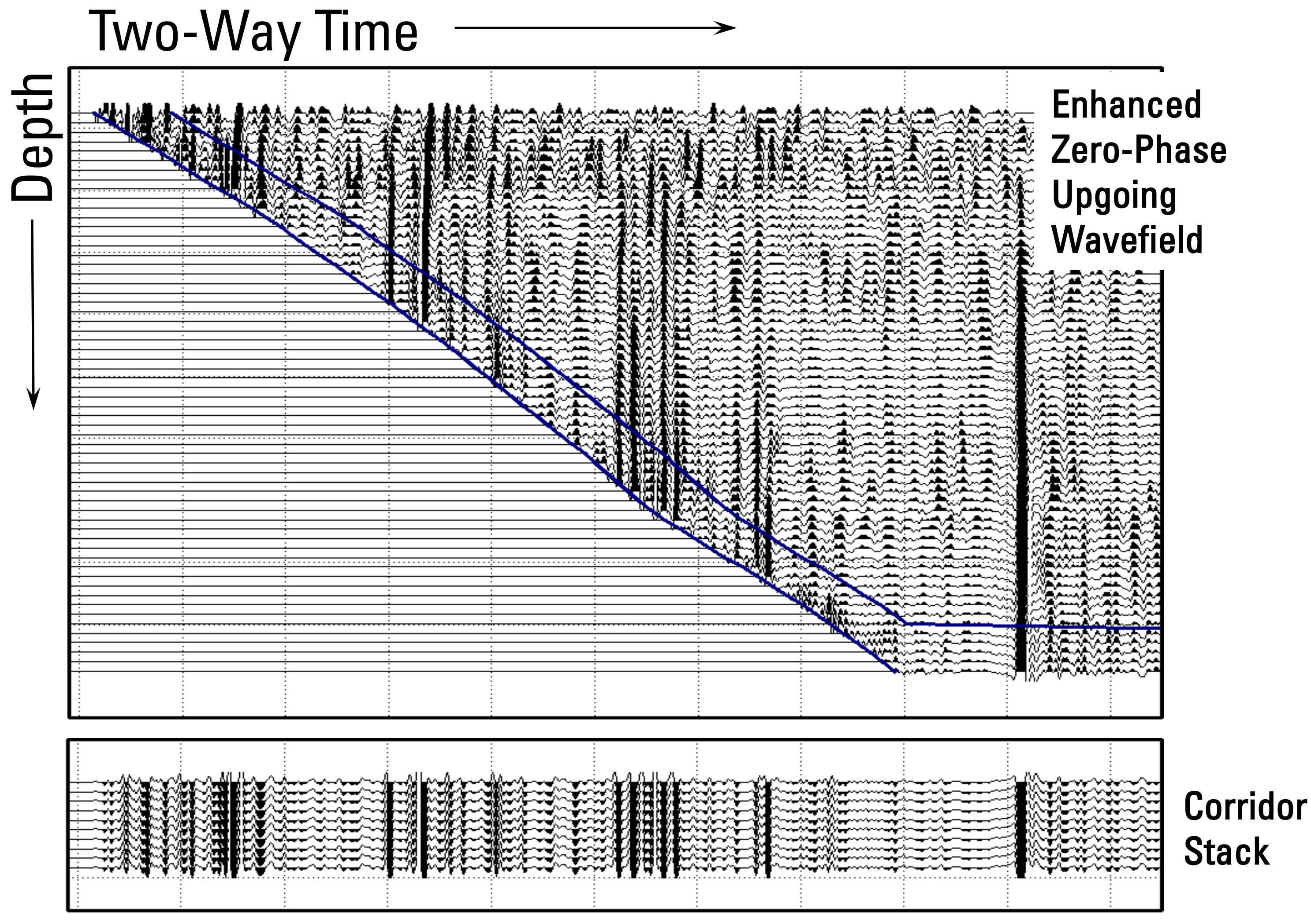
The corridor stack is used to:

(1) enhance signal close to the well

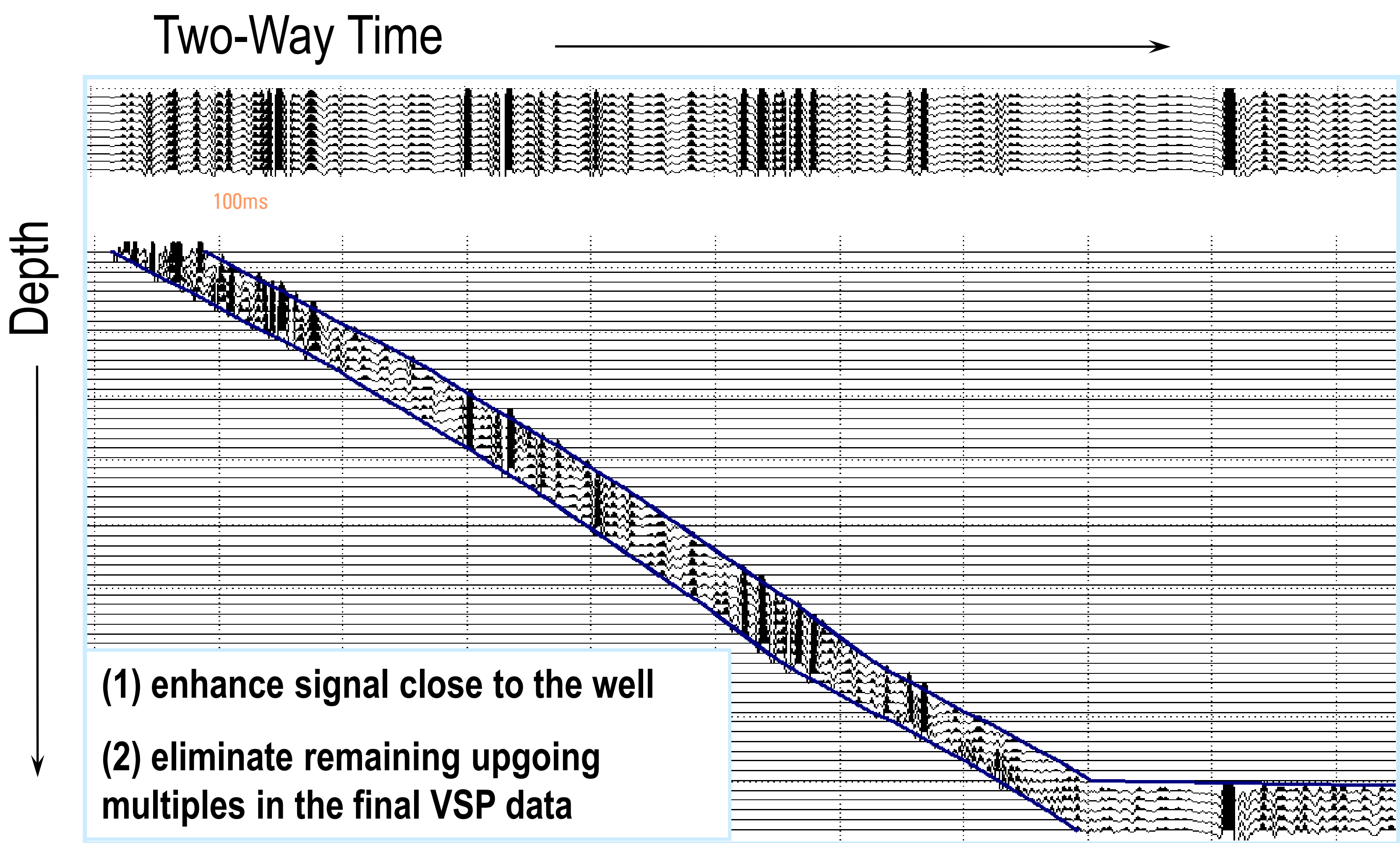
(2) eliminate possible residual weak upgoing multiples in the final VSP data

This data is what is correlated to the surface seismic.

Corridor Stack



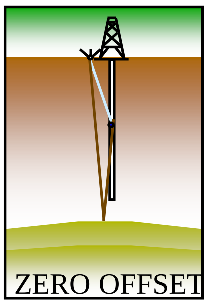
Corridor Stack

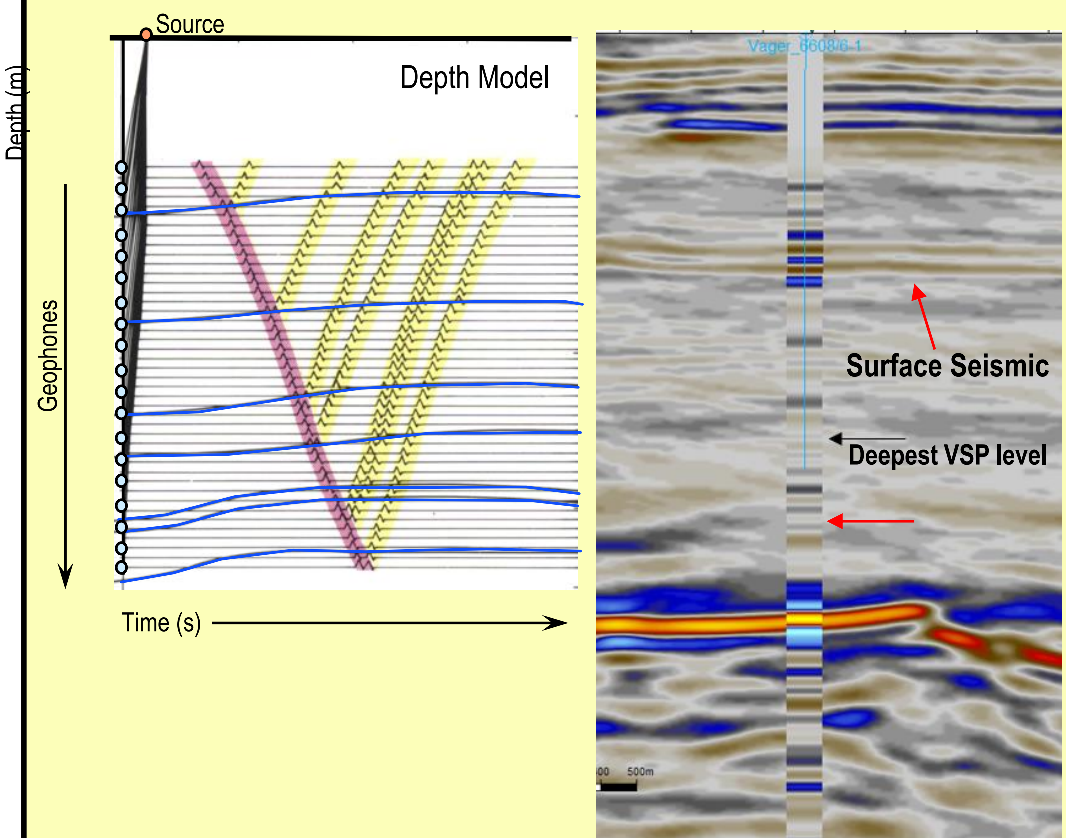


(1) enhance signal close to the well

(2) eliminate remaining upgoing multiples in the final VSP data

VSP Applications





Surface Seismic Correlation

Wavelet Processing

Formation Velocities

Quantitative phase analysis - seismic

Q Factor Estimation

Multiple Pattern Identification

Look Ahead

High Resolution VSP

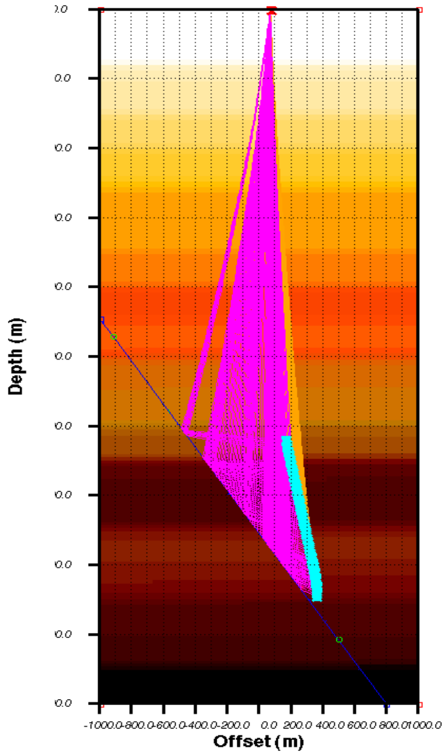
Out of Plane

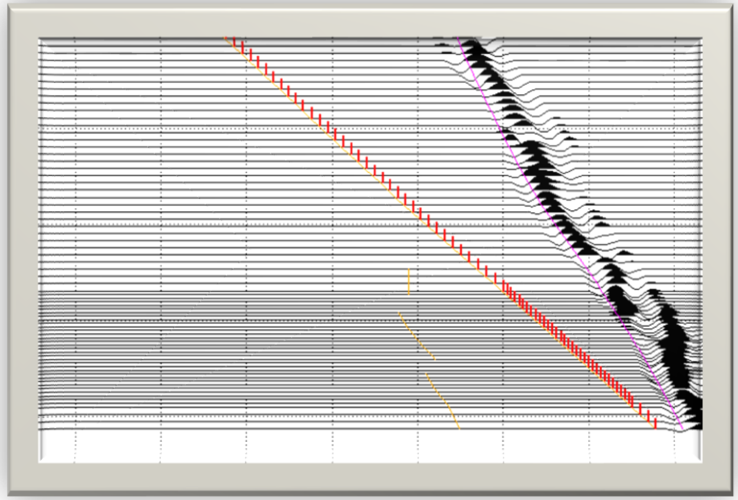
Shear Waves

Walkaway VSP

I know it was too long….

Questions, Comments

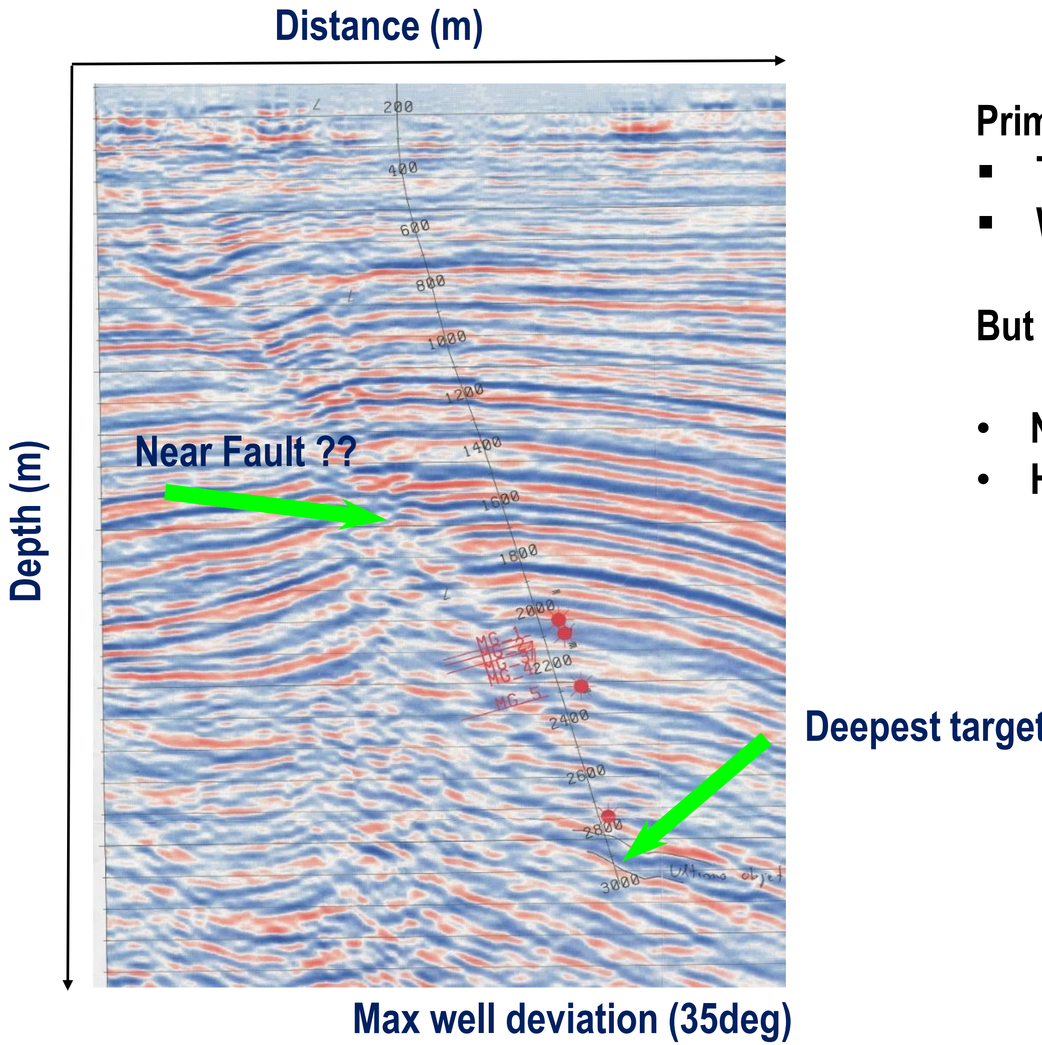




VSP Events out of Plane

Stavanger, 04-Oct-2022

Vertical Incidence VSP



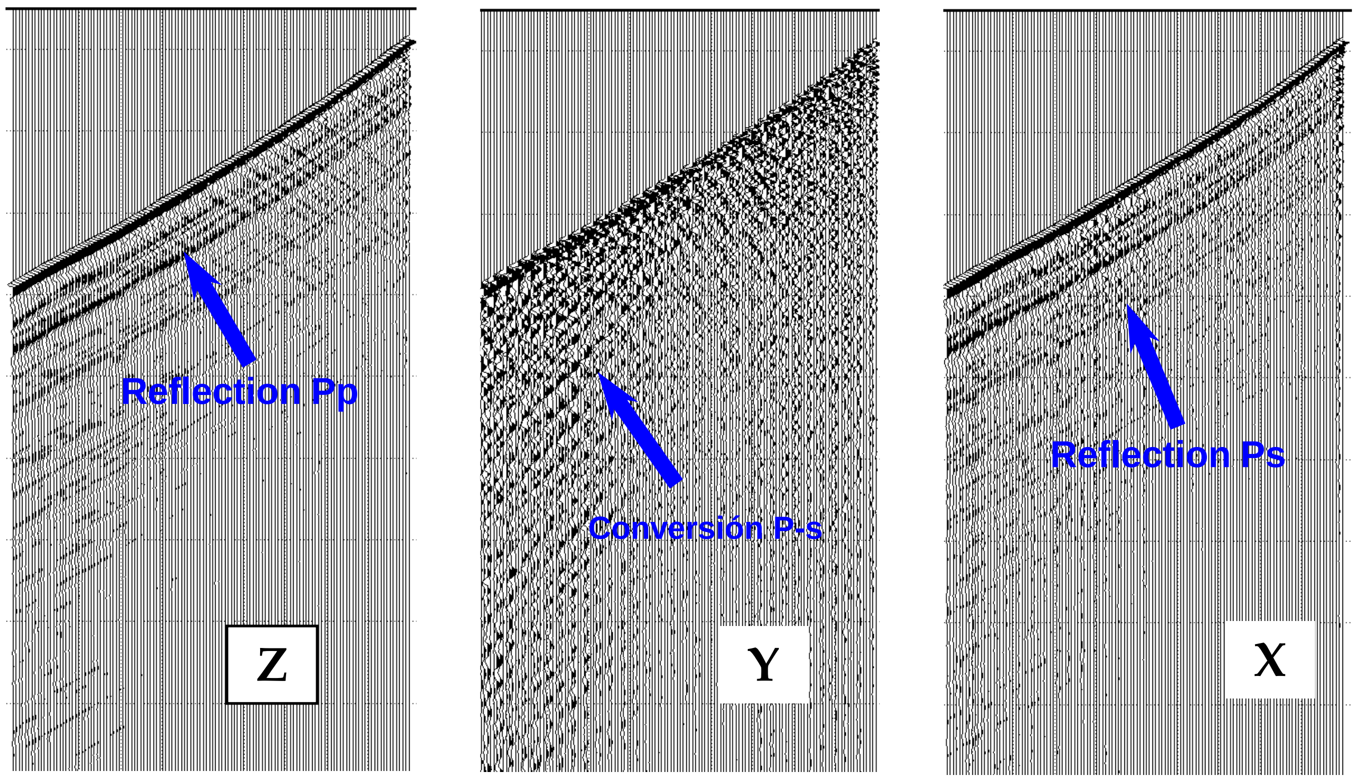
Primary objectives:

- T-Z Function
- Well Tie

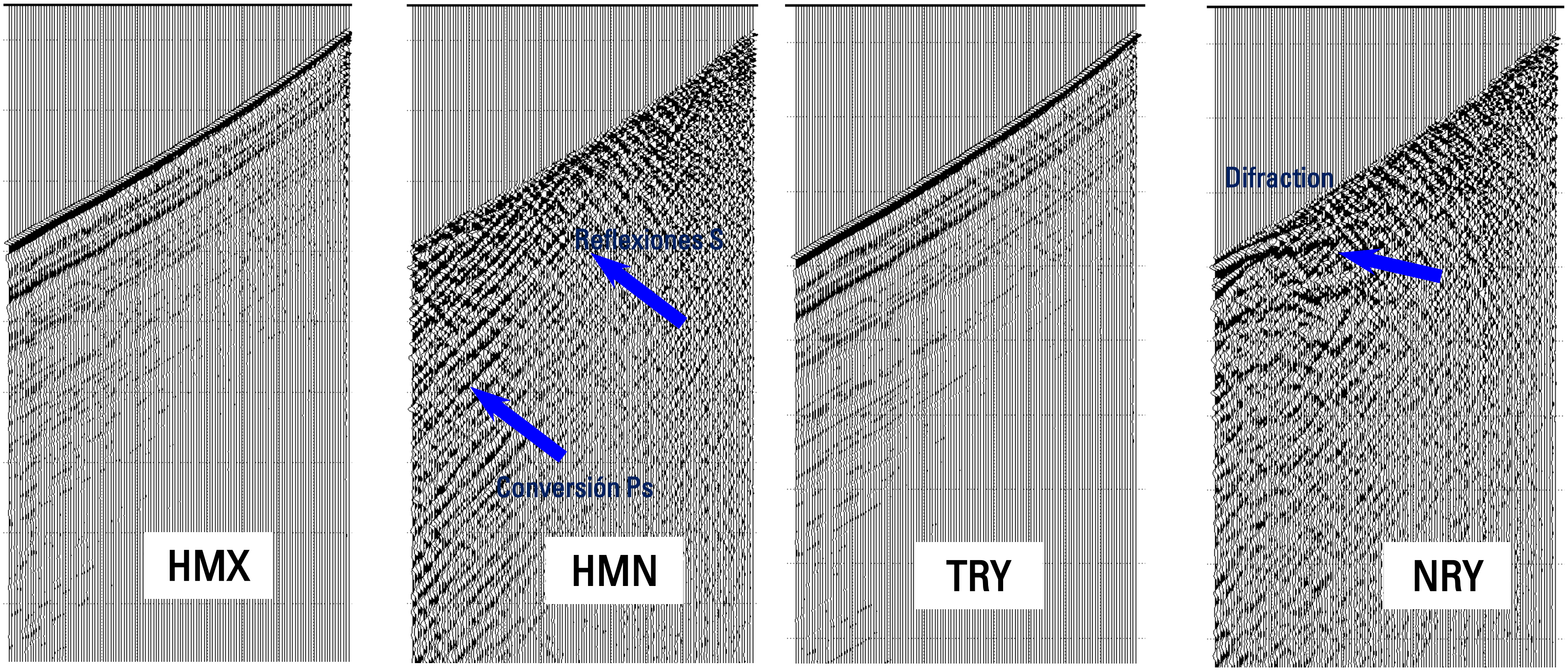
But …

- Near to the fault?
- Hit target?

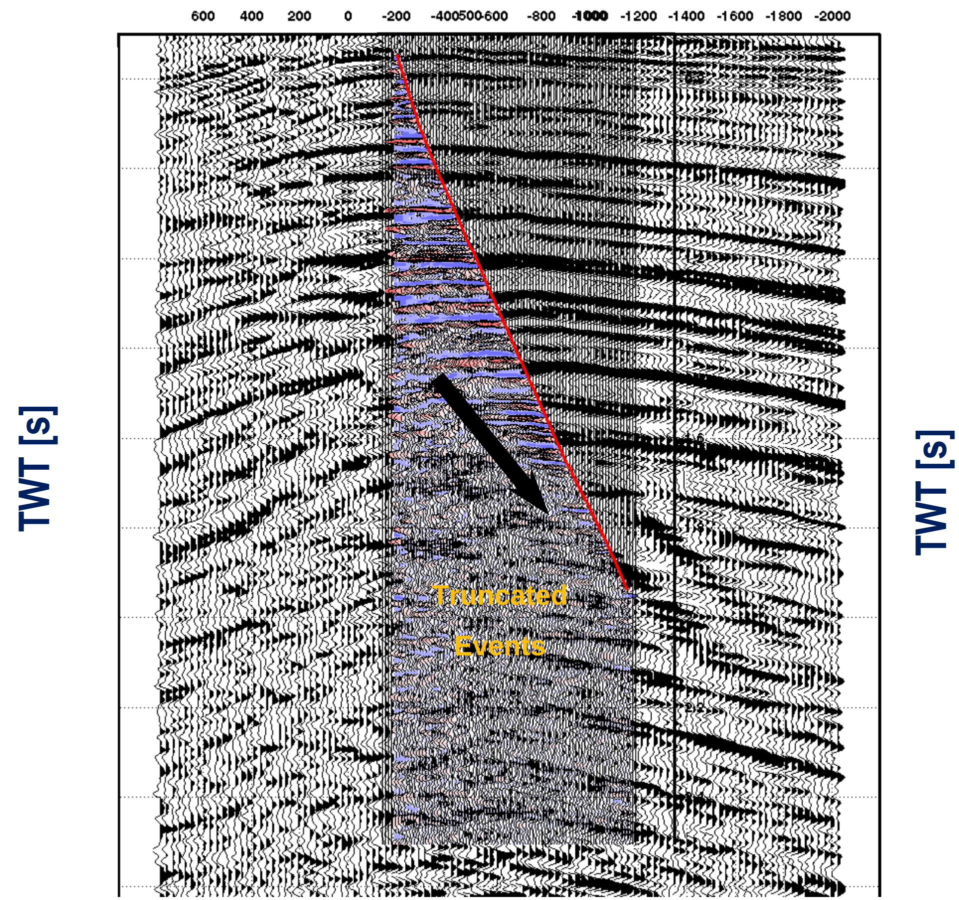
VIVSP Raw Data



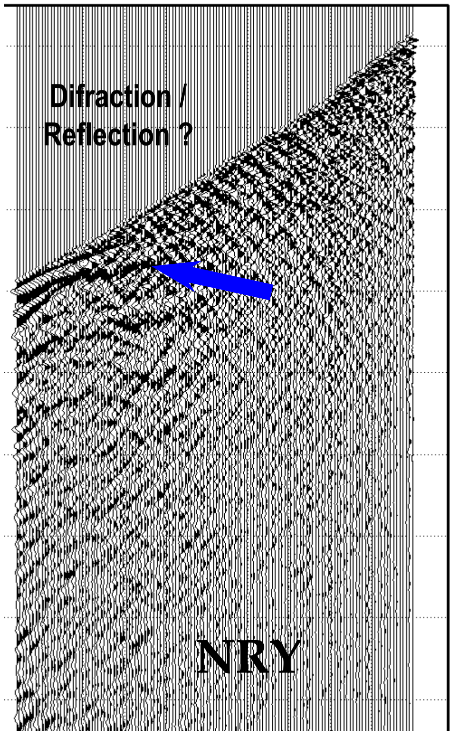
VIVSP Rotated Data

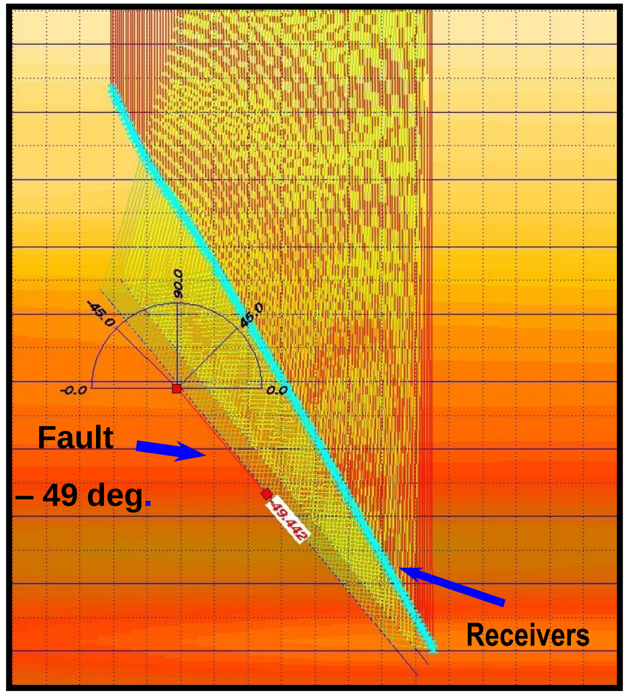


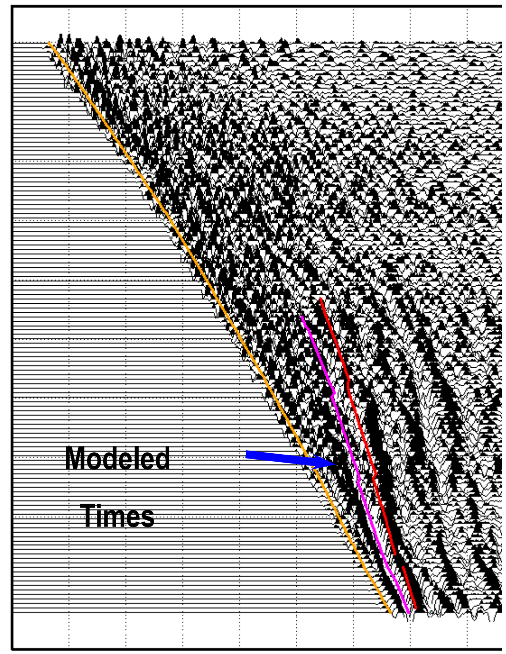
VIVSP Migrated Image and Surface Seismic



VIVSP, NRY Component Analyses





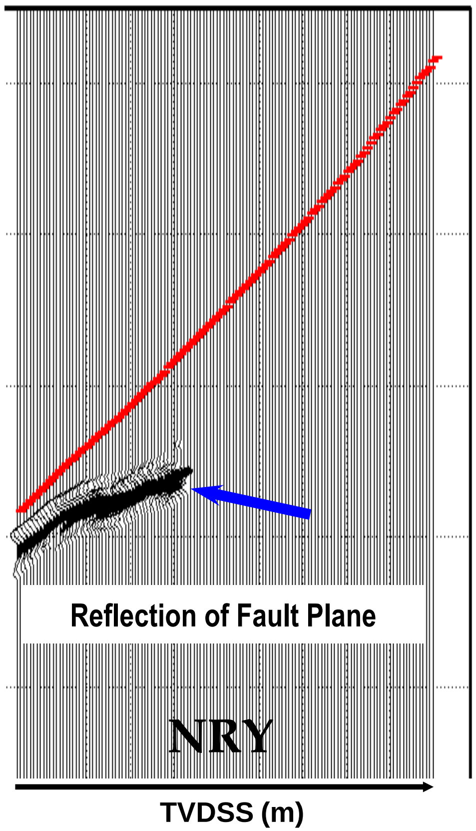


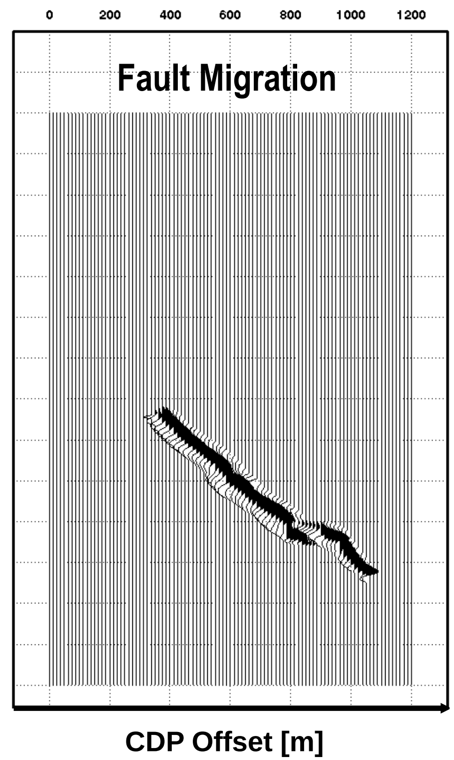
Diffraction produced by fault?

Faults added to velocity model to match VIVSP events moveout

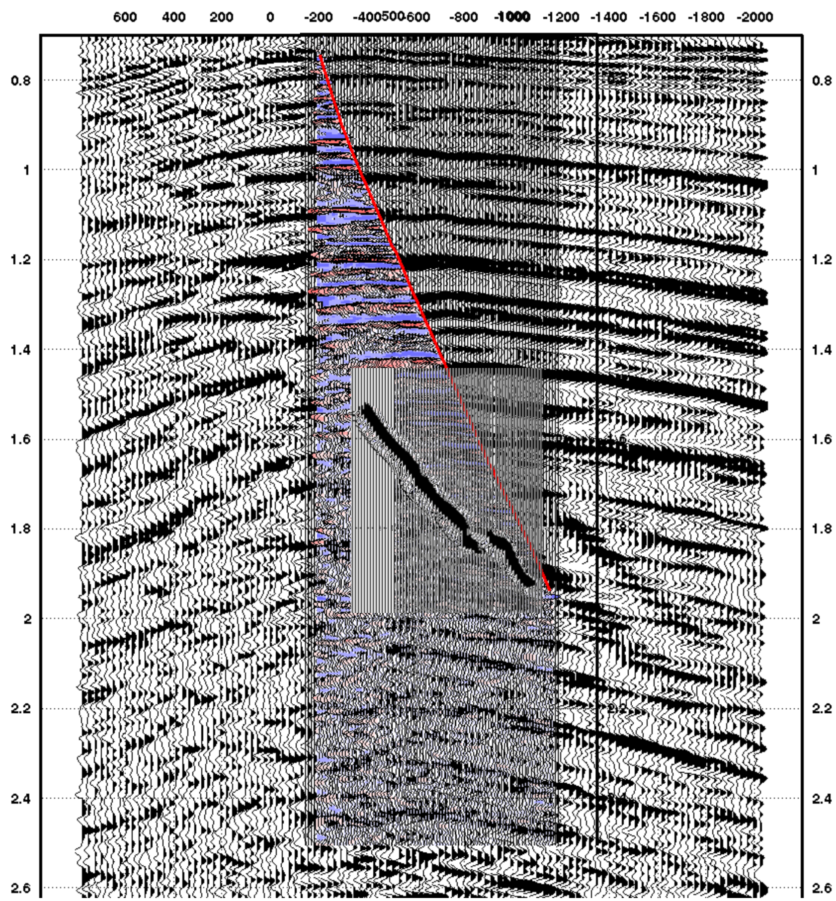
- → **Process the event**
- → **Calibrate model**
- → **Depth/Time migration**

Produced Image After Event Isolation and Deconvolution



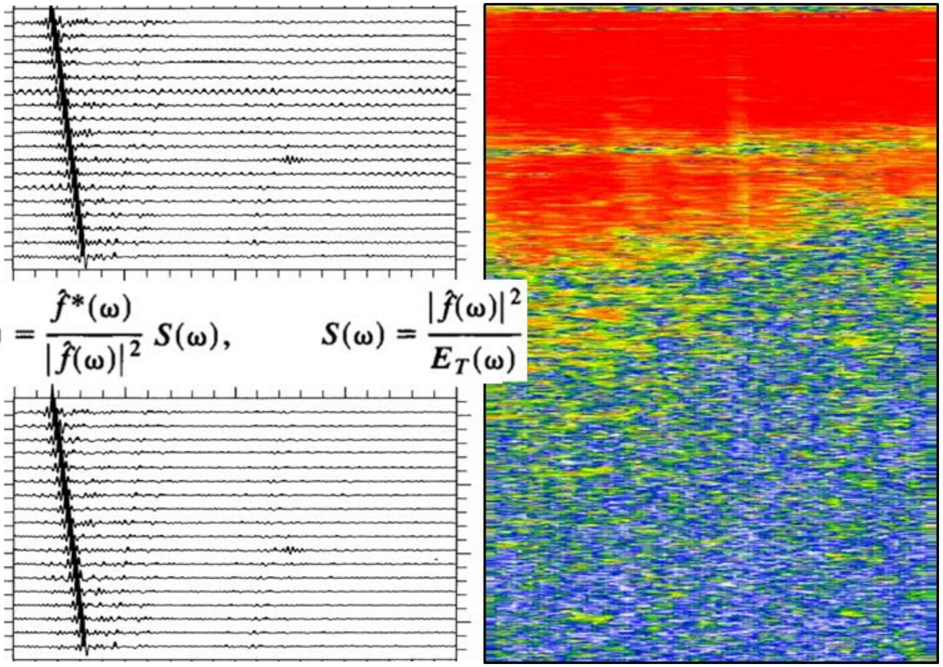


VIVSP Images



Benefits

- **High Resolution VIVSP Image to identify targets**
- **Fault Confirmation**



$$F(\omega) = \frac{\hat{f}^*(\omega)}{|\hat{f}(\omega)|^2} S(\omega), \qquad S(\omega) = \frac{|\hat{f}(\omega)|^2}{E_T(\omega)}$$

Enhancing VSP resolution

Stavanger, 04-Oct-2022

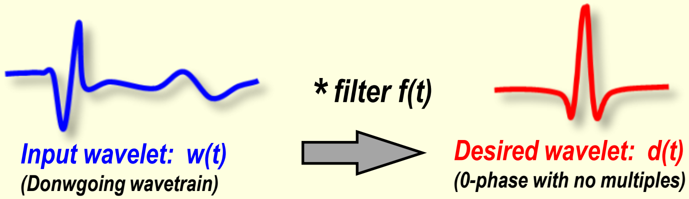
Motivation for ZVSP Semblance Deconvolution

(Haldorsen et al., 1994)

- **ZVSPs are supposed to have higher resolution compared to surface seismic, however broadband and shallow high-resolution seismic surveys often challenge that**
- **Standard VSP processing often uses fixed bandwidth deterministic VSP deconvolution, adjusting limits at the deep target zone, thus throwing away data in shallower intervals**
- **Semblance Weighted Deconvolution allows outputting maximum bandwidth zero-phase time variant corridor stacks, like surface seismic data**
- **The maximum bandwidth is estimated "automatically" based on semblance**
- **Semblance Weighted Deconvolution allows ZVSP to match or surpass very high-resolution surface seismic surveys everywhere *(except possibly over very low frequencies due to limitations of the VSP seismic source***

Semblance Weighted Deconvolution

Summary of Waveshaping Deconvolution in the Frequency Domain



*s(t) = w(t)*r(t) + n(t)* : *Convolutional model with noise*

S(f) = W(f) R(f) + N(f) : *Multiplication in Frequency Domain*

F(f) = 1 / W(f) : *Simple inverse filter, blows up noise!*

F(f) = W / (|W²| + e²)* : *Wiener filter with white noise e added*

F(f) = D W / (|W²| + e²)* : *Wave-shaping Wiener filter*

The result of applying the last filter to the input data is:

- *Band-limited reflectivity:* *D(f)*R(f) ~ F(f)*S(f)*
- *Desired time wavelet:* *d(t) * r(t) ~ f(t)*s(t)*

Haldorsen, J., Miller, D. and Walsh, J. [1994] Multichannel Wiener deconvolution of vertical seismic profiles. Geophysics 59

$$\hat{f}(\omega) = \frac{1}{N} \sum_{n=1}^{N} s_n(\omega) e^{-i\omega t_n}. \qquad (5)$$

$$F(\omega) = \frac{\hat{f}^*(\omega)}{E_T(\omega)}, \qquad E_T(\omega) = \frac{1}{N} \sum_{n=1}^{N} |s_n(\omega)|^2.$$

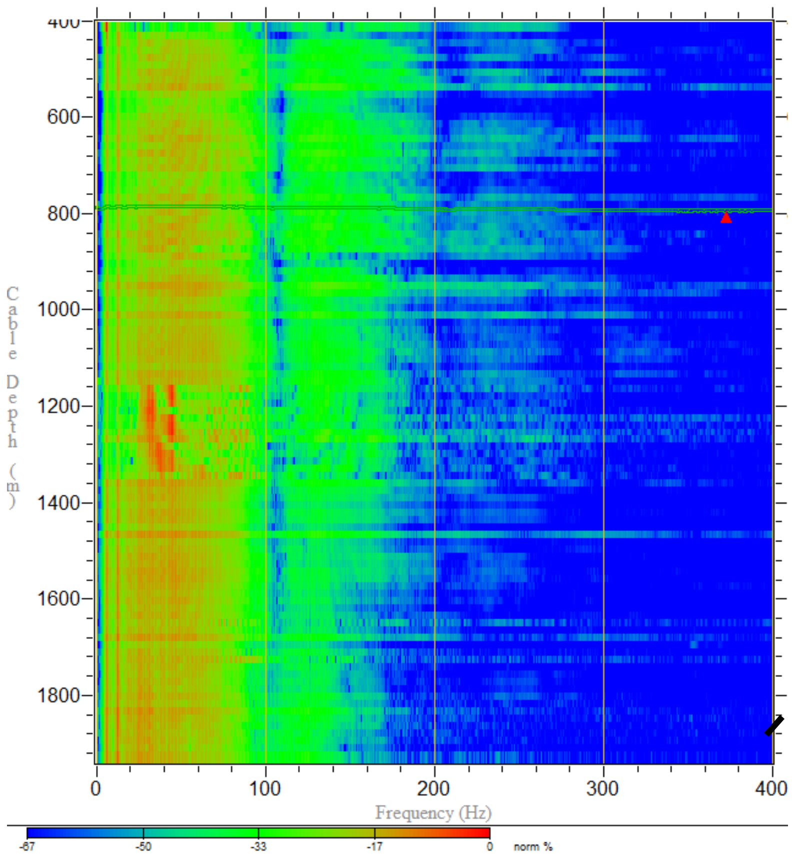
$$F(\omega) = \frac{\hat{f}^*(\omega)}{|\hat{f}(\omega)|^2} S(\omega), \qquad S(\omega) = \frac{|\hat{f}(\omega)|^2}{E_T(\omega)}$$

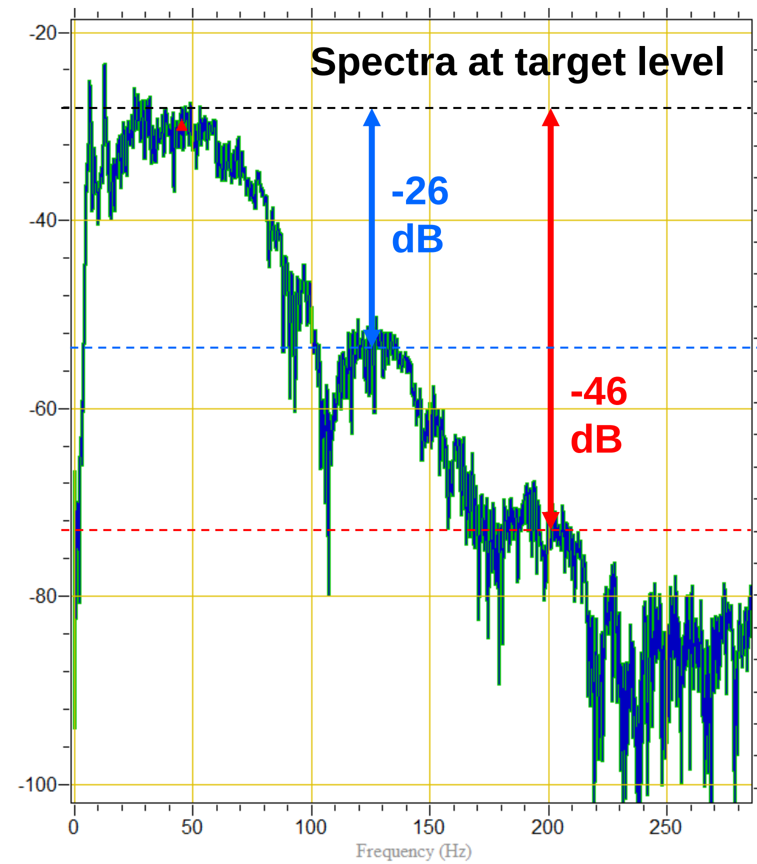
→ **In Semblance Weighted decon there is no white noise**

→ **The average downgoing signal is weighted at each frequency by the semblance across the receiver array**

→ **These Semblance Weighted decon filter attain two conflicting objectives of adaptively spiking the direct arrivals and of minimizing the incoherent noise**

Possible trap with Z-stacks spectra

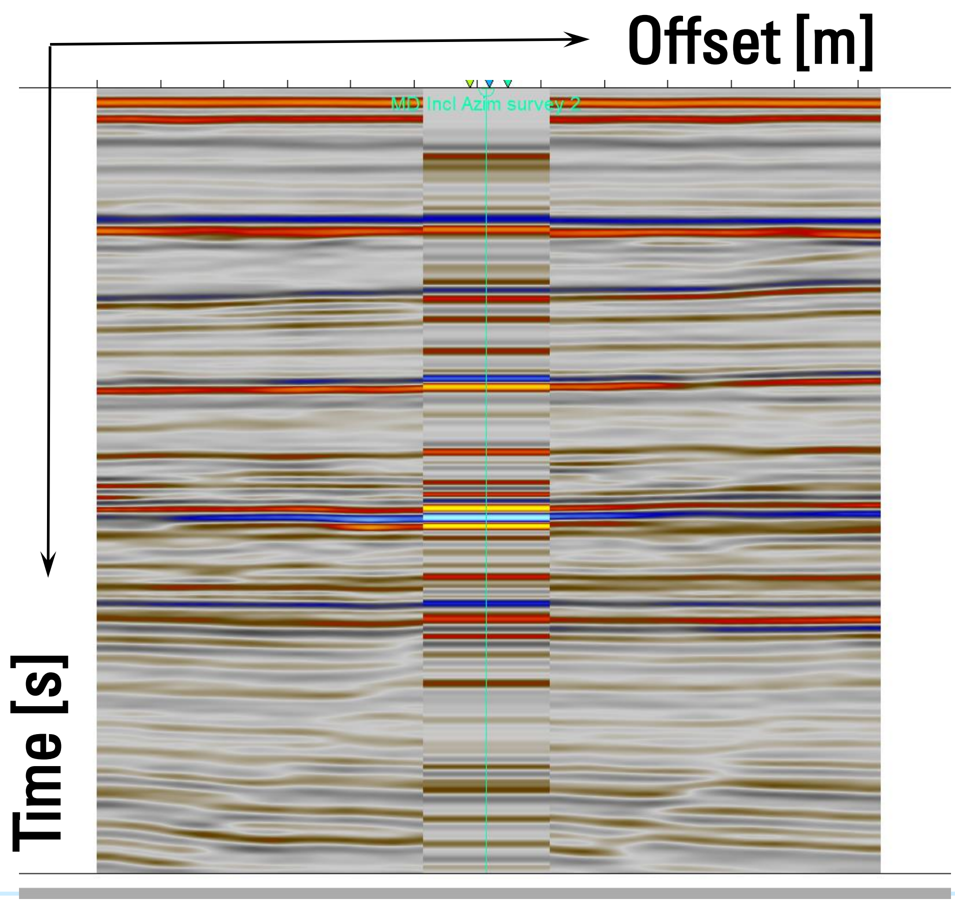




Well Tie – Standard Corridor Stack (5-95Hz) and Surface Seismic

Surface Seismic XLINE
+2ms shift to seismic to tie corridor stack

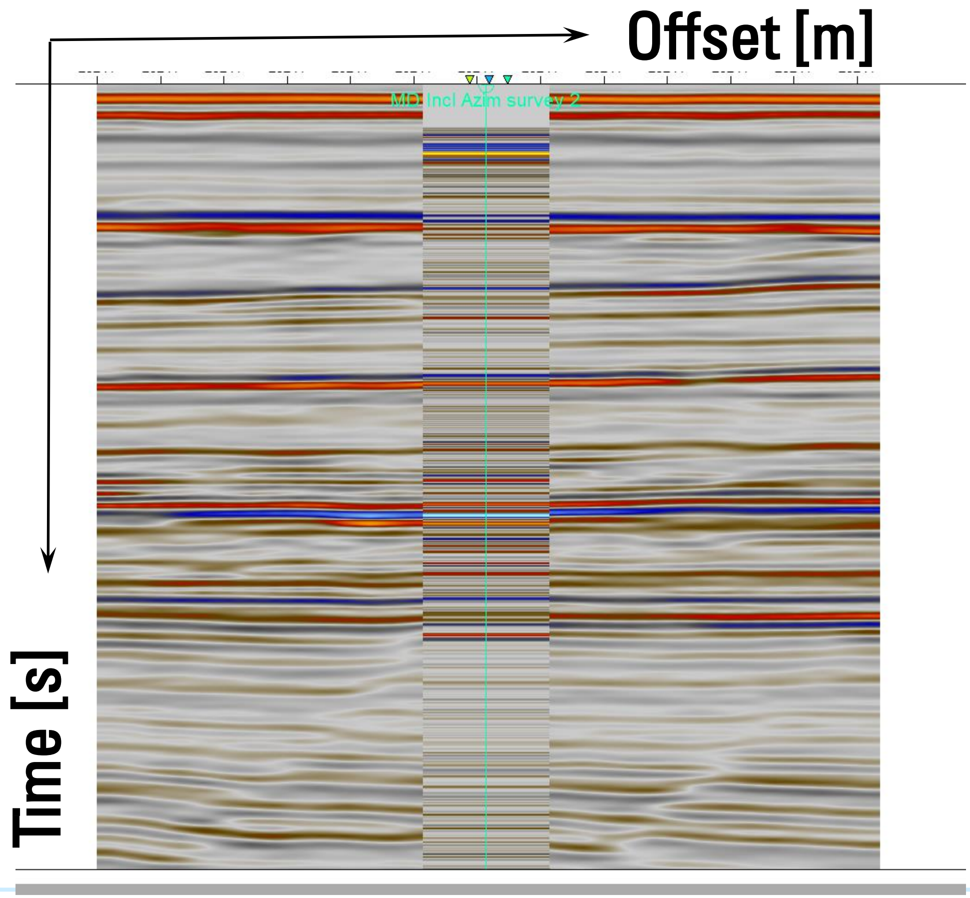
Standard Corridor Stack
and Standard Res Seismic



Well Tie – Semblance Decon Corridor Stack and Surface Seismic

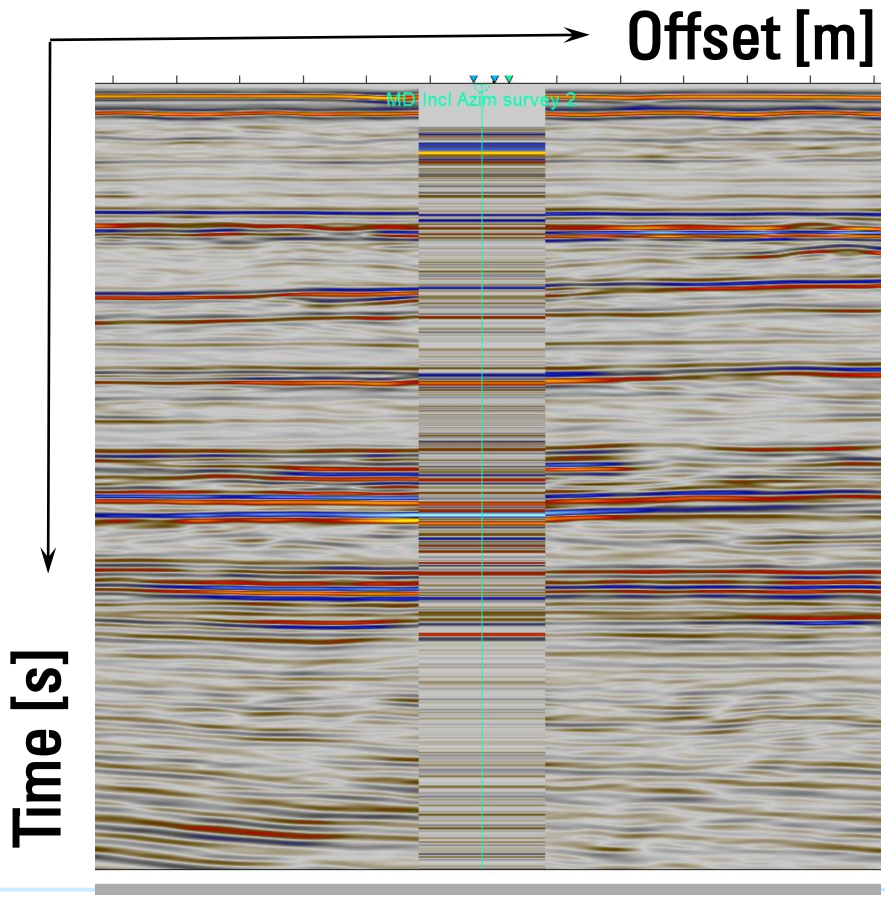
Surface Seismic XLINE
+2ms shift to seismic to tie corridor stack

Corridor Stack up to 220Hz



Well Tie – Semblance Decon Corridor Stack and High-Resolution Surface Seismic

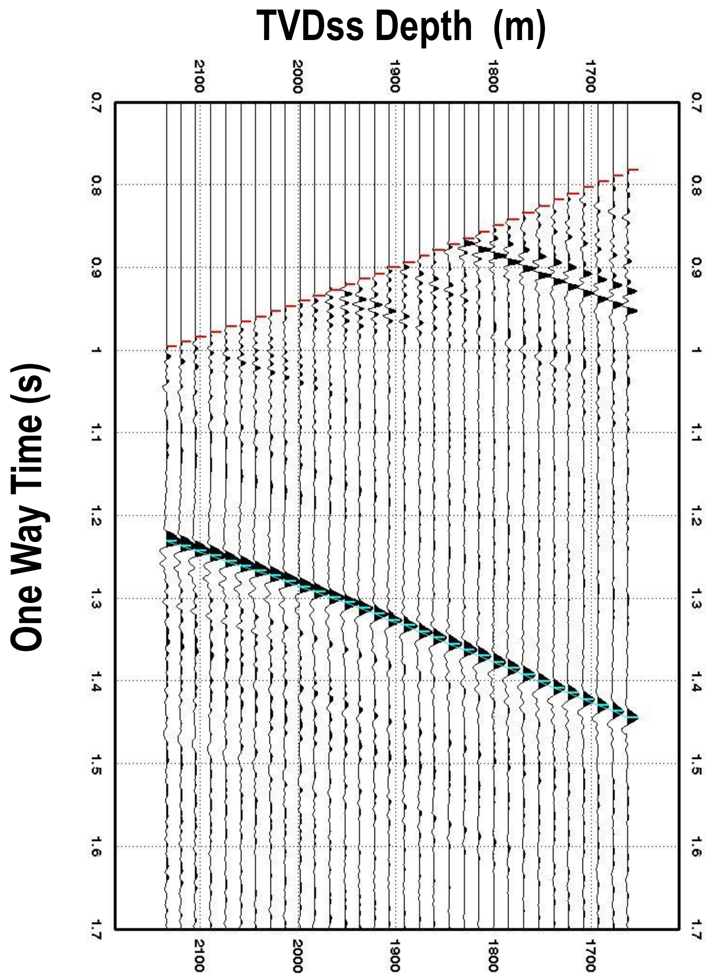
Surface Seismic XLINE
+2ms shift to seismic to tie corridor stack

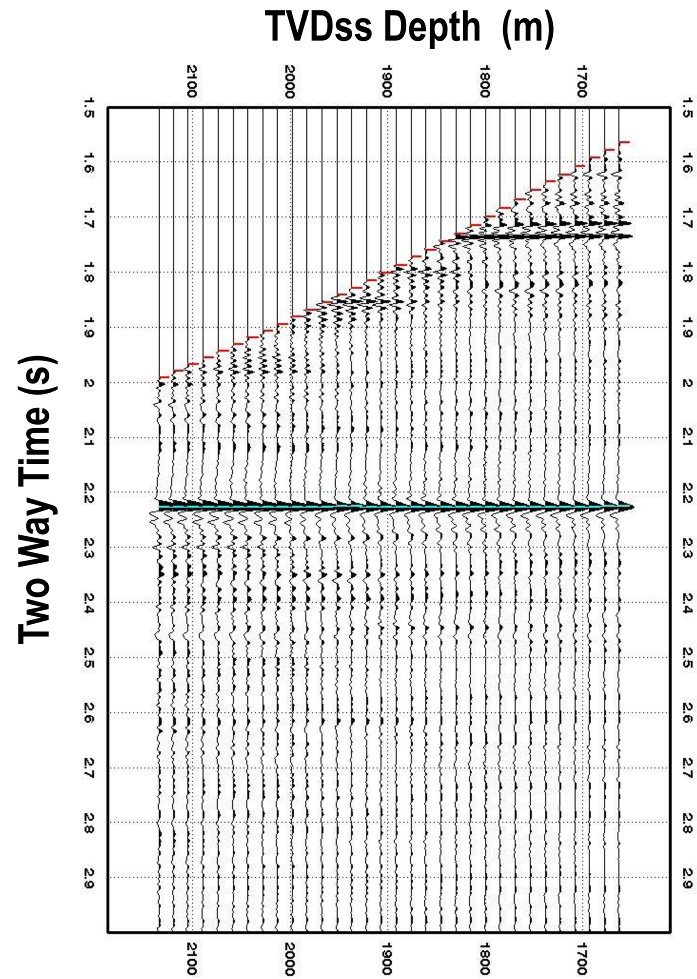


Observations

New results using Semblance Weighted Deconvolution (Semblance Decon) show the following:

1. **Previous observed well tie time-shift differences are maintained**
2. **WSD corridor stack is 0-phase with > 4-220 Hz in shallower section to ~ 4-150 Hz in the deeper TD section**
3. **Semblance Decon deconvolution effectively fills-in the 7 m depth source ghost notch around 107 Hz**



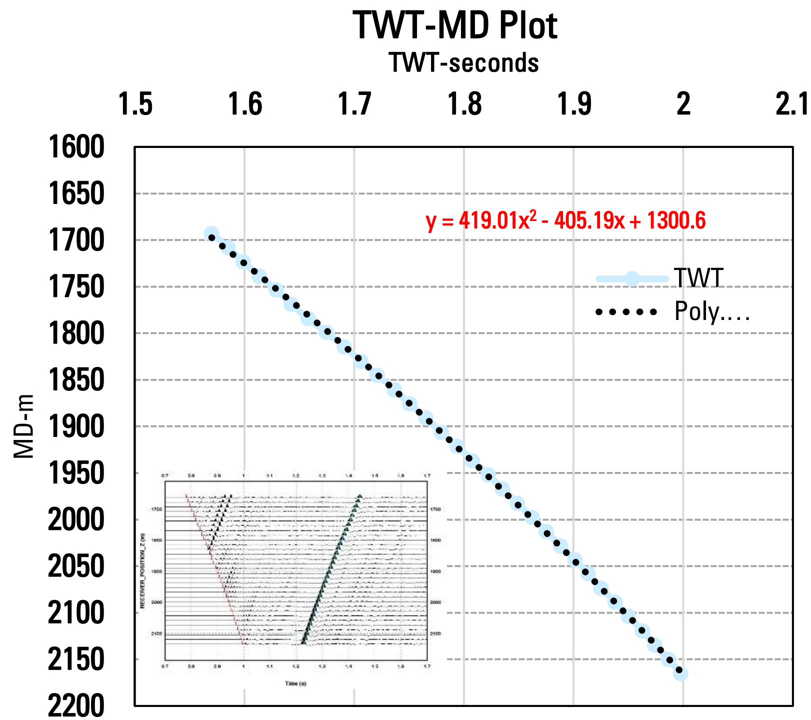


Look Ahead

Stavanger, 04-Oct-2022

Look Ahead Prediction Using VSP Downgoing TD Extrapolation

MD	OWT-SRD	TWT-SRD
1692.876587	0.785014	1.570028
1708.117554	0.792523	1.585046
1723.358521	0.79945	1.5989
1738.599609	0.806656	1.613312
1753.618042	0.814513	1.629026
1768.859009	0.821243	1.642486
1784.099976	0.829002	1.658004
1799.341064	0.8374	1.6748
1814.788818	0.845512	1.691024
1830.029907	0.853044	1.706088
1845.270752	0.860545	1.72109
1860.511963	0.868298	1.736596
1875.746338	0.875217	1.750434
1890.987183	0.882669	1.765338
1906.228271	0.889697	1.779394
1921.46936	0.897031	1.794062
1936.767334	0.903776	1.807552
1952.008301	0.911088	1.822176
1967.249268	0.917615	1.83523
1982.490356	0.924373	1.848746
1997.648682	0.931048	1.862096
2012.889526	0.937543	1.875086
2028.130615	0.944084	1.888168
2043.371582	0.95072	1.90144
2058.308838	0.956621	1.913242
2073.549805	0.962534	1.925068
2088.790771	0.968871	1.937742
2104.031738	0.974948	1.949896
2119.596436	0.981396	1.962792
2134.837402	0.987005	1.97401
2150.078369	0.99326	1.98652
2165.319336	0.998801	1.997602



2nd order Polynomial Fitting D=$419.01t^2 - 405.19t + 1300.6$

TWT of Top Permian Carbonate: X.2306sec

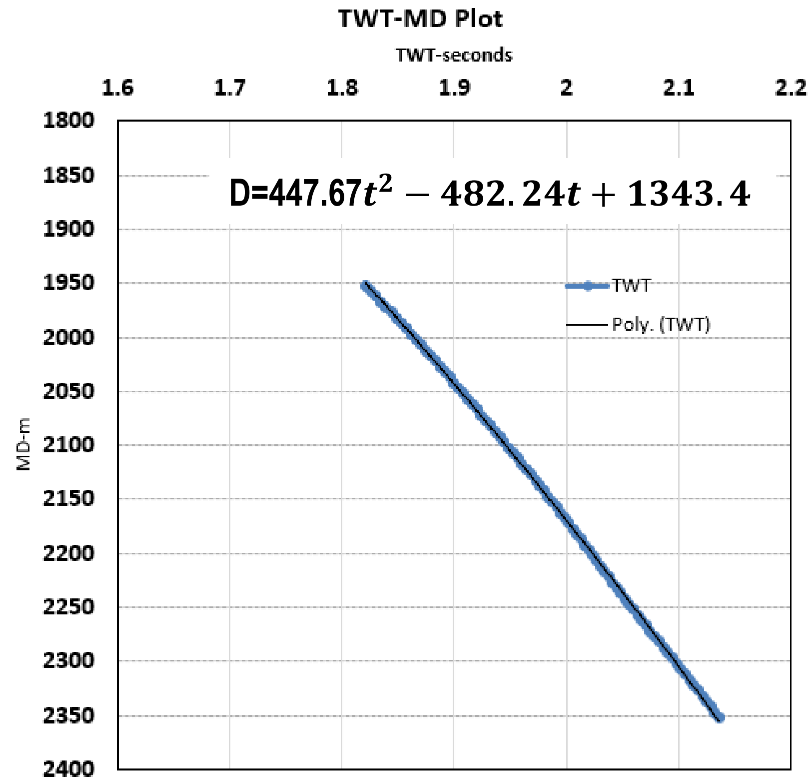
Predicted Depth: XX81.5m MD

Sonic not used for Extrapolation

Look-Ahead VSP

Look Ahead Prediction Using VSP-Calibrated RT-Sonic

MD	OWT-SRD	TWT-SRD
1717.2205	0.79659	1.59318
1722.2205	0.79898	1.59796
1727.2205	0.8014	1.6028
1732.2205	0.80377	1.60754
1737.2205	0.80611	1.61222
1742.2205	0.80843	1.61686
1747.2205	0.8108	1.6216
1752.2205	0.81305	1.6261
1757.2205	0.81543	1.63086
1762.2205	0.81803	1.63606
1767.2205	0.8206	1.6412
1772.2205	0.82321	1.64642
1777.2205	0.82582	1.65164
1782.2205	0.82825	1.6565
1787.2205	0.83088	1.66176
1792.2205	0.83343	1.66686
1797.2205	0.83608	1.67216
1802.2205	0.83862	1.67724
1807.2205	0.84125	1.6825
1812.2205	0.84383	1.68766
1817.2205	0.84646	1.69292
1822.2205	0.84895	1.6979
1827.2205	0.85159	1.70318
1832.2205	0.85421	1.70842
1837.2205	0.85651	1.71302
1842.2205	0.85899	1.71798
1847.2205	0.86147	1.72294
1852.2205	0.86398	1.72796
1857.2205	0.86656	1.73312
1862.2205	0.86903	1.73806
1867.2205	0.8714	1.7428
1872.2205	0.87369	1.74738
1877.2205	0.87592	1.75184
1882.2205	0.87823	1.75646
2332.2205	1.06056	2.12112
2337.2205	1.06246	2.12492
2342.2205	1.06431	2.12862
2347.2205	1.06617	2.13234
2352.2205	1.06803	2.13606



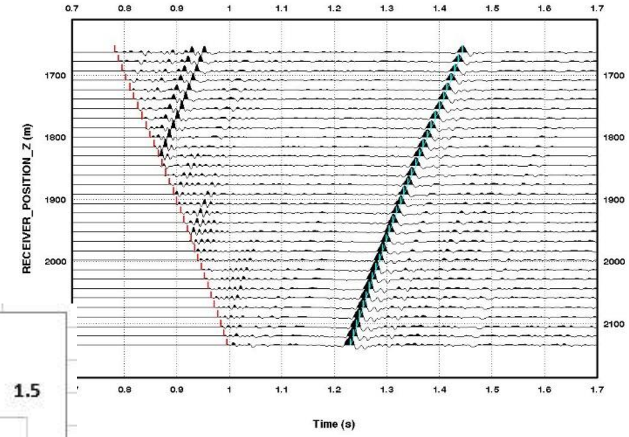
2nd order Polynomial Fitting: $D=447.67t^2 - 482.24t + 1343.4$

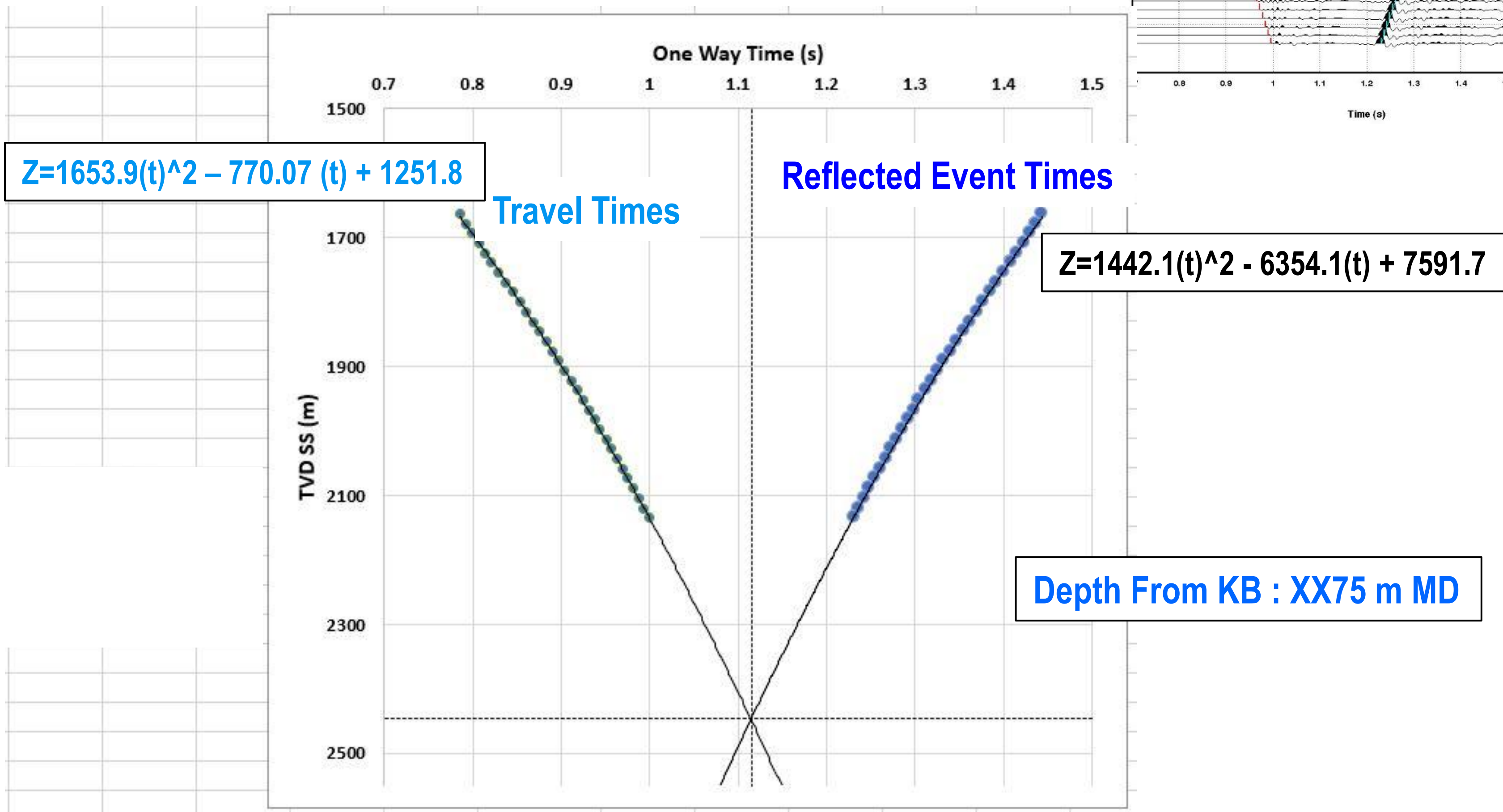
TWT of Top Permian Carbonate: X.2306 s

Predicted Depth: XX75.0 m MD

Since Sonic log extends till XX52m MD, we have better control over the Depth extrapolation

Travel Time Fitting – Look Ahead



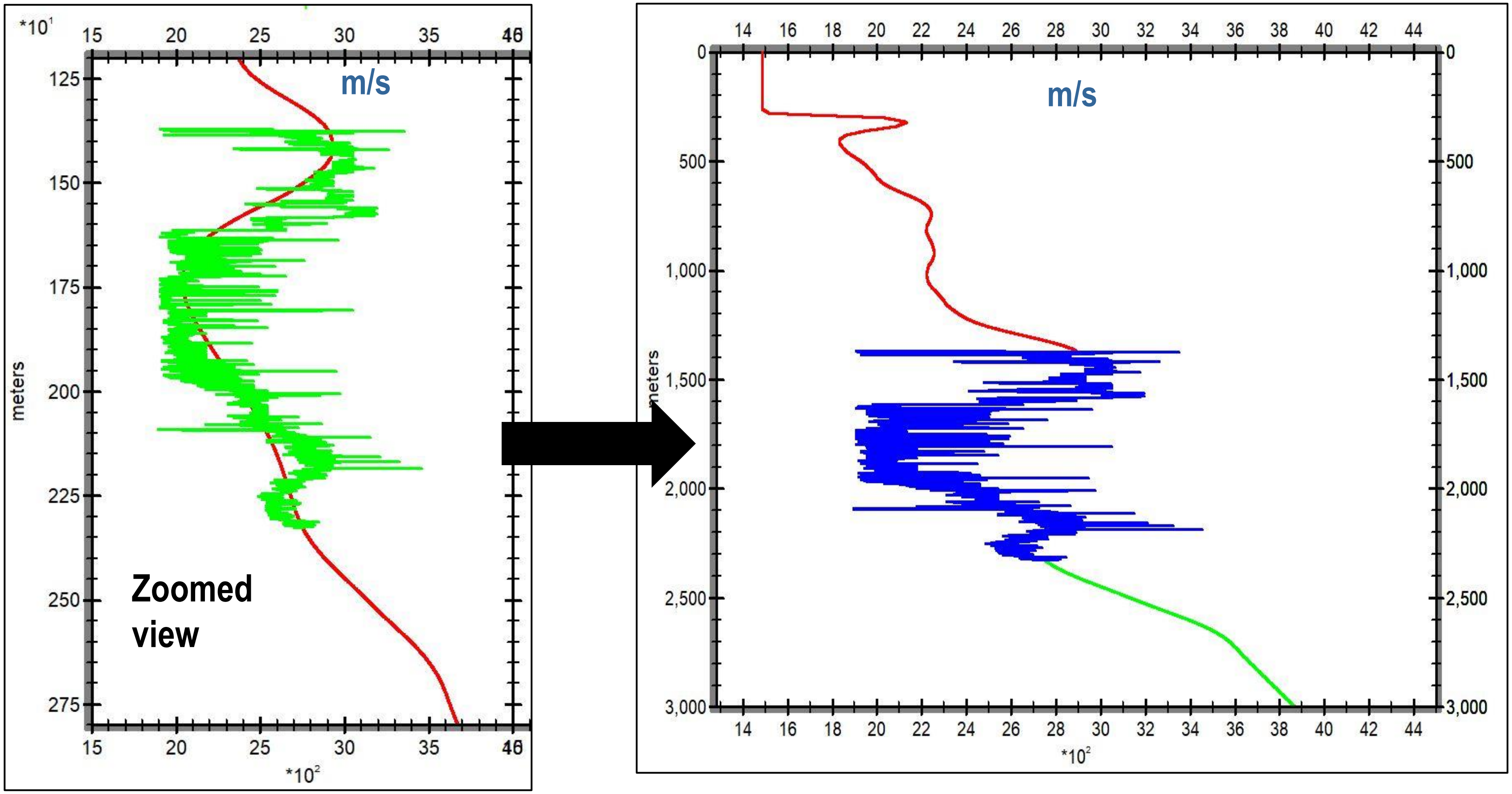


Look-Ahead VSP

Look Ahead Prediction using RT-Sonic Log and Seismic Velocity

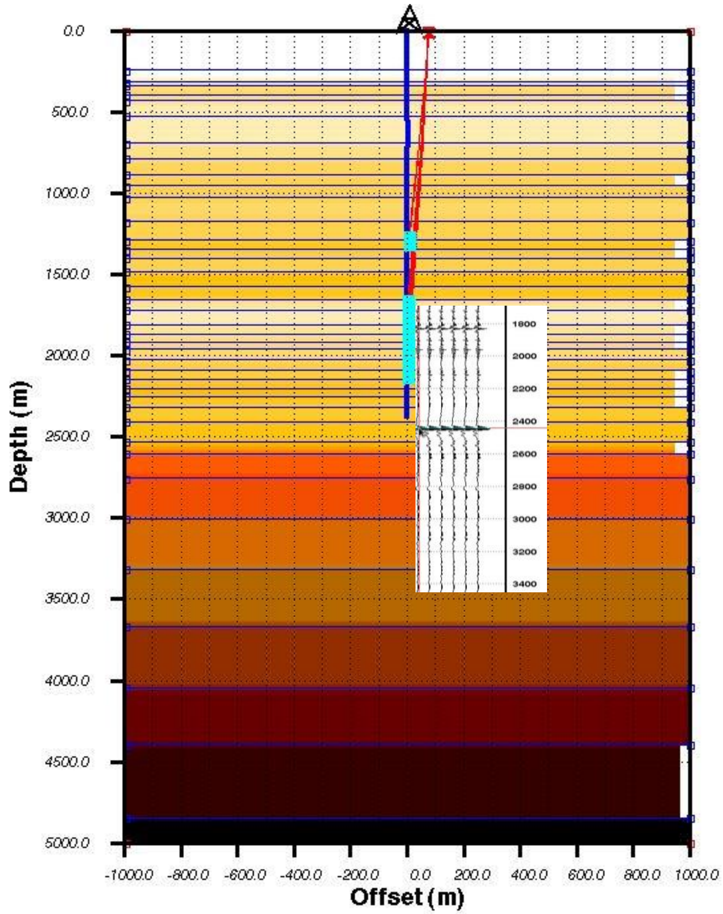
Sonic Velocity
Seismic Velocity

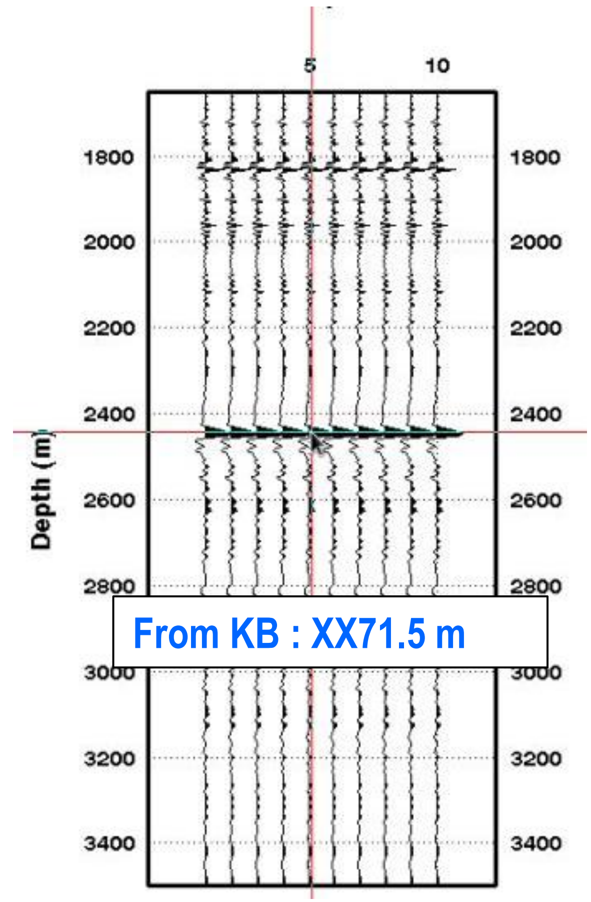
Seismic Velocity
Sonic Velocity
Seismic Velocity



Integrating seismic and sonic velocity gives more accurate profile compared to Seismic alone

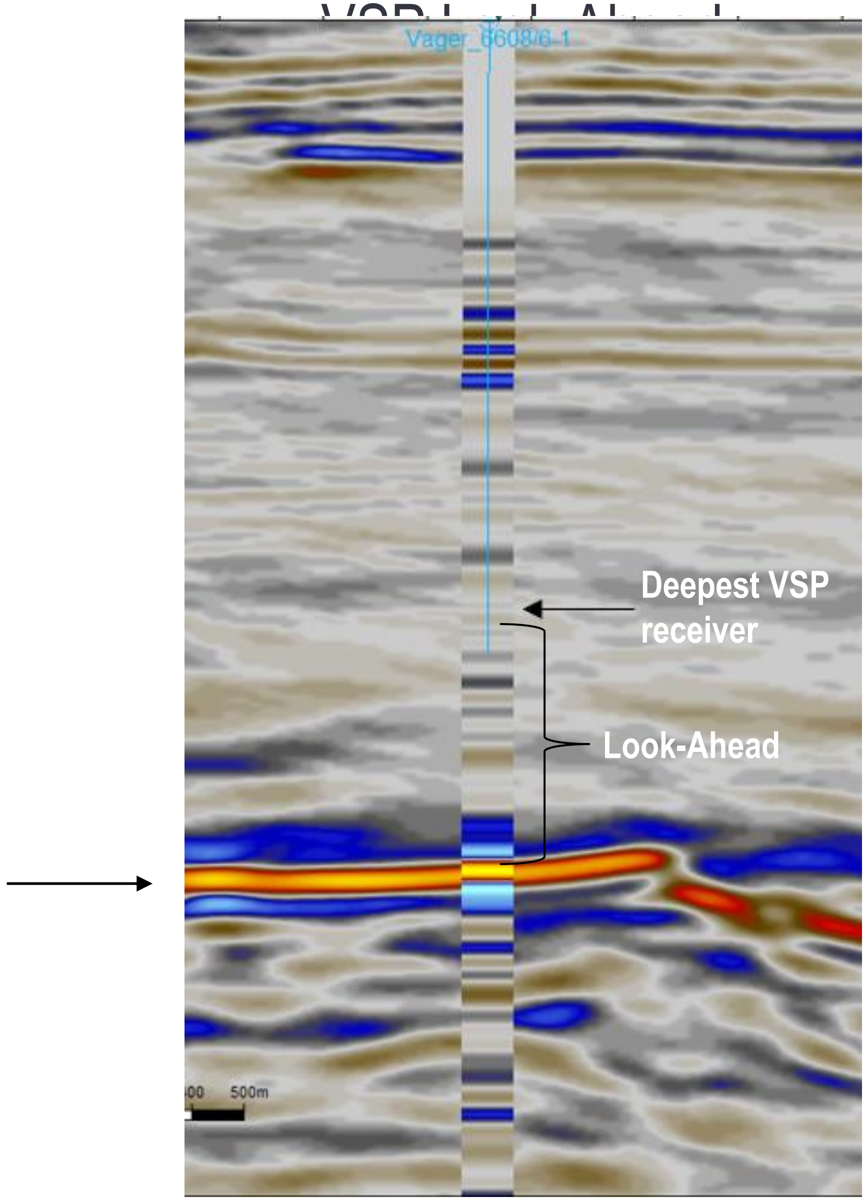
Depth Corridor Stack: Time to Depth Conversion Using Calibrated Velocity Model by Travel Time Tomography





Previous model was blocked and calibrated with VSP times (left) used for depth converting corridor stack (right)

Look-Ahead VSP


Vager_6608/6-1
Deepest VSP receiver
Look-Ahead
500m

Summary

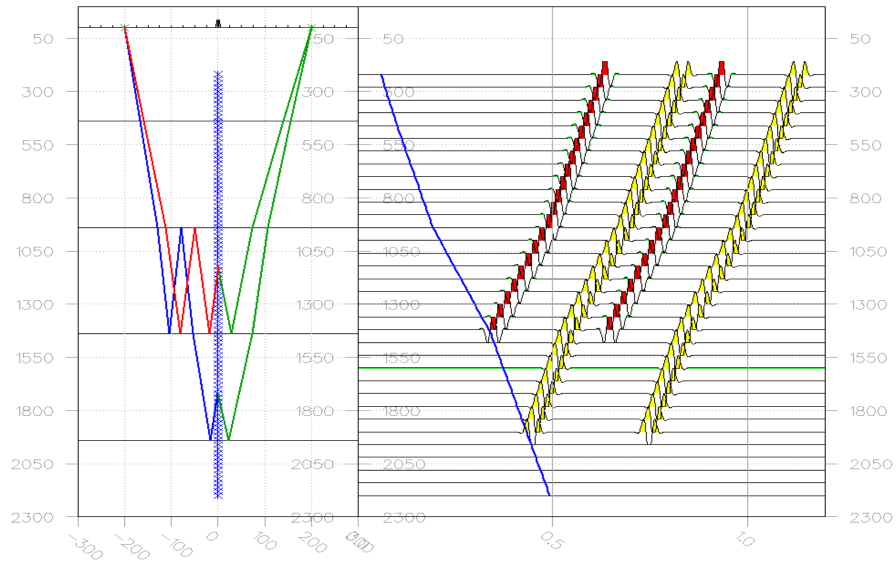
- From the different used methodologies, the estimated top of carbonates depths were obtained
- ➢ Predicted depth different methods:

  XX81m MD, XX75m MD, XX71m MD & XX79m MD

AVG : XX76.5 m MD. (+5 m from final drilled depth)

Multiples – Analysis

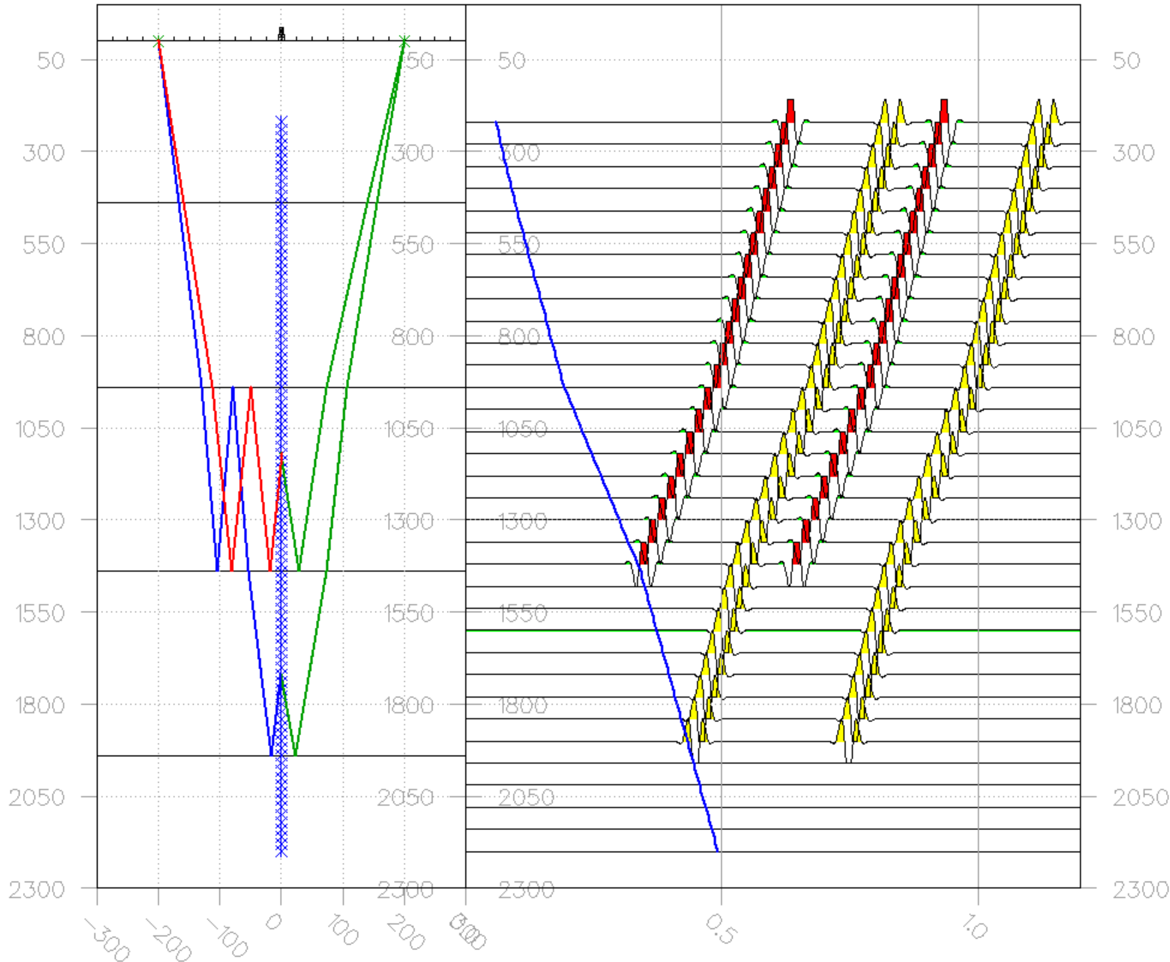
From VSP



Stavanger, 04-Oct-2022

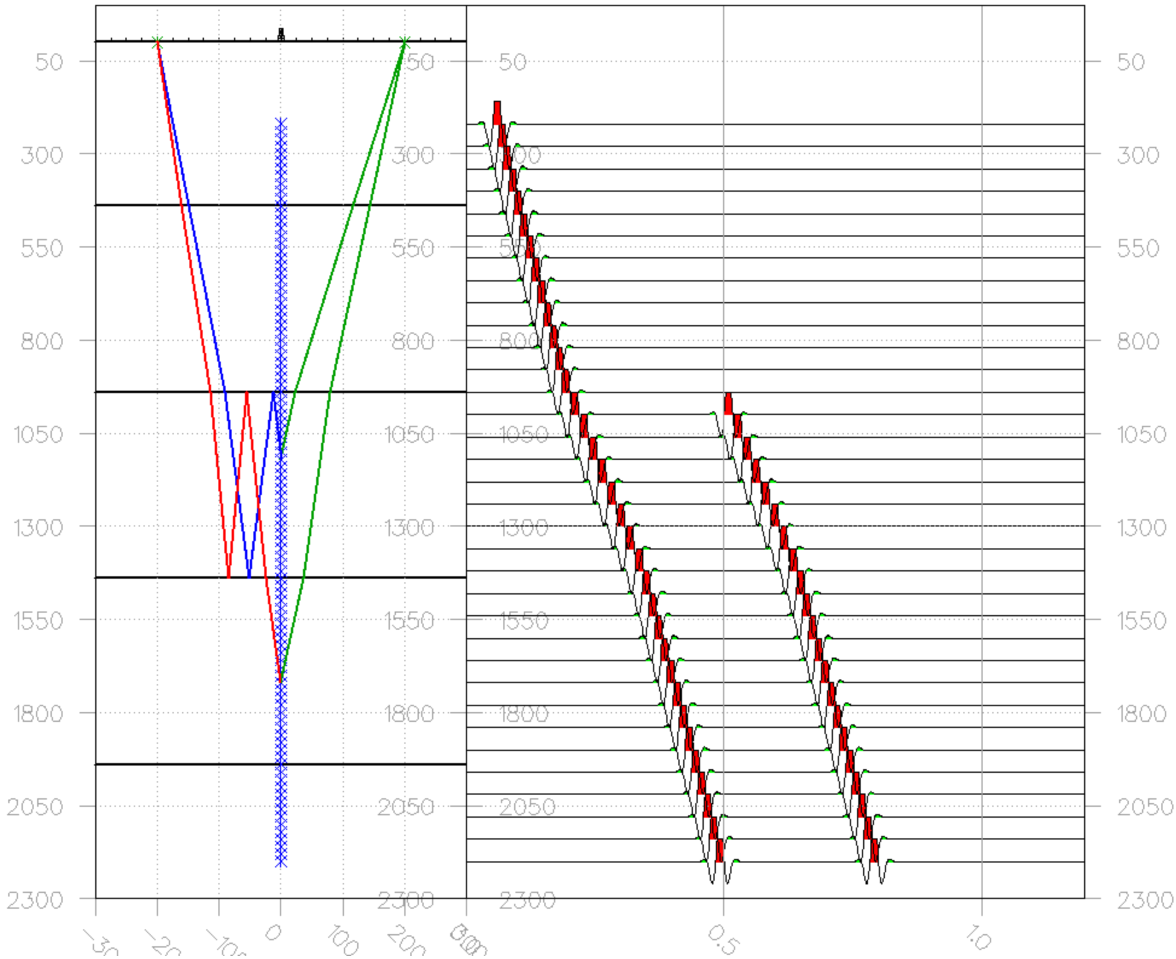
Borehole Multiples

Upgoing Multiples



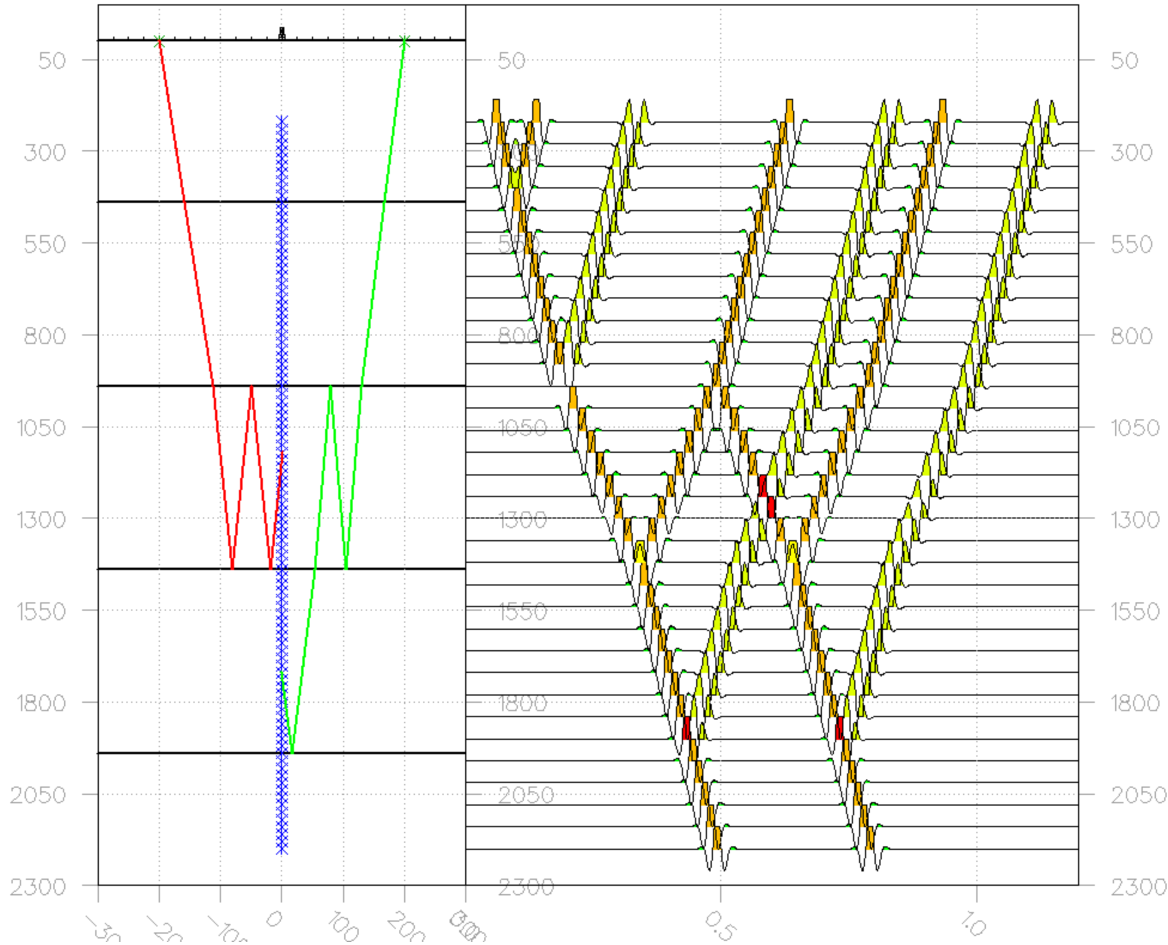
Borehole Multiples

Downgoing Multiple

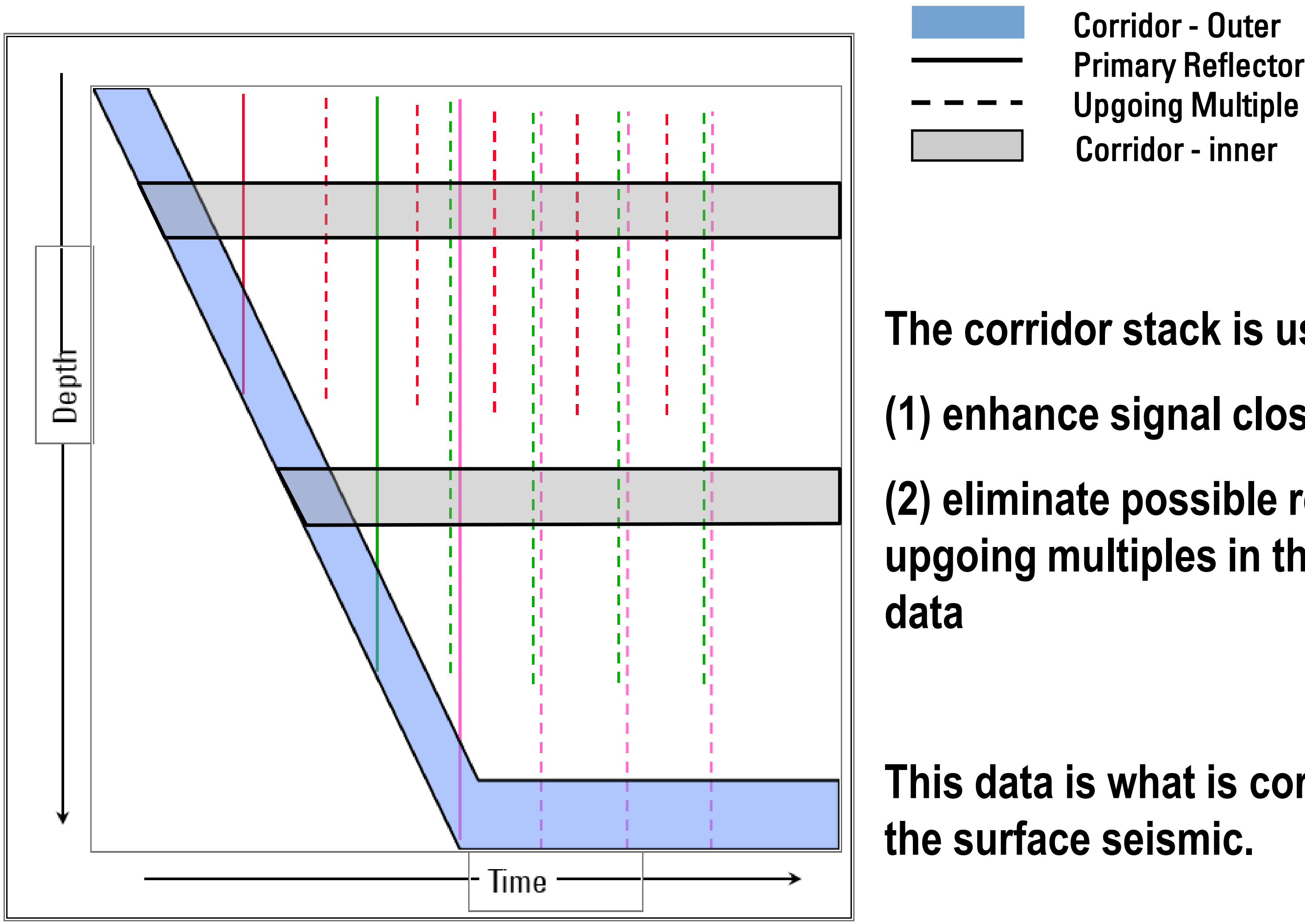


Borehole Multiples

All Multiples



Corridor Stack



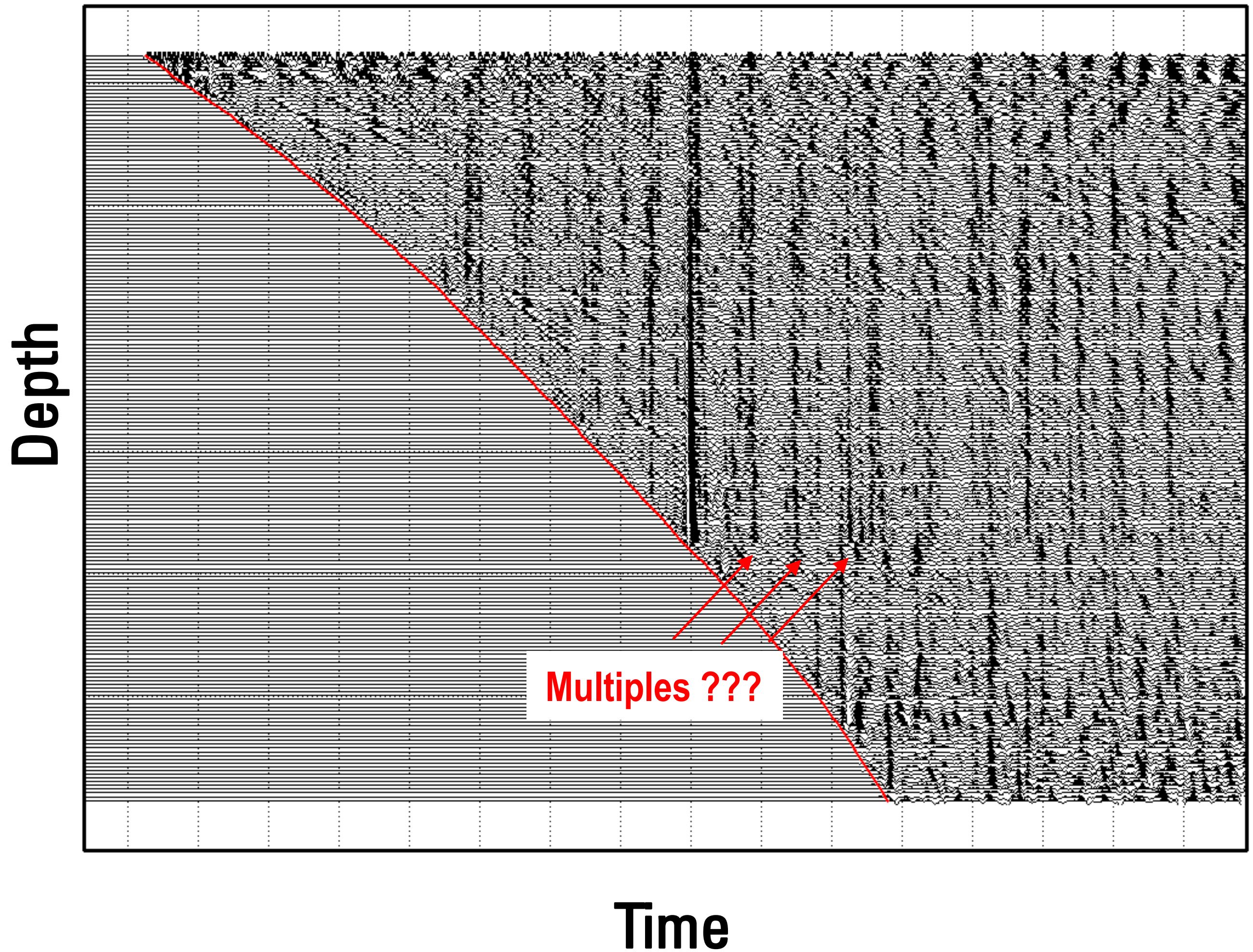
The corridor stack is used to:

(1) enhance signal close to the well

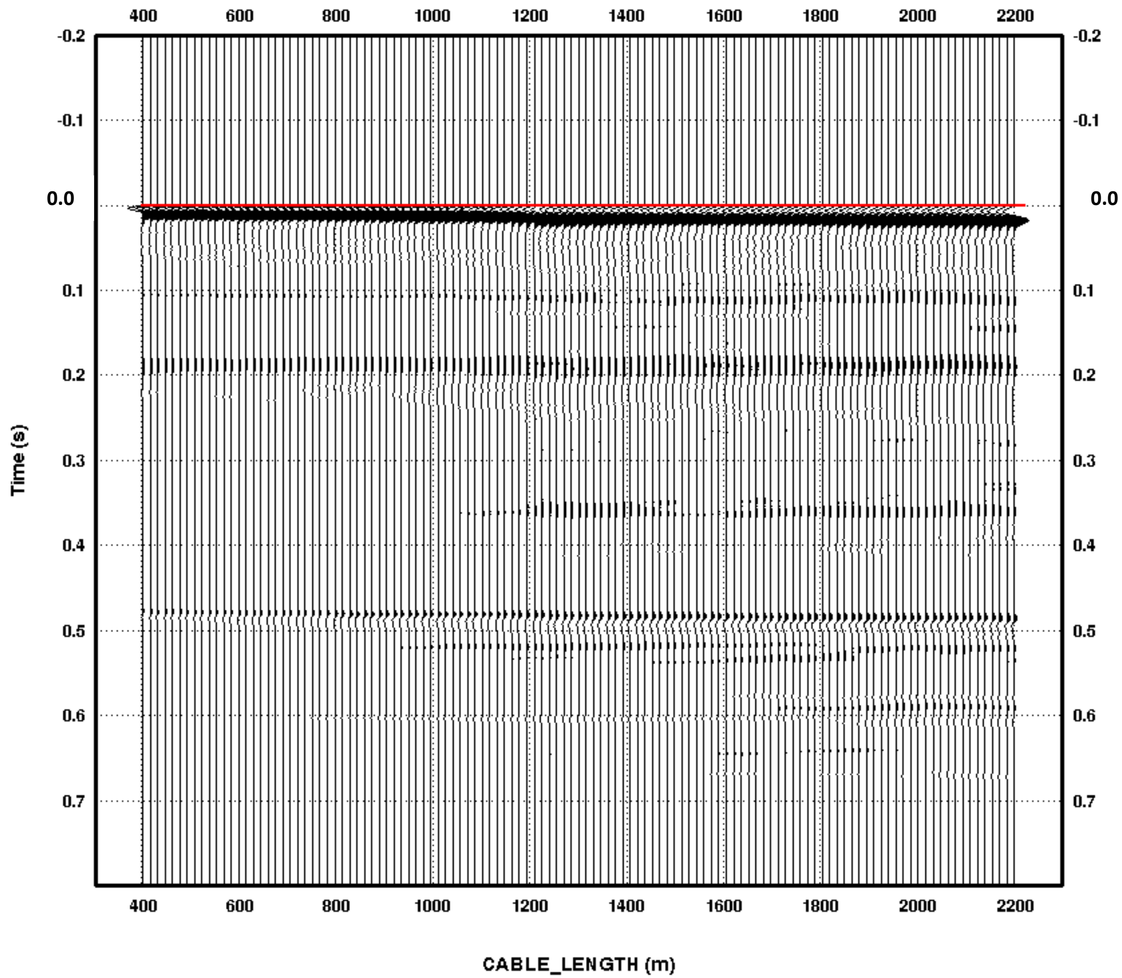
(2) eliminate possible residual weak upgoing multiples in the final VSP data

This data is what is correlated to the surface seismic.

First Residual Wavefield (Wavefield Separation)

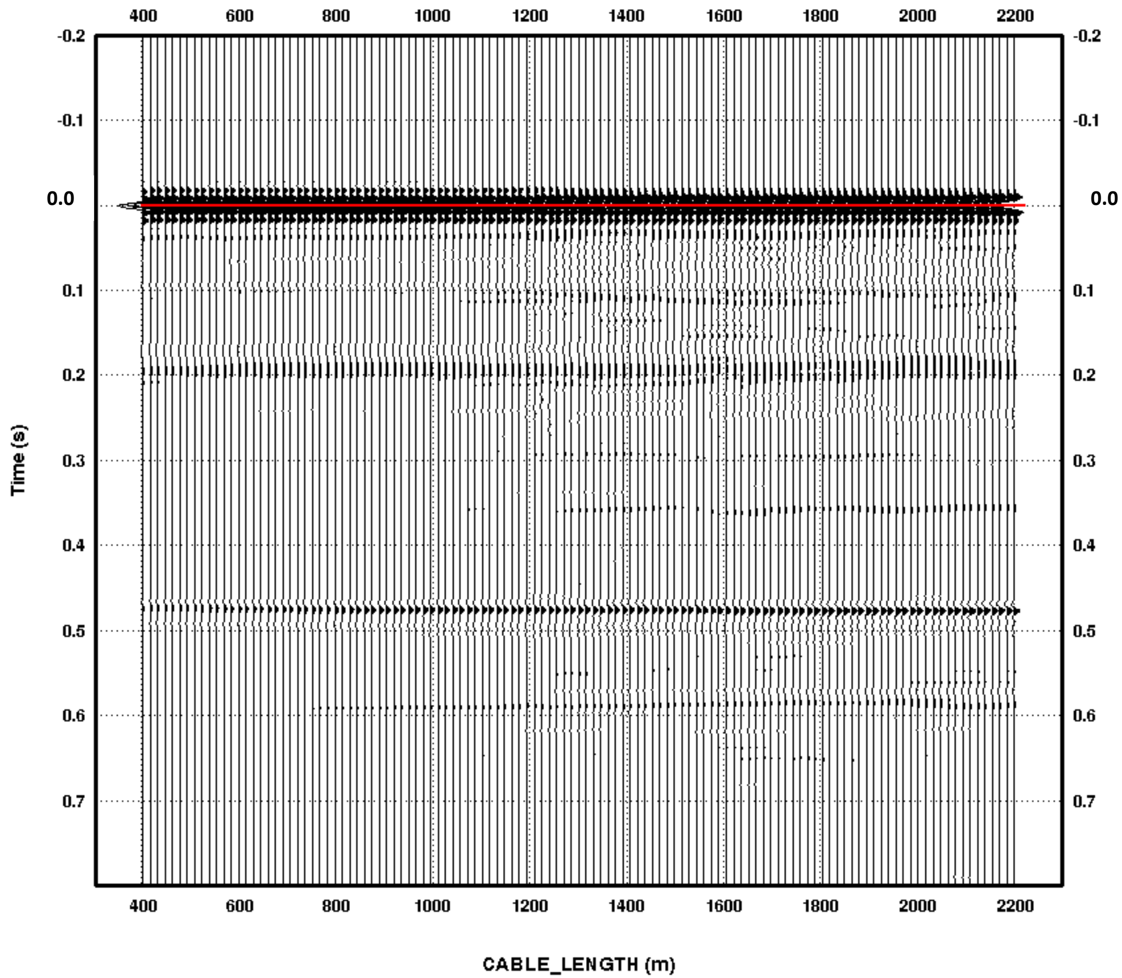


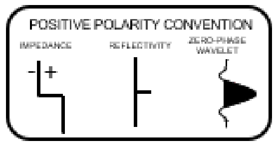
Input: Downgoing After Wavefield Separation



Downgoing (Primaries and Multiples) – Zero Phase

Deconvolved Downgoing wavefield : Prediction Time (2.5sec), Waveshaping Deconvolution (50ms)





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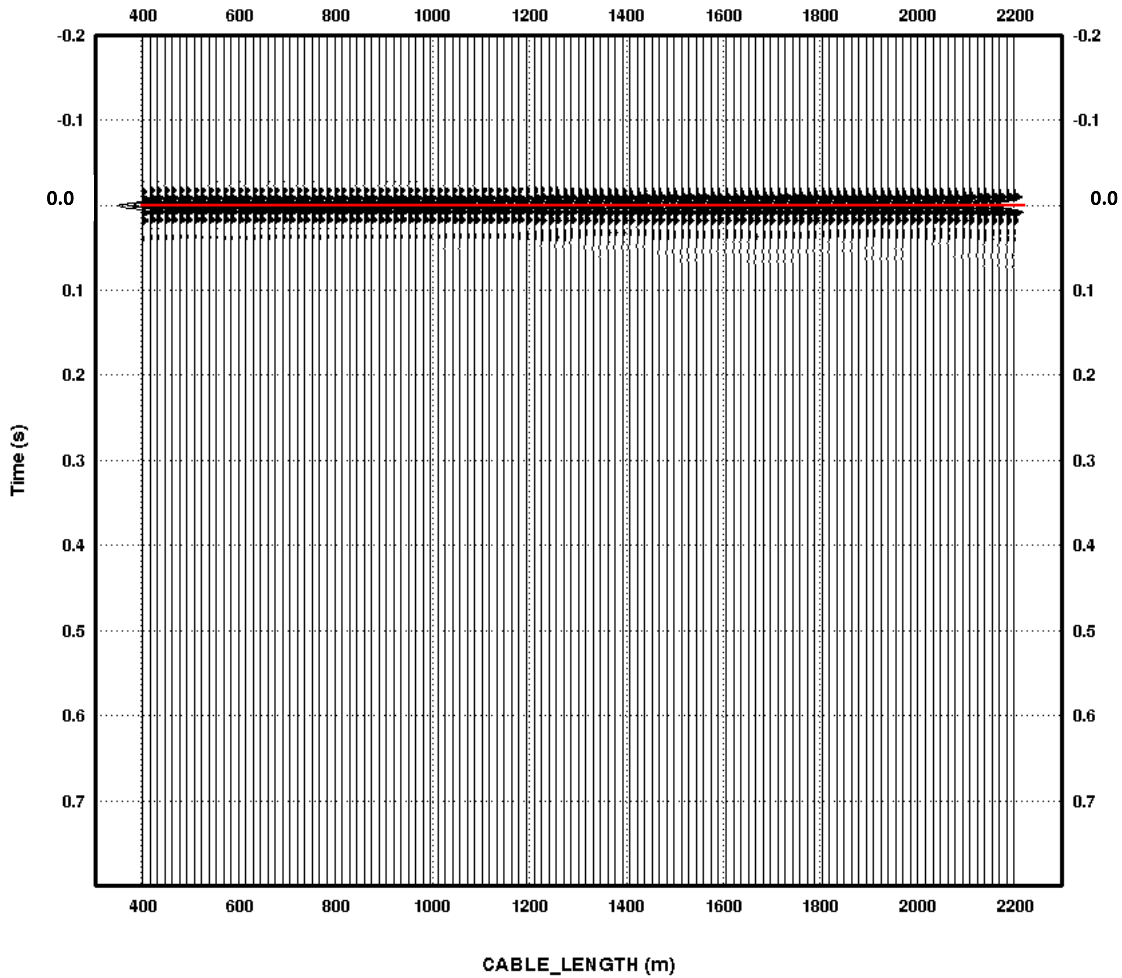
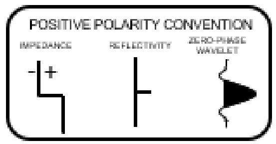
Downgoing (Primaries Only) – Zero Phase

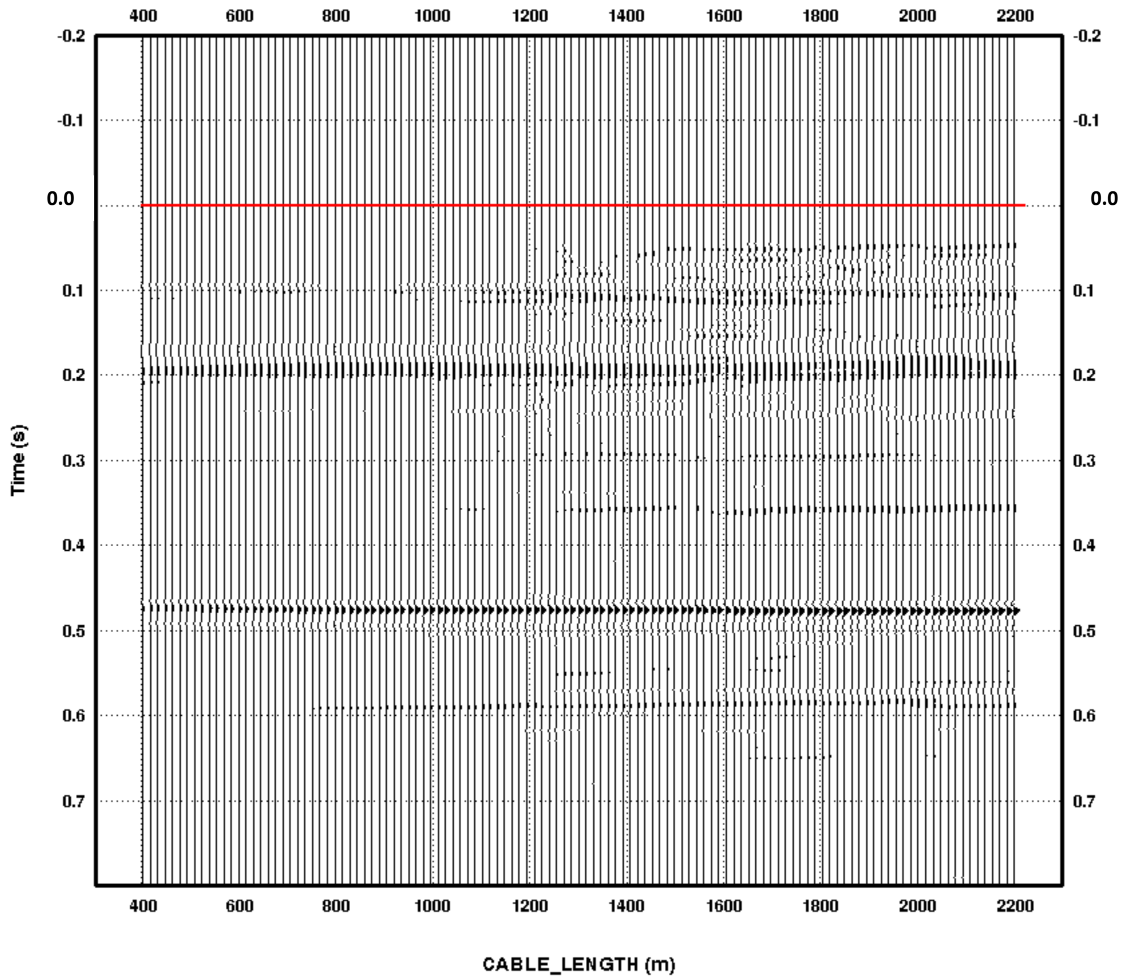
Deconvolved Downgoing wavefield : Prediction Time (50ms), Waveshaping Deconvolution (50ms)

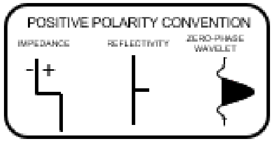




Downgoing (Multiples Only) – Zero Phase

Deconvolved Downgoing wavefield : Subtraction of wavefields





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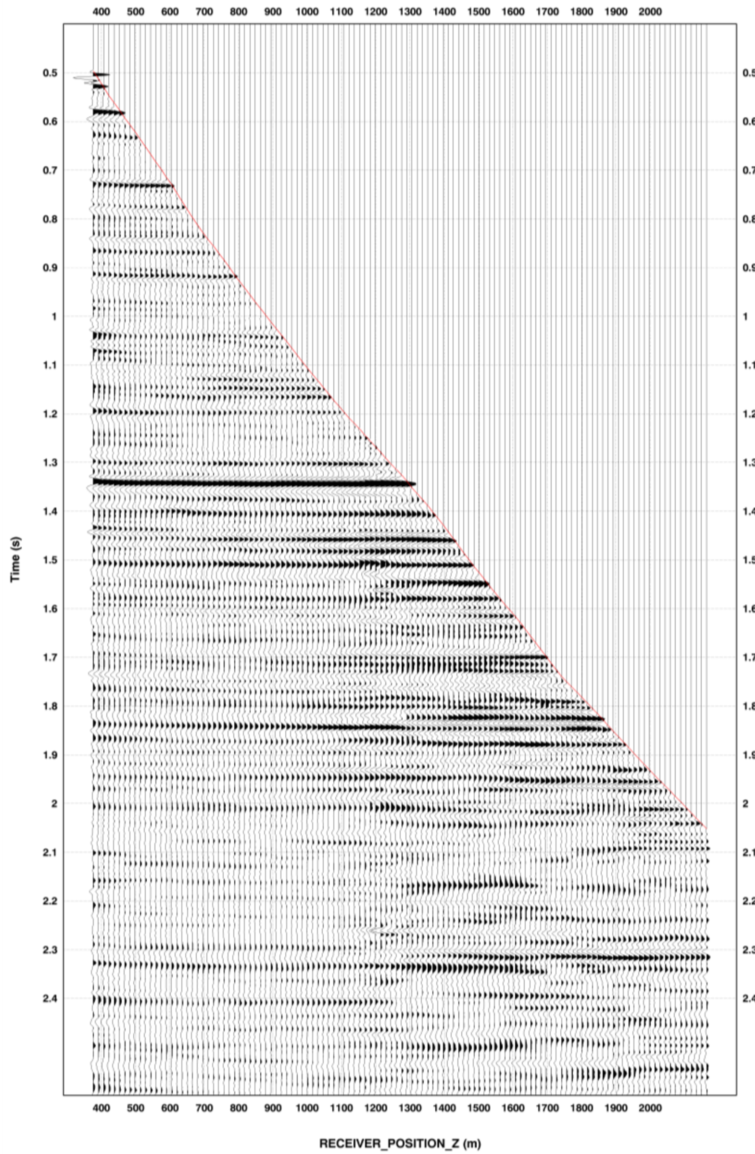
Input: Upgoing after Wavefield Separation



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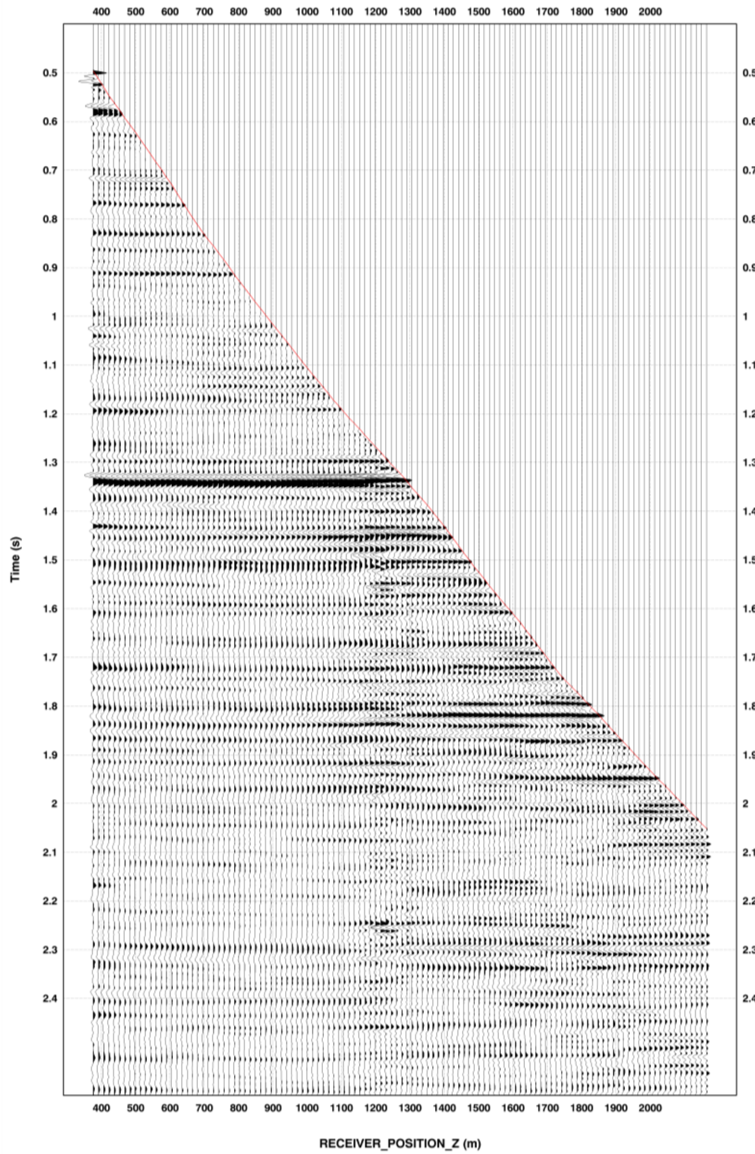
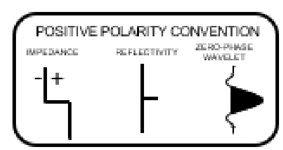
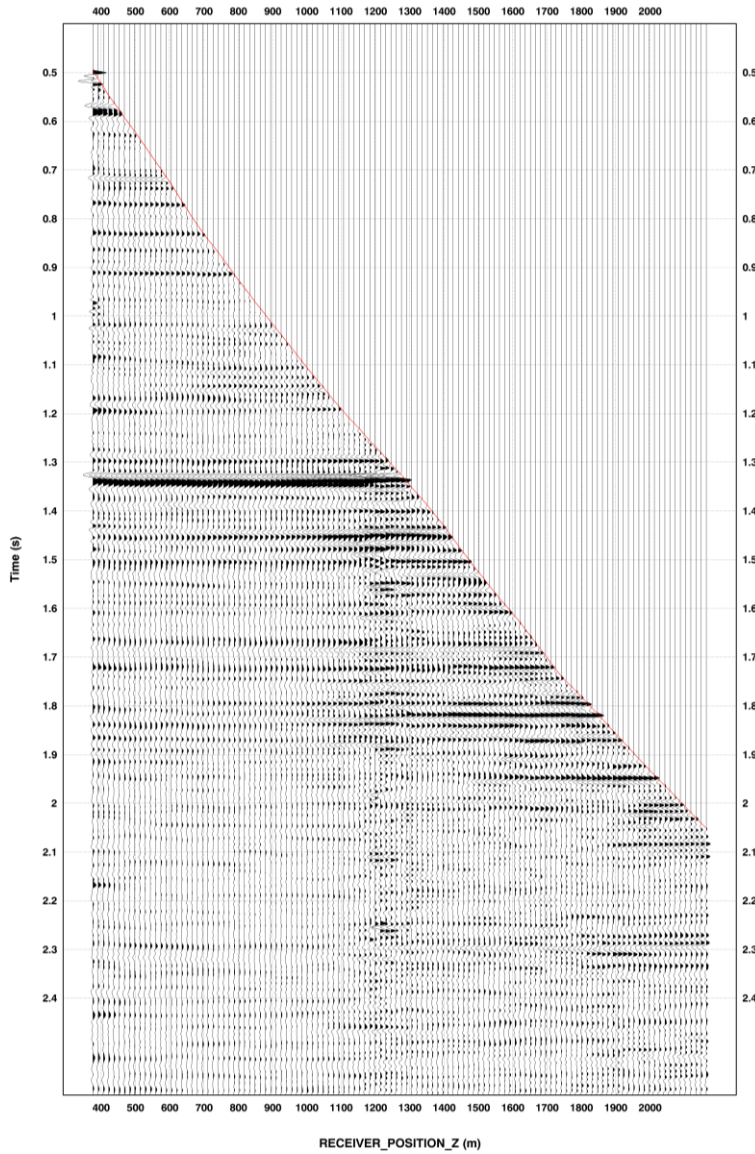
Upgoing (Primaries and Multiples) – Zero Phase



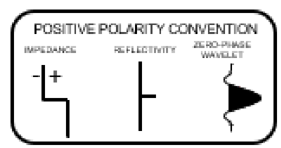
Deconvolved Upgoing wavefield : Prediction Time (2.5 sec), Waveshaping Deconvolution (50ms)



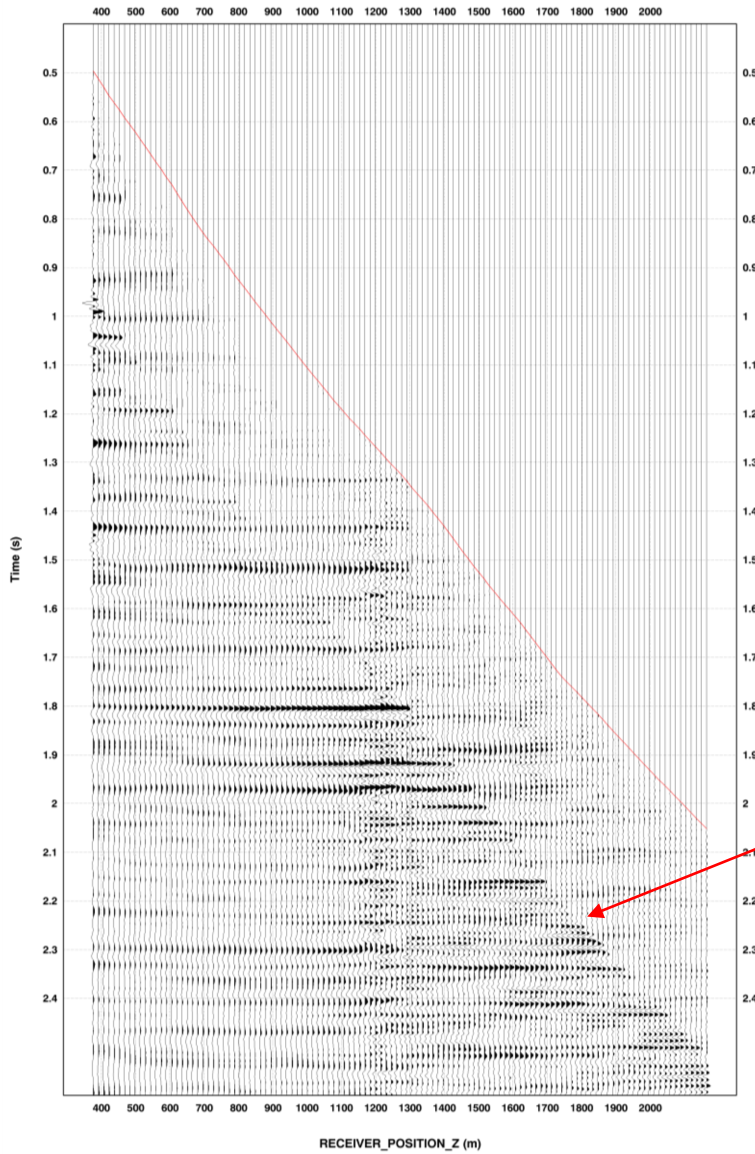
Upgoing (Primaries Only) – Zero Phase



Deconvolved Upgoing wavefield : Prediction Time (50ms)
Waveshaping Deconvolution (50ms)

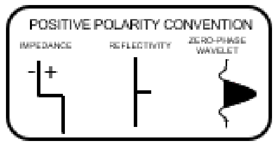


Upgoing (Multiples Only) – Zero Phase



Deconvolved Upgoing wavefield : Subtraction of wavefields

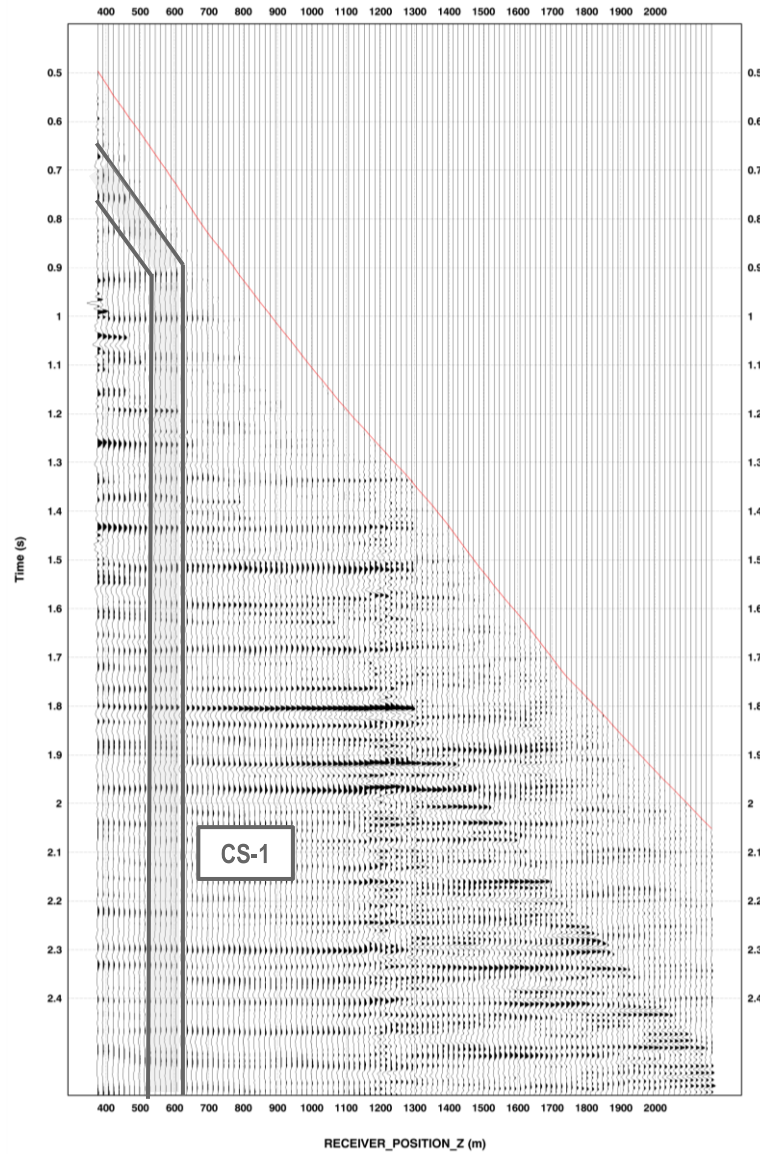
Multiples from Water layer



Fundamentals of Borehole Seismic Technology *(Kelsall, Rufino & Guerra, 2022)*

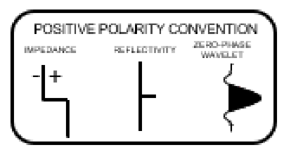
True Amplitude

Upgoing (Multiples Only) – Zero Phase & Multiple Corridor Stack 1



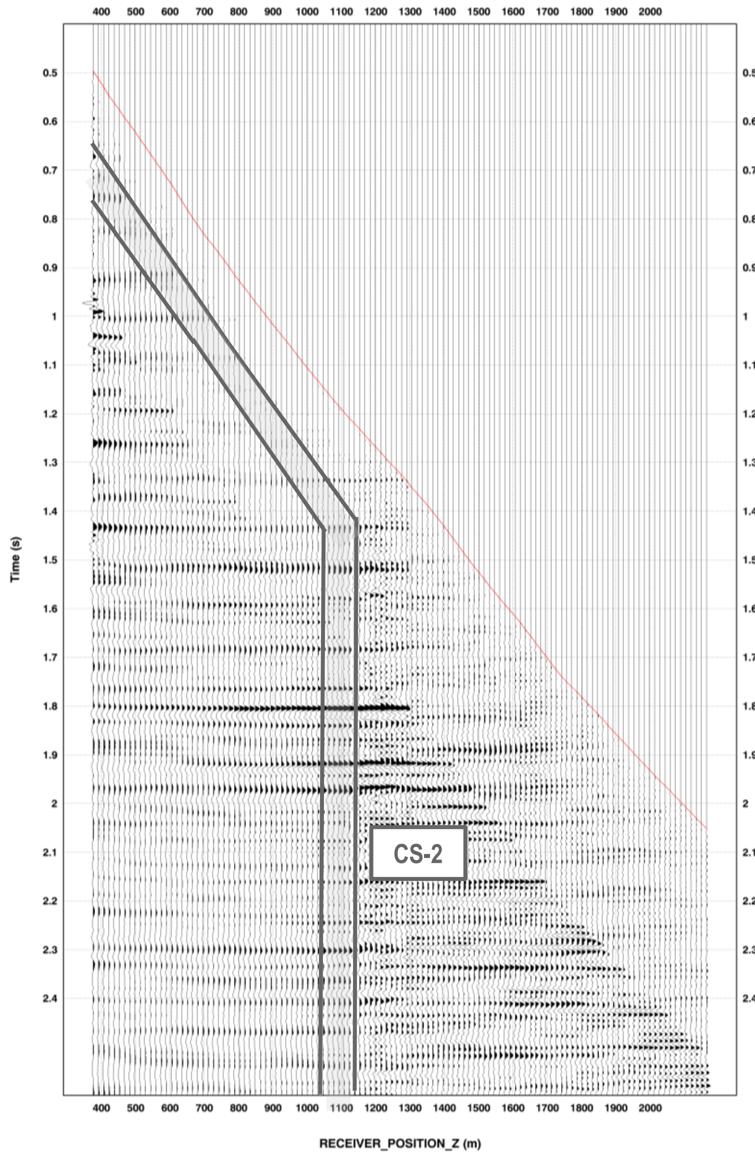
Deconvolved Upgoing wavefield : Subtraction of wavefields

CS1: Start Time: TT + 150ms
Window Length: 100ms, and 8 traces above 605.27m TVDSS are chosen for the look ahead section.



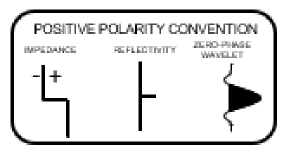
True Amplitude

Upgoing (Multiples Only) – Zero Phase & Multiple Corridor Stack 2

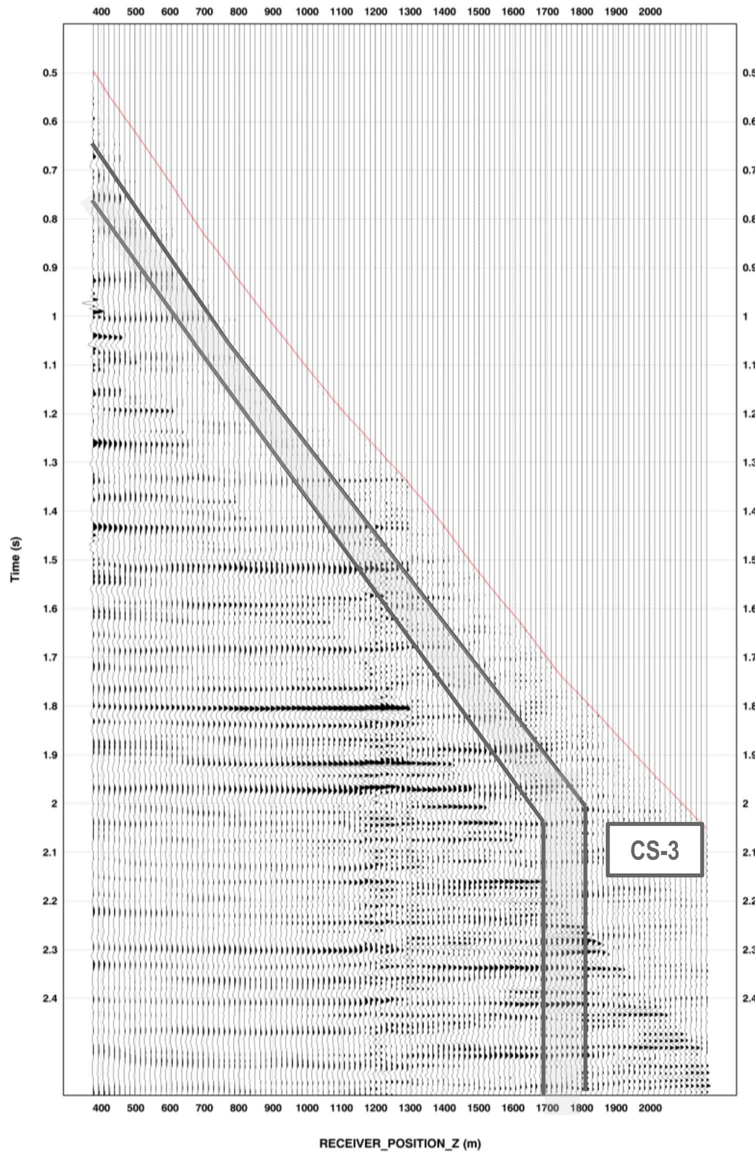


Deconvolved Upgoing wavefield : Subtraction of wavefields

CS2: Start Time: TT + 150ms
Window Length: 100ms, and 8 traces above 1092.75m TVDSS are chosen for the look ahead section.

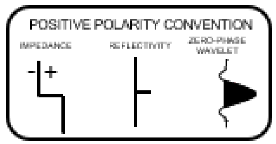


Upgoing (Multiples Only) – Zero Phase & Multiple Corridor Stack 3



Deconvolved Upgoing wavefield : Subtraction of wavefields

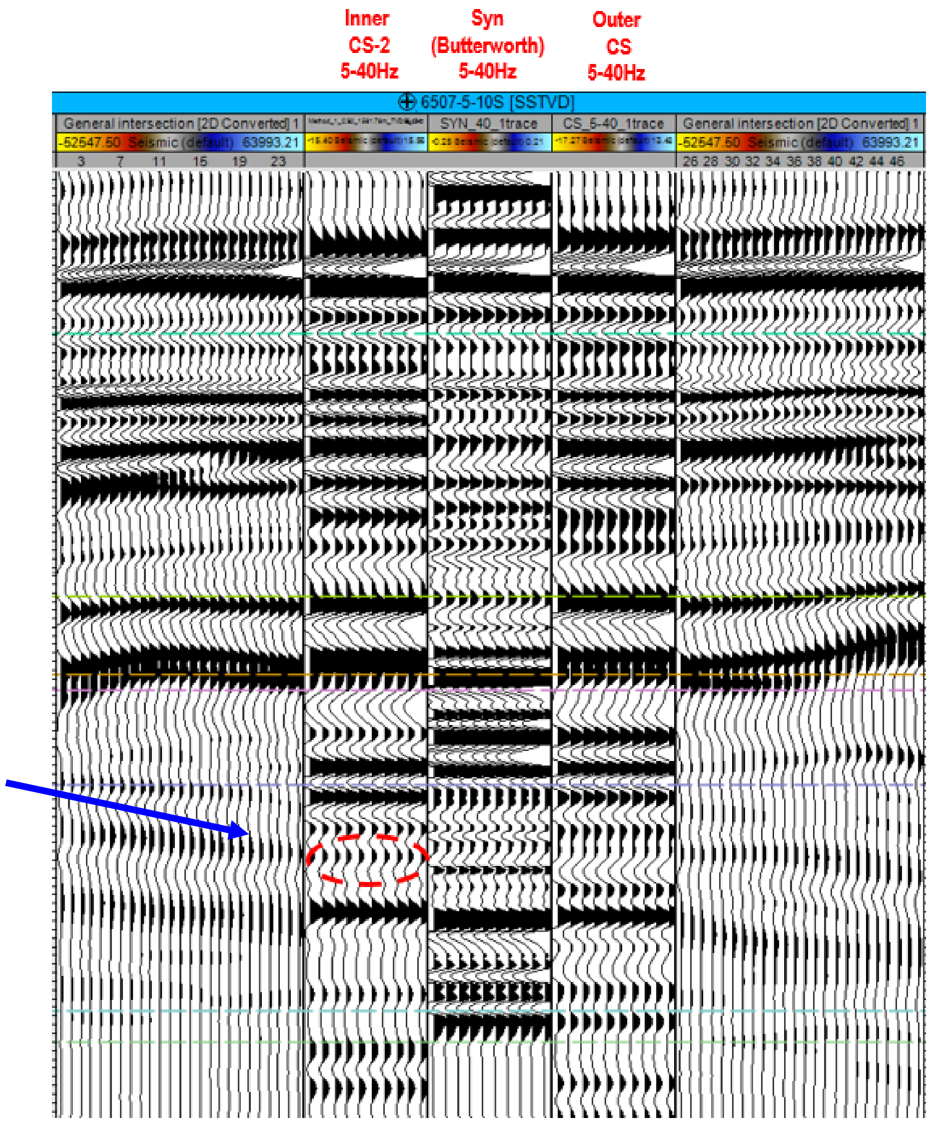
CS3: Start Time: TT + 150ms
Window Length: 100ms, and 8 traces above 1802.03m TVDSS are chosen for the look ahead section.

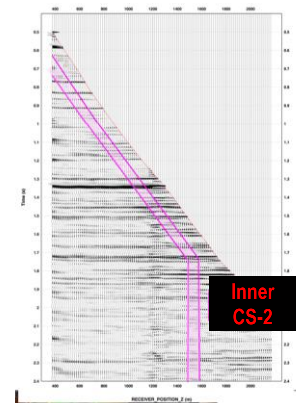


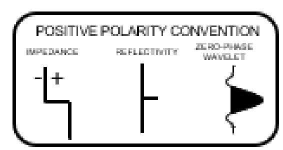
Fundamentals of Borehole Seismic Technology *(Kelsall, Rufino & Guerra, 2022)*

Corridor Stacks (Multiples and Primaries) with Surface Seismic - TOP

No shift applied to Surface Seismic







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NORWEGIAN PETROLEUM DIRECTORATE
50 years

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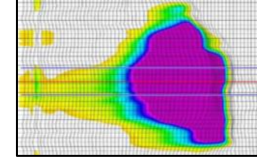
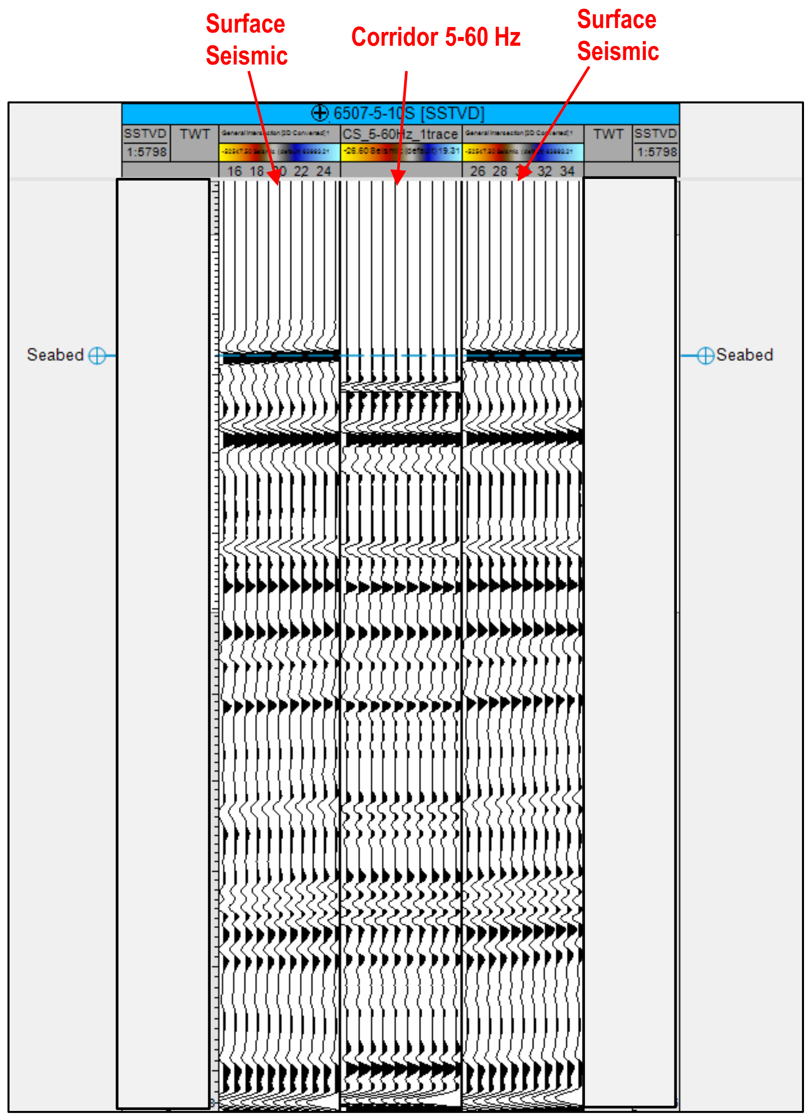


Phase Analysis
&
Borehole Seismic Quantitative Match

Stavanger, 04-Oct-2022

Corridor Stack with Seismic along well – Time – Top

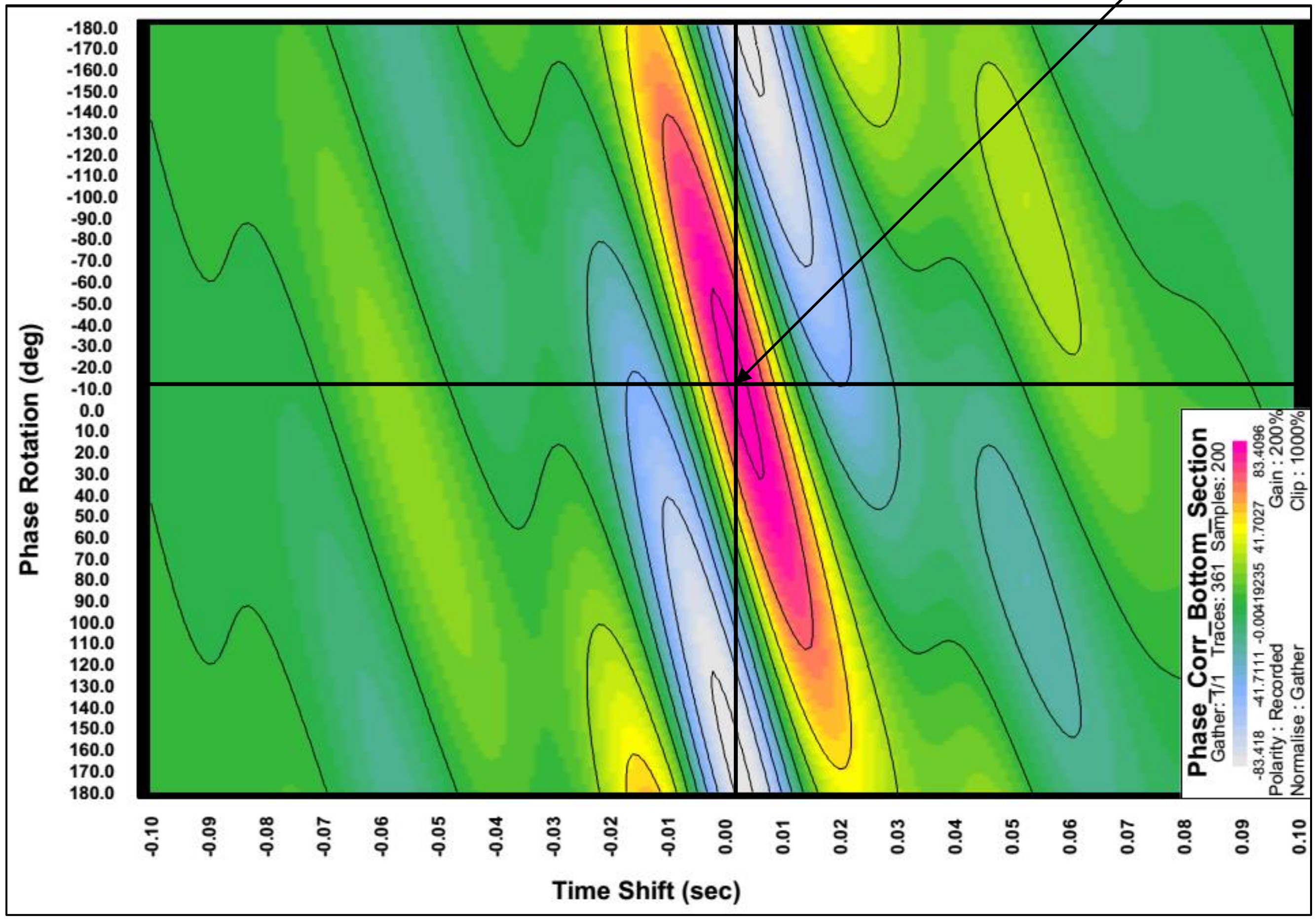


No time and phase shift is applied to the surface seismic

Phase Analysis – Correlation Map

- **Maximum coherence of 0.8341 is observed at -0.002s time shift and 13deg phase shift.**
- **Without any phase shift the maximum coherence is at -0.003s time shift**

Maximum Correlation Point



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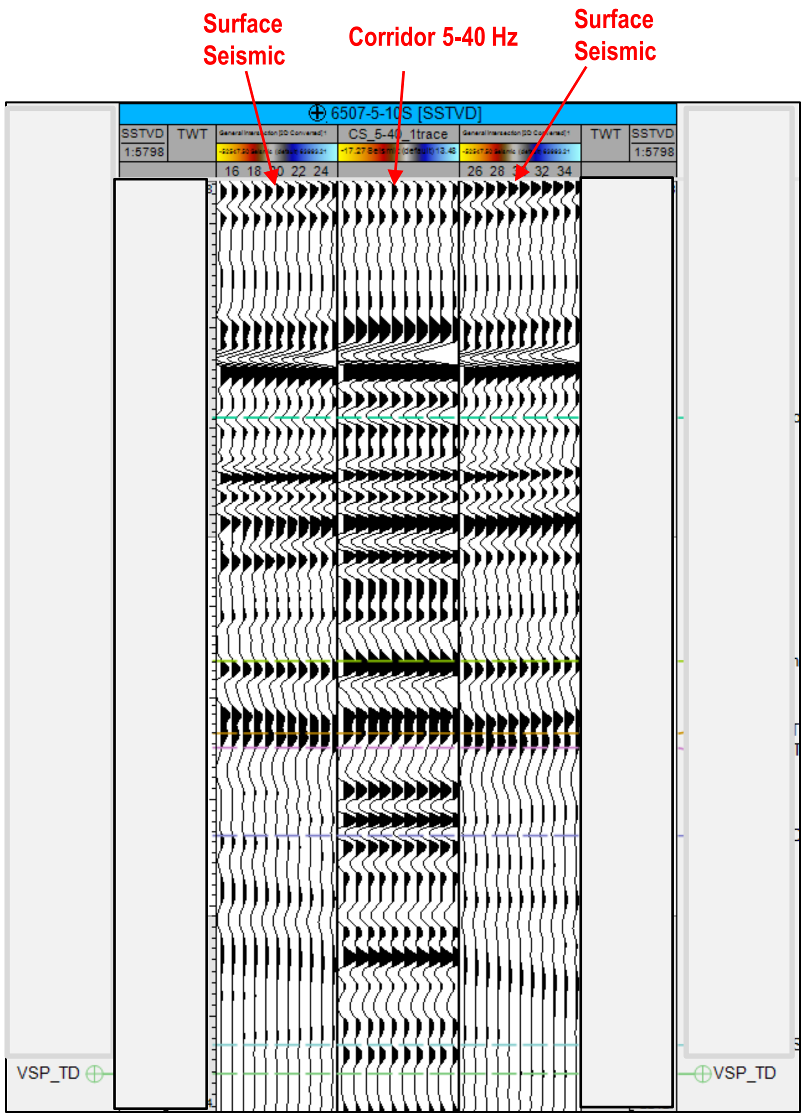
Fundamentals of Borehole Seismic Technology *(Kelsall, Rufino & Guerra, 2022)*

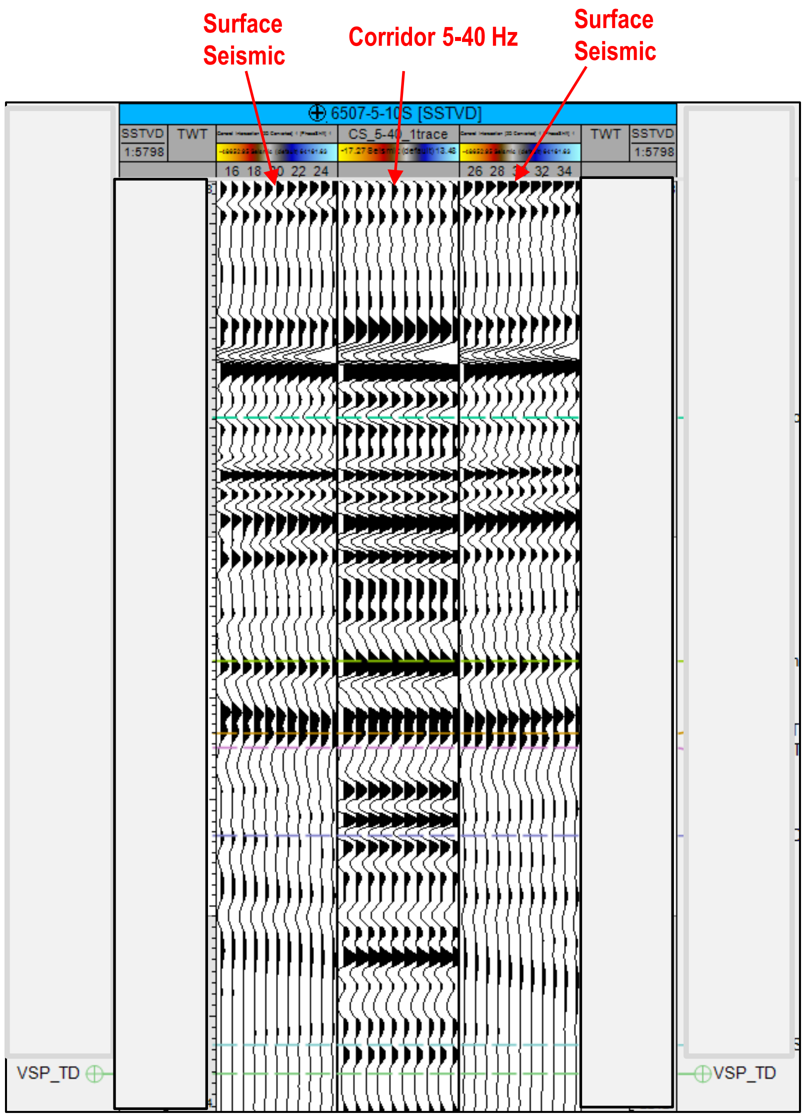
Corridor Stack with Seismic along well – Time – Top



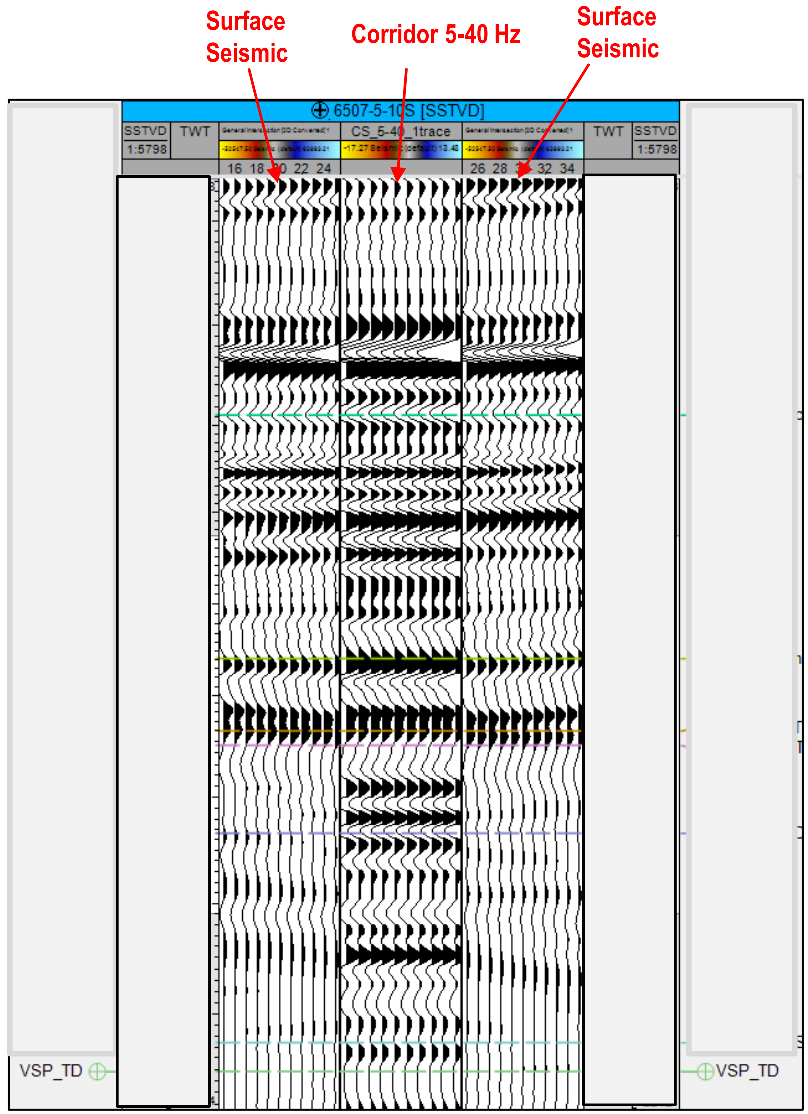
No time and phase shift is applied to the surface seismic

Corridor Stack with Phase and Time Shifted Seismic

A -0.002s time shift and 13deg phase shift is applied to the surface seismic



Quantitative Borehole Matching - terminology



A -0.003s time shift is applied to the surface seismic

Quantitative Borehole Matching *- terminology*

- The algorithms derive from Roy White's original partial coherency matching (1980), *extended to include frequency-dependent Predictability and Confidence*
- **Predictability** - frequency-dependent measure of similarity between two traces
- **Confidence** - statistical confidence measure calculated for the Predictability
- **Goodness of Fit** - normalized cross-correlation between filtered VSP and Seismic
- **Transfer Function (wavelet)** – from spectral division between Seismic and VSP

$$seismic(t) \sim vsp(t) * tf(t) \rightarrow \quad w1(t) \sim w2(t) * tf(t)$$

$$\rightarrow \quad TF(f) \sim W1(f)W2^*(f) \,/\, W2(f)W2^*(f)$$

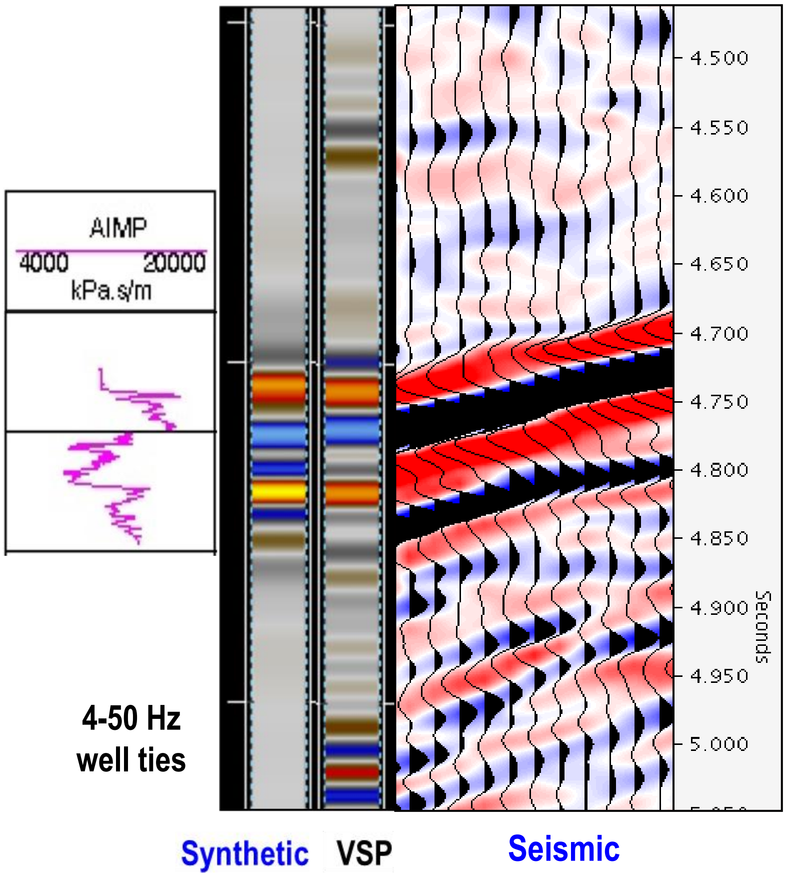
Guerra et al -2021

Geophysical Prospecting, 1980, 28, 333–358.

PARTIAL COHERENCE MATCHING OF SYNTHETIC SEISMOGRAMS WITH SEISMIC TRACES*

R.E. WHITE**

Standard three-way well ties



Standard well tying workflows provide:

- Indicators of match quality using synthetics & VSP: *correlation coefficient, time and phase shifts*
- Best matching location using synthetic
- Seismic wavelet extracted using reflectivity log

Quantitative borehole matching makes full use of the VSP corridor stack.

→ ***What does it provide?***

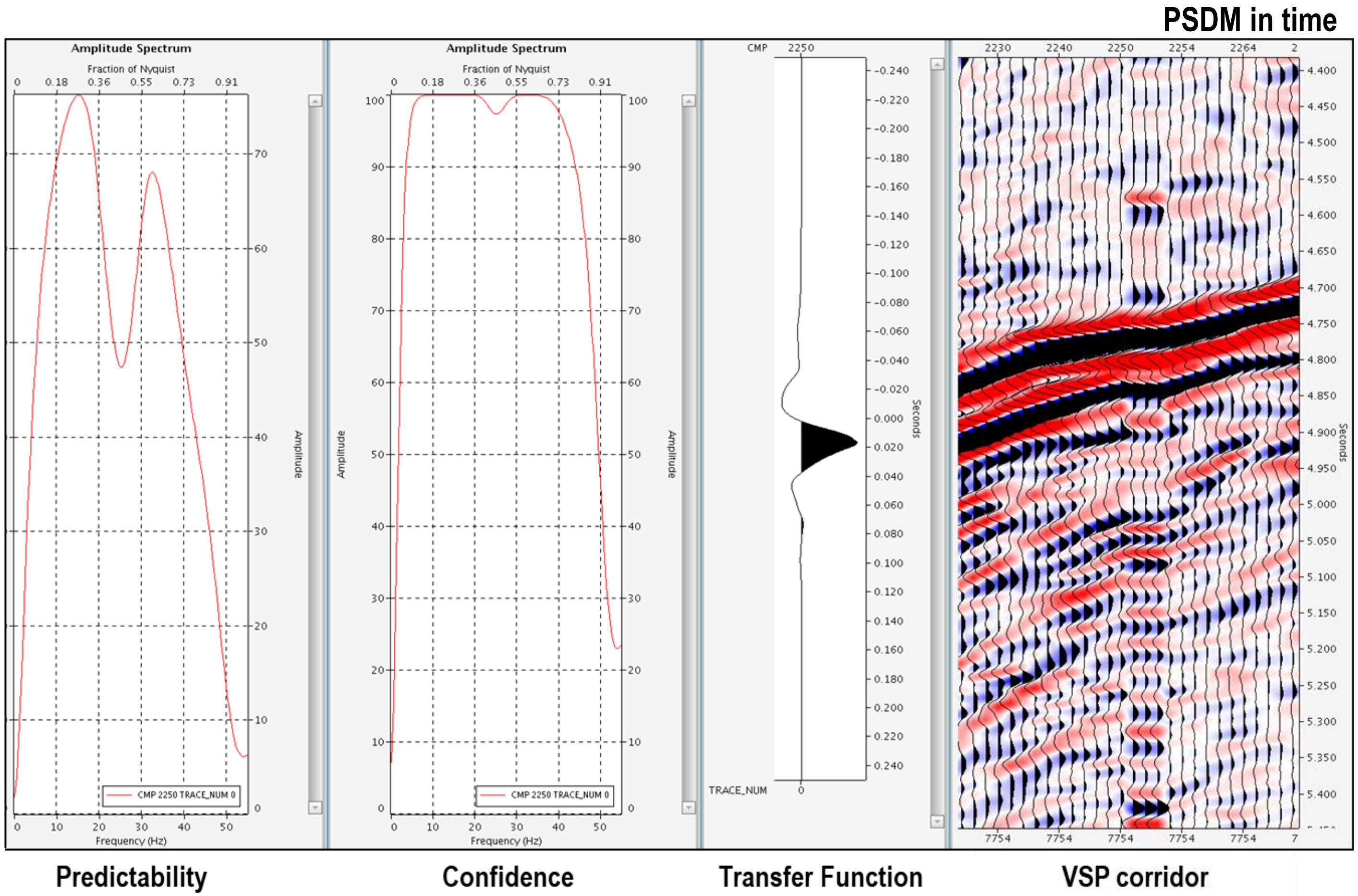
Guerra et al -2021

Predictability, confidence and seismic wavelet

Using VSP corridor stack:

- Analysis time window of 450 ms around target
- Predictability over ~ 5 - 45Hz
- Confidence > 90% over 5 - 45Hz
- The Transfer Function is a simple wavelet, carrying the time and phase-shifts

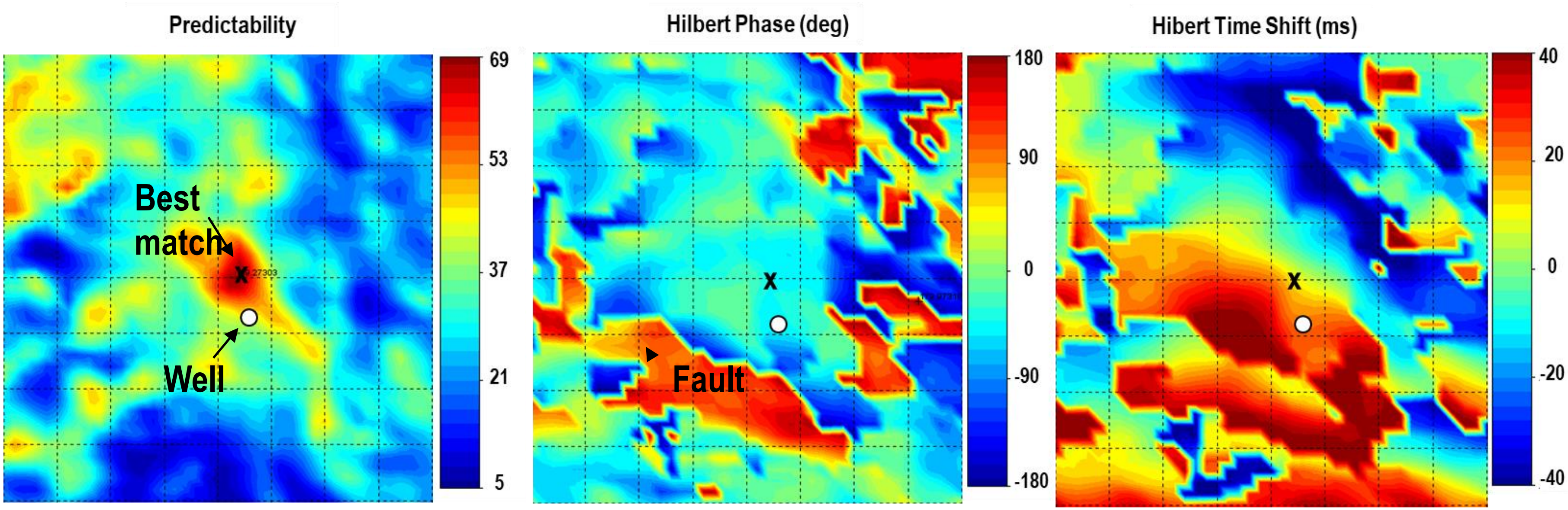
9



Guerra et al -2021

VSP scanning around the well

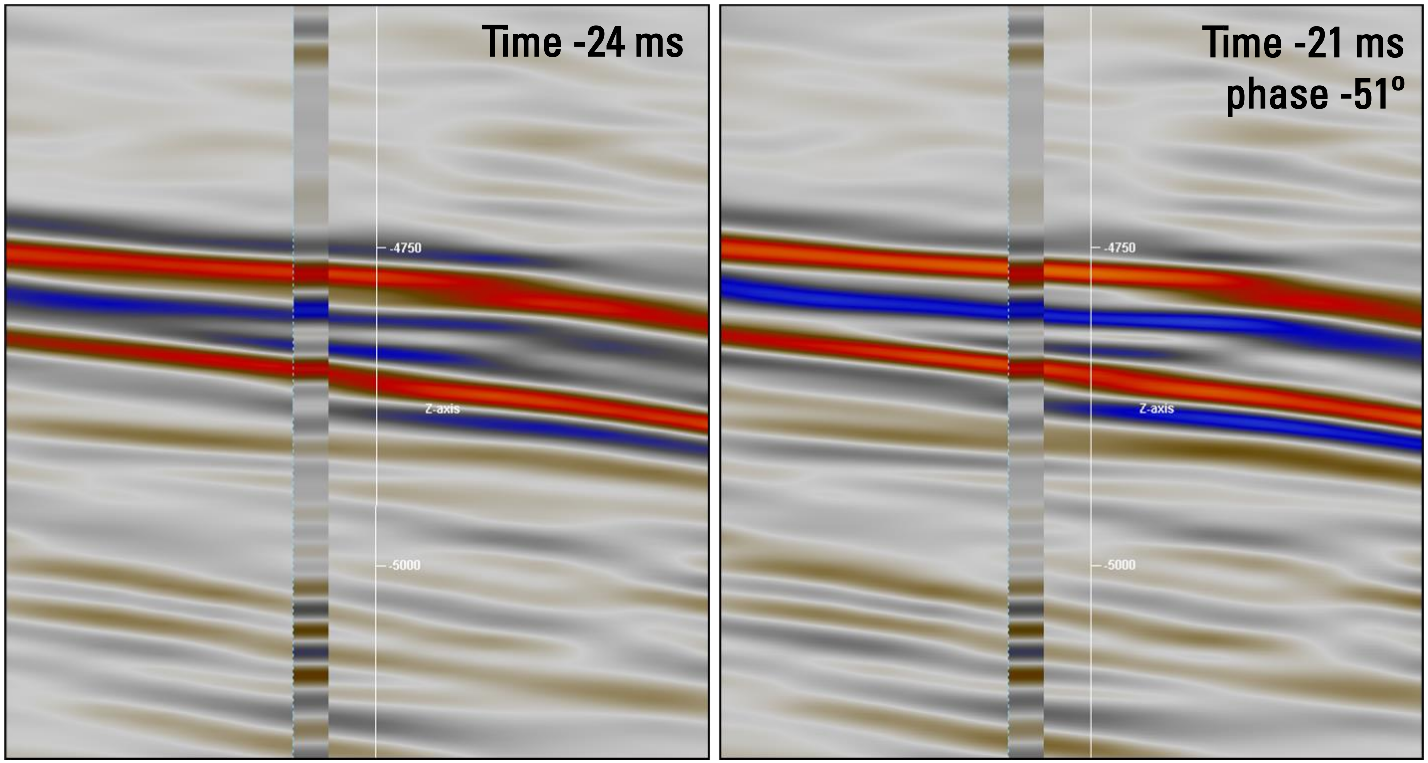
Area of study:
2 km x 2km



- At best match location with predictability of 69%, the seismic is phase rotated 41° and shifted 12 ms
- At well location, the seismic is phase rotated by 51° and shifted 21 ms relative to the VSP
- The cross-correlation of VSP & seismic is low far from the well and there are faults, thus the discontinuities

Guerra et al -2021

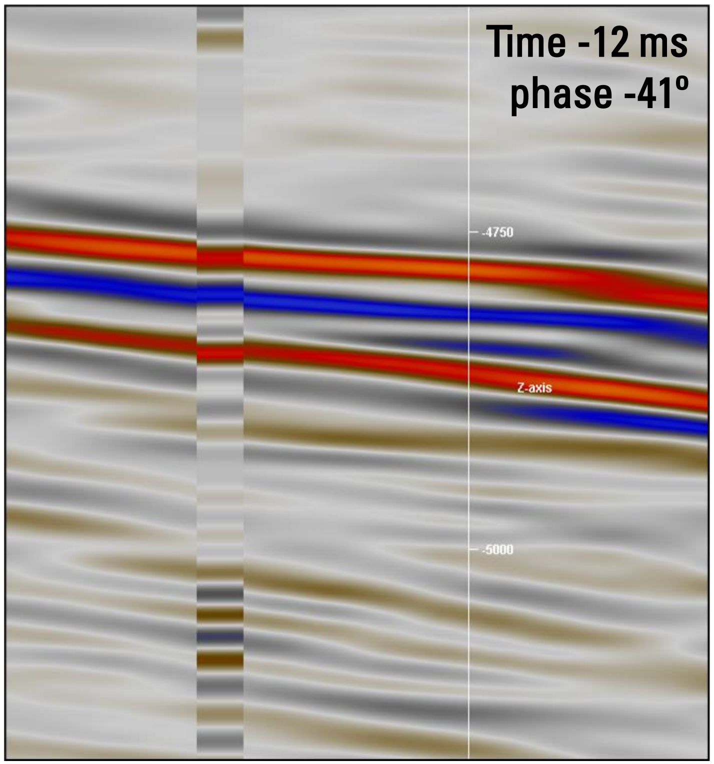
Correcting time and phase shifts *(inline)*



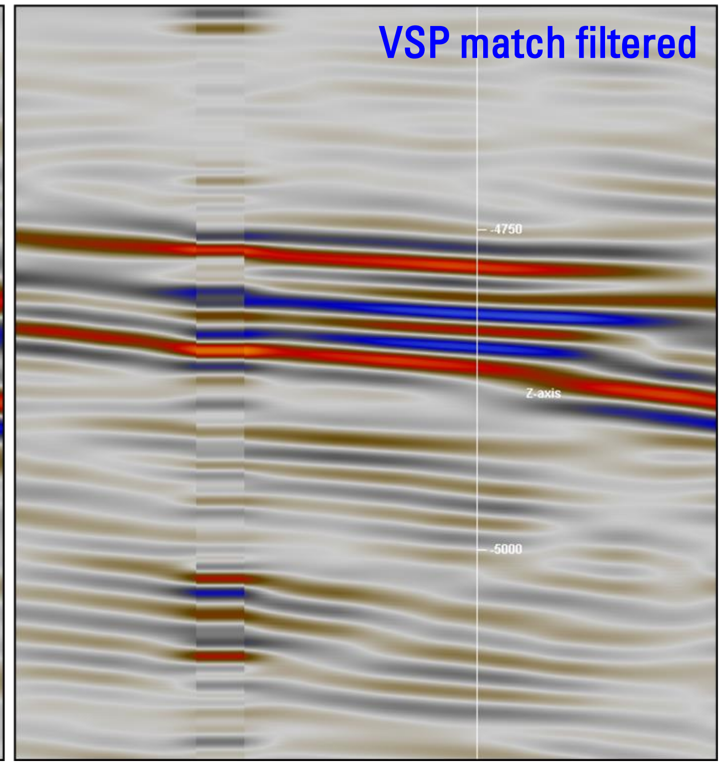
Guerra et al -2021

Correcting also the amplitude spectra *(inline)*

4-30 Hz corridor stack
at best matching location



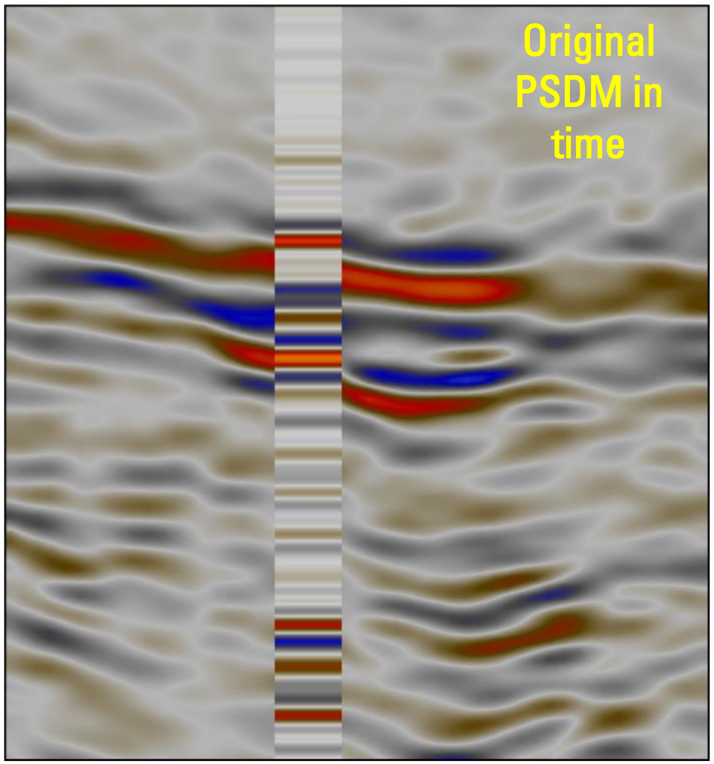
4-80 Hz corridor stack
at best matching location



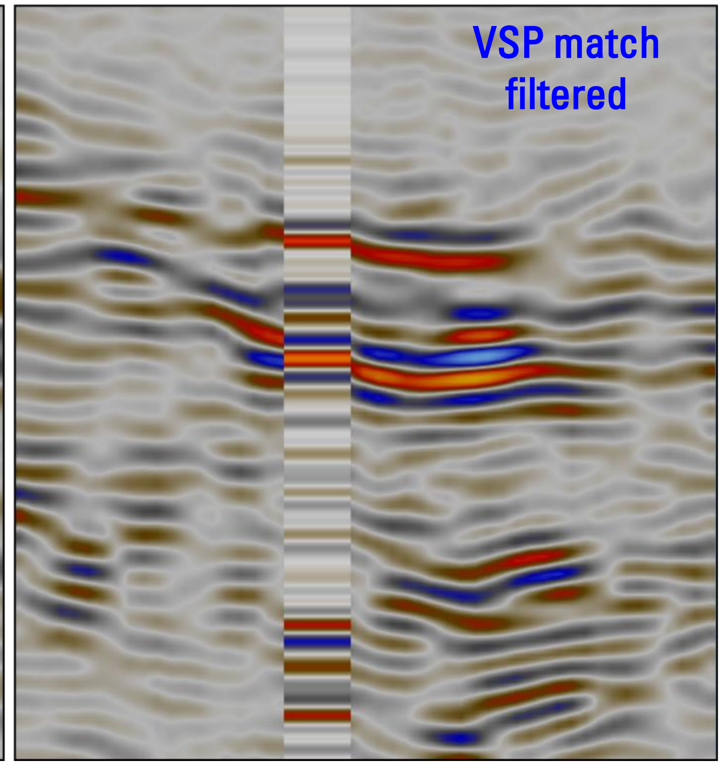
Guerra et al -2021

Correcting also the amplitude spectra *(crossline)*

4-80 Hz corridor stack
at best matching location



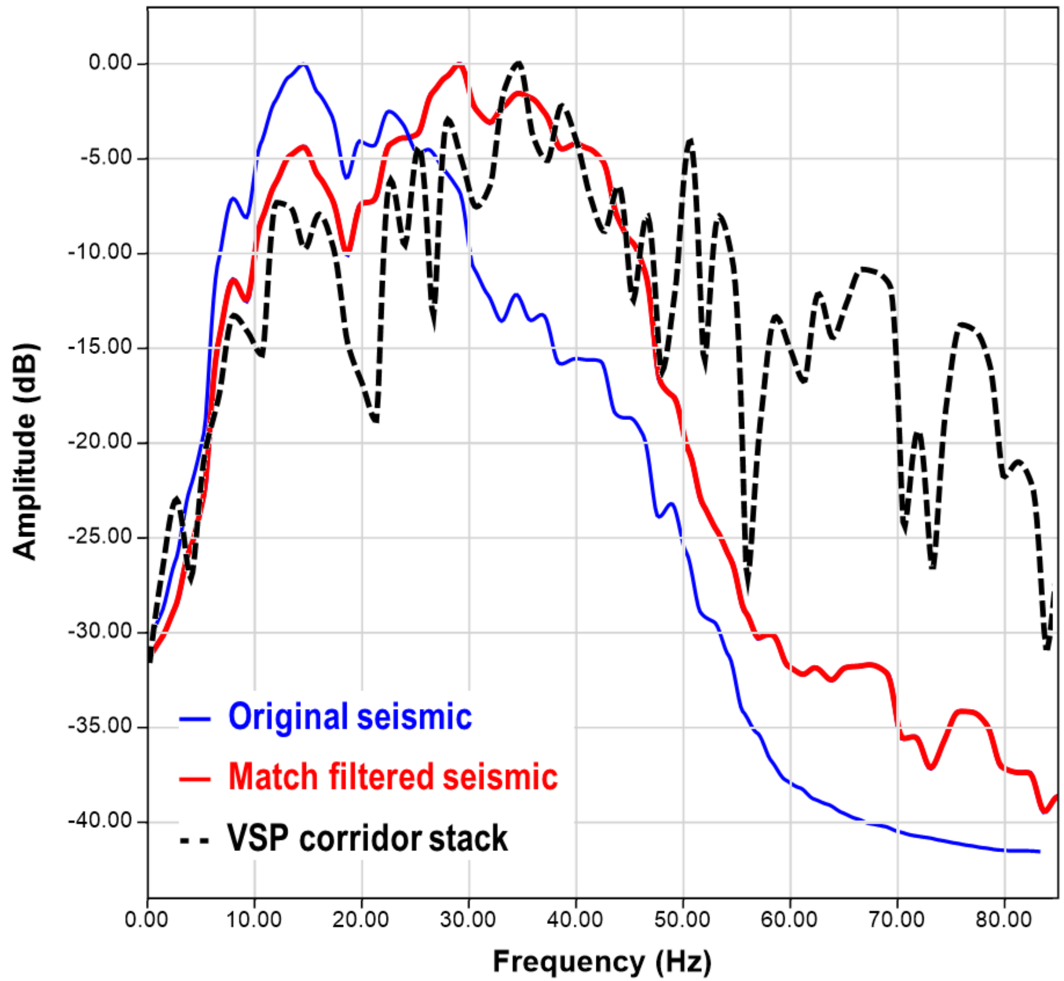
4-80 Hz corridor stack
at best matching location



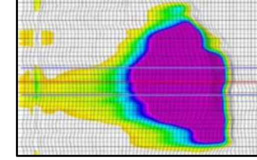
Guerra et al -2021

Frequency Spectra

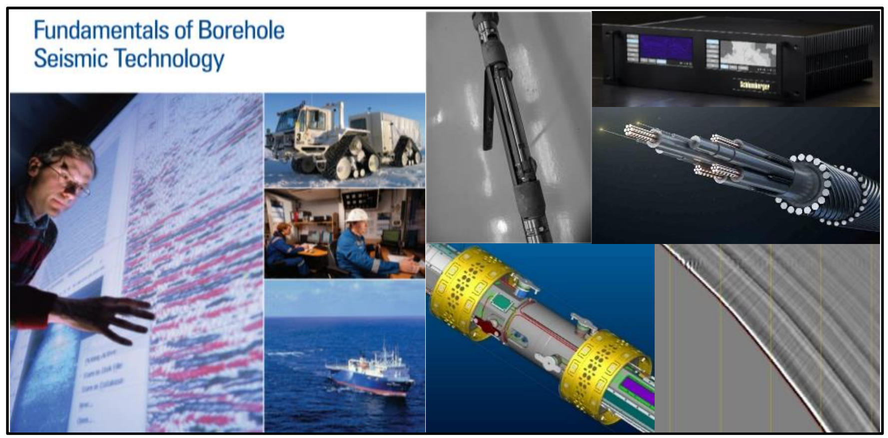
- Surface seismic frequency spectrum is not flat
- VSP waveshape deconvolution wavelet is Butterworth 6th order
- After match filtering the surface seismic spectrum is balanced over the usable bandwidth



Guerra et al -2021



Q(z) Factor



Stavanger, 04-Oct-2022

Q Analysis

What is Q?

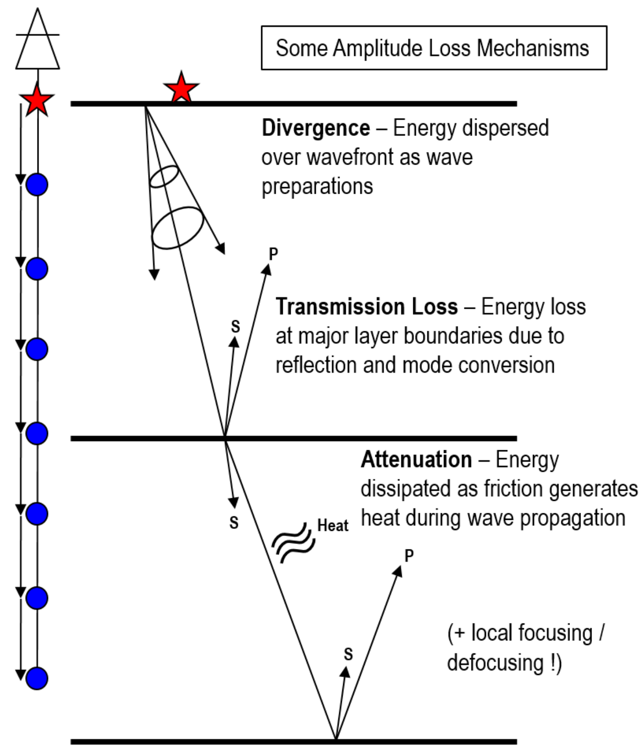
- **Q (Quality Factor)** is a measure of the anelastic attenuation of seismic waves.

  = a measure of the absorption strength of a material.
  = a measure of the quality of a rock in transmitting high frequencies.

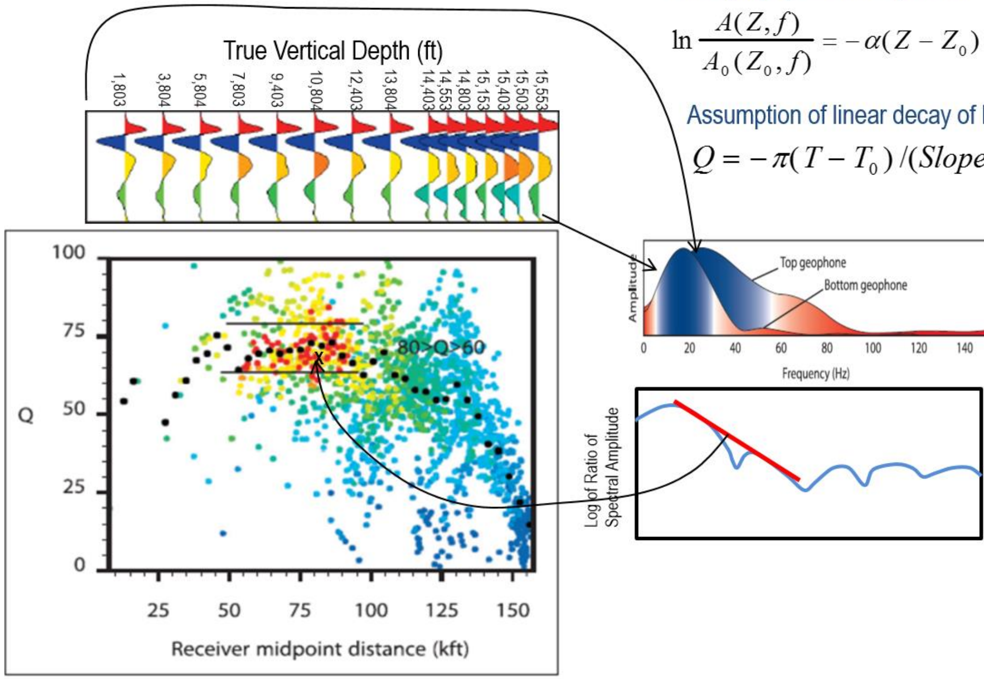
- **VSP** can provide direct Q measurement because the downward propagating pulse can be isolated at each depth in the well.
  - Advantage to detect Q variation in depth

- Q definition in this analysis
  - High Q value = Less attenuation
  - Low Q value = Significant attenuation

Q Measurement by VSP



Q Analysis by Spectral Ratio Method

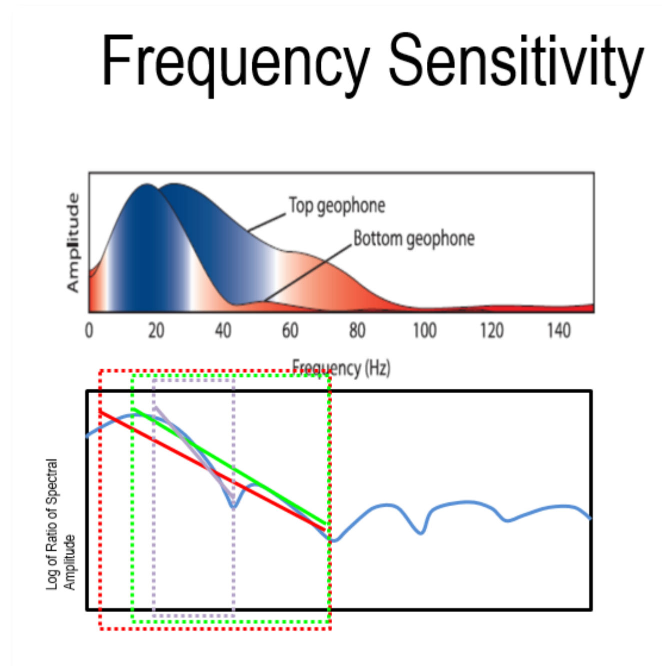


Wave propagation in logarithm

$$\ln \frac{A(Z,f)}{A_0(Z_0,f)} = -\alpha(Z - Z_0) = -\pi f(T - T_0)/Q$$

Assumption of linear decay of ln(A):

$$Q = -\pi(T - T_0)/(Slope)$$



The multi spectral ratio method uses all possible pairs of receivers to improve the statistical significance of Q estimates. The total number of trace pairs available from N traces is N (N-1)/2. In practice about half of all possible receiver point pairs have insufficient time difference and can be discarded based on a quality of fit condition coefficient threshold.

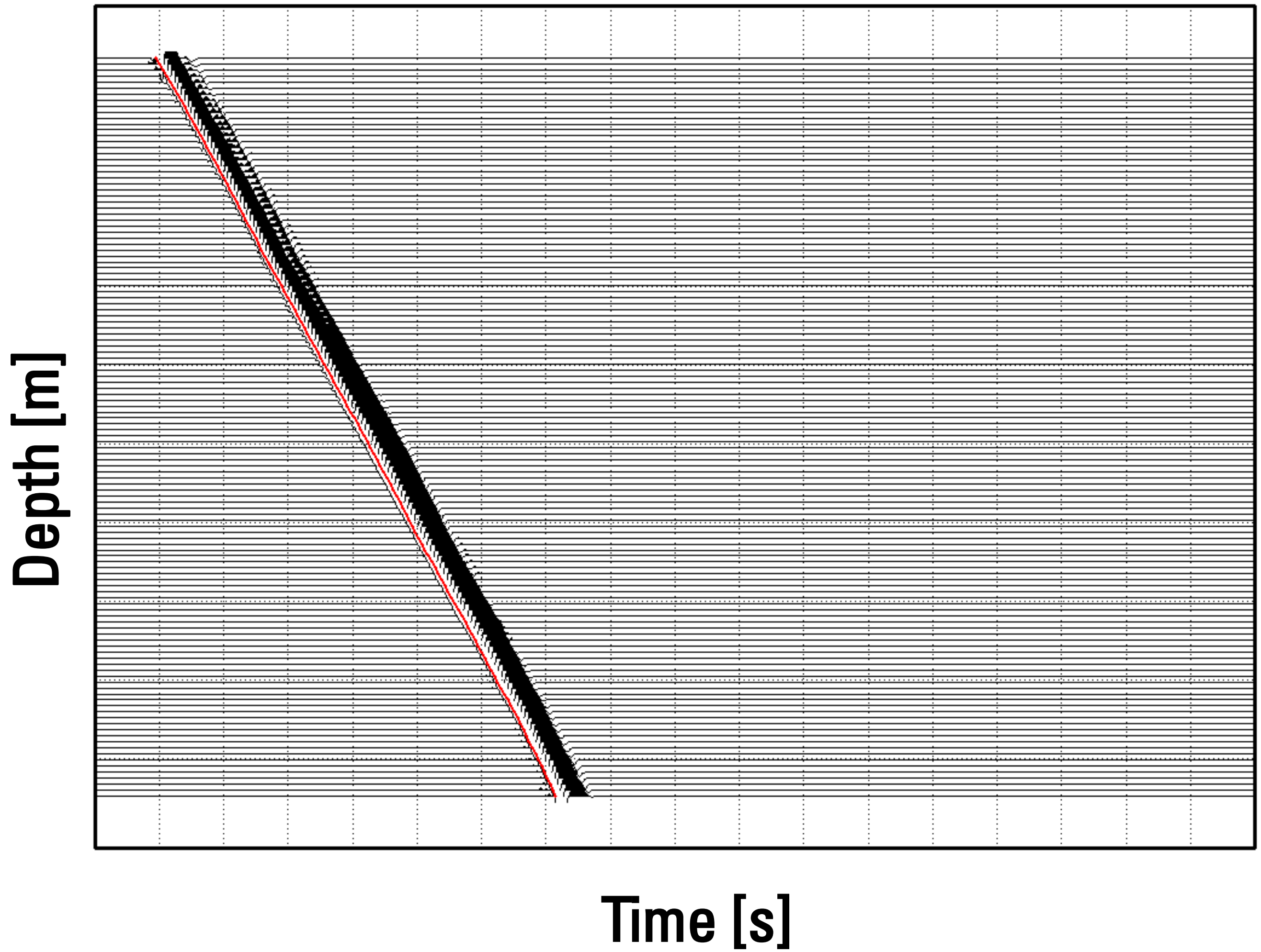
True amplitude

Cable Legth = Measured Depth

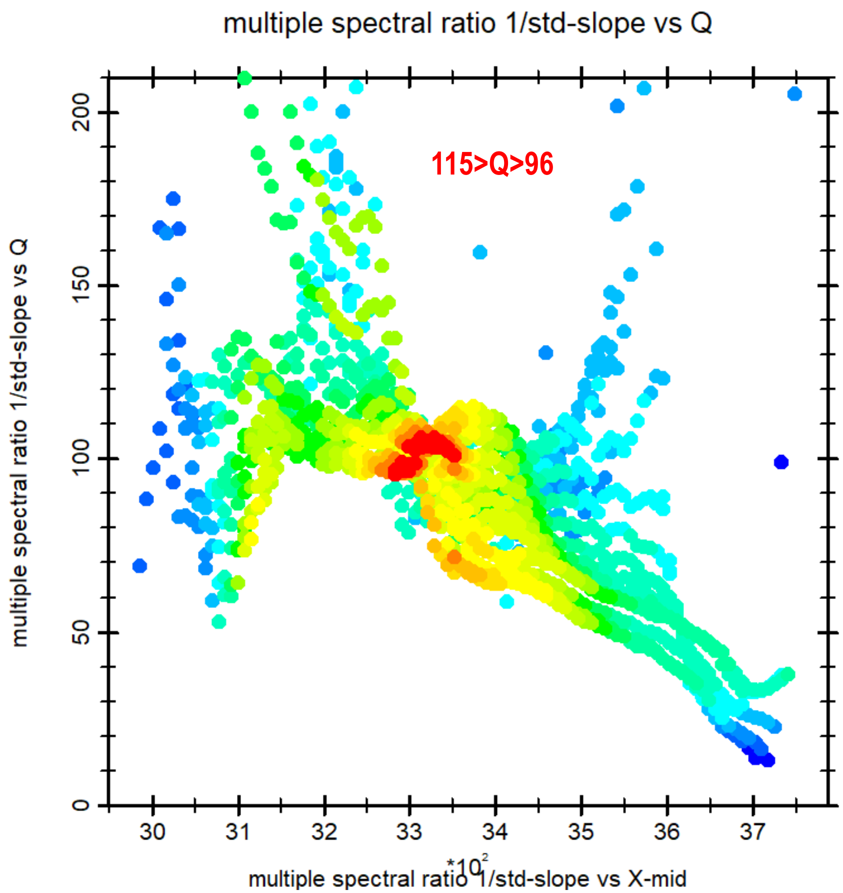
Muted Downgoing Wavefield – Input for Q(z) Analysis

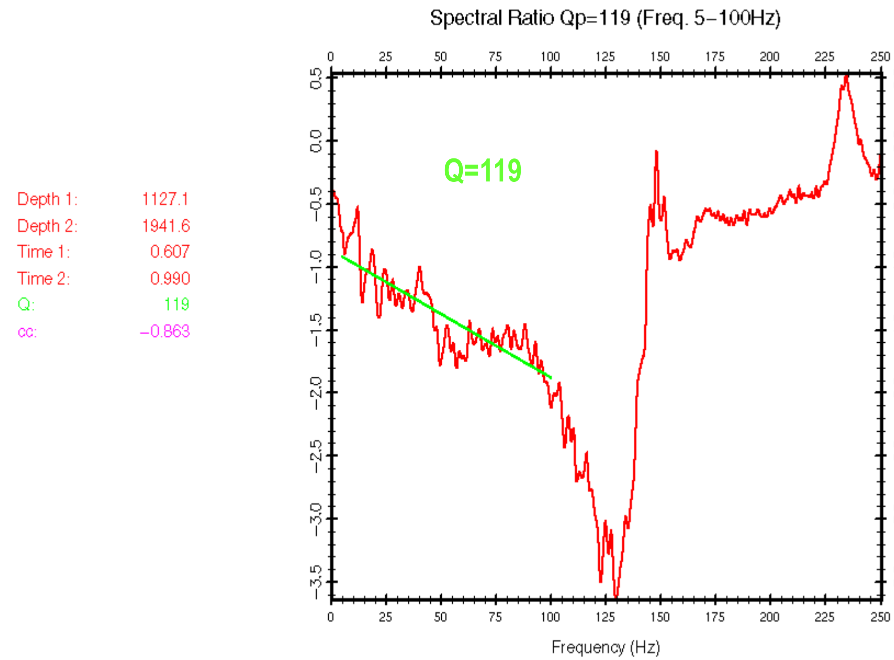
Processing:

- Source Signature Deconvolution in Raw Shots
- Stack Raw Shot after SSD
- - Wave field separation
    - Velocity filter
- Muting around First Arrival
    - 60ms



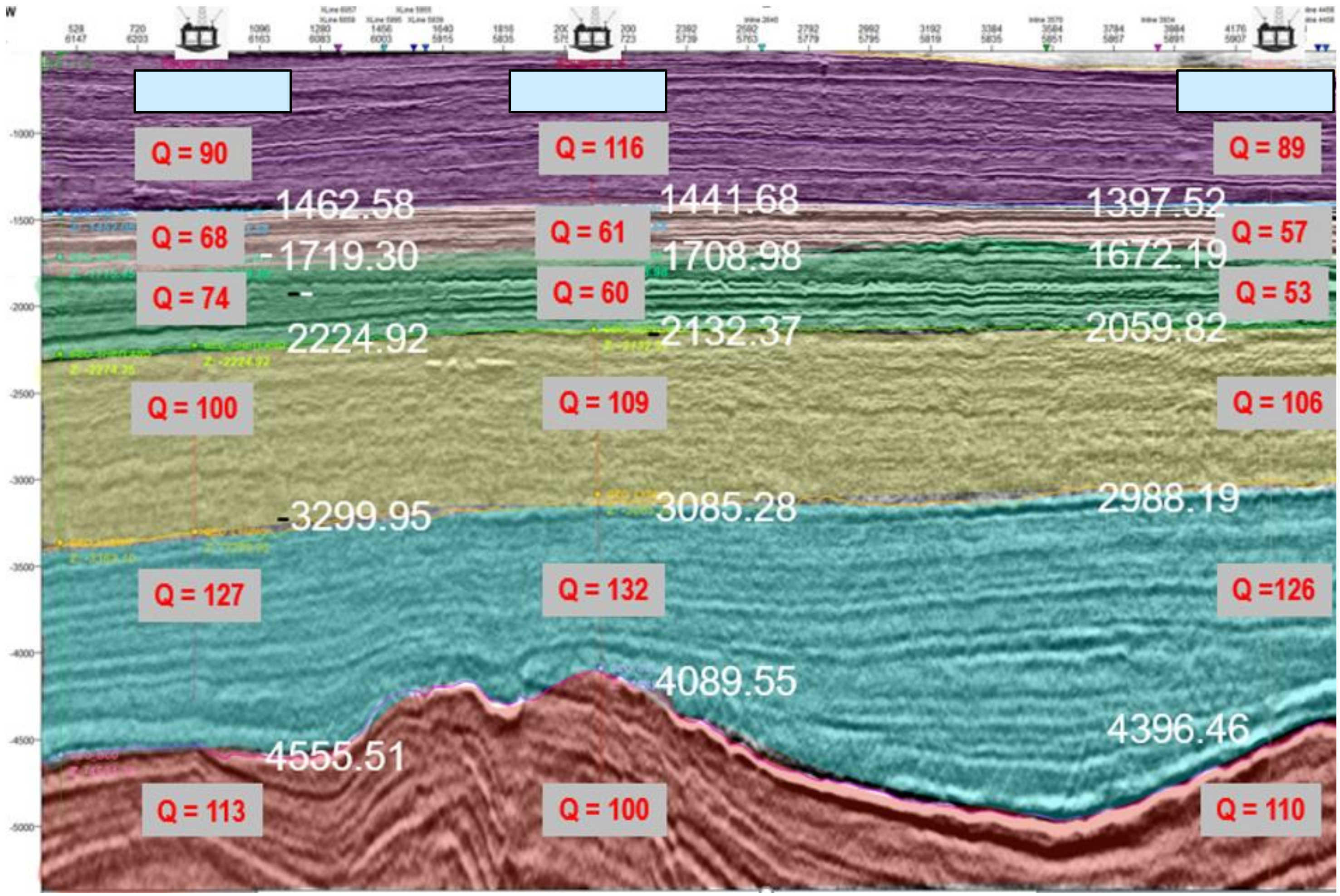
Q Analysis –Multi-Spectral Ratios and Spectral Ratios





Uses top and bottom selected receiver

Q(z) VSP layered Velocity Model
– Input for Surface Seismic Migration

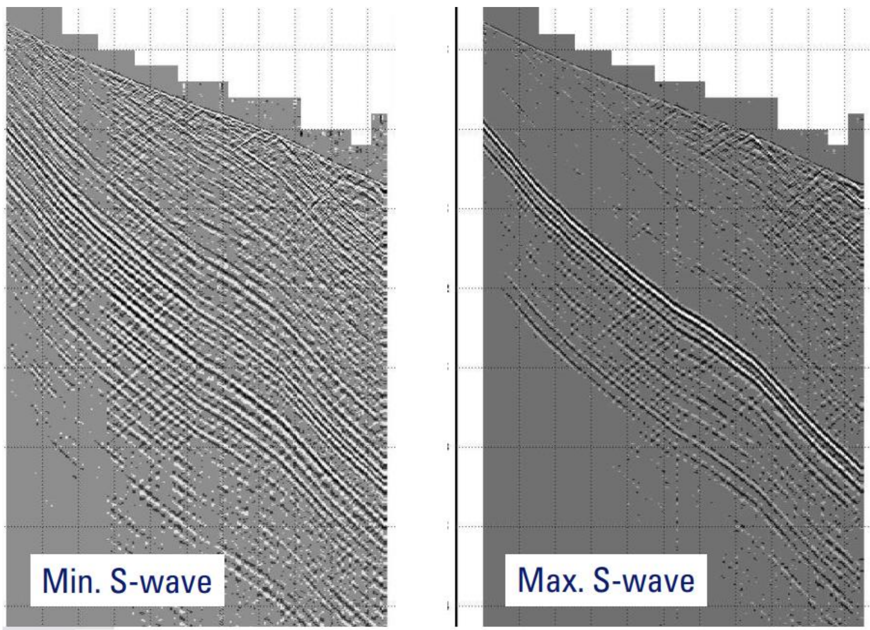


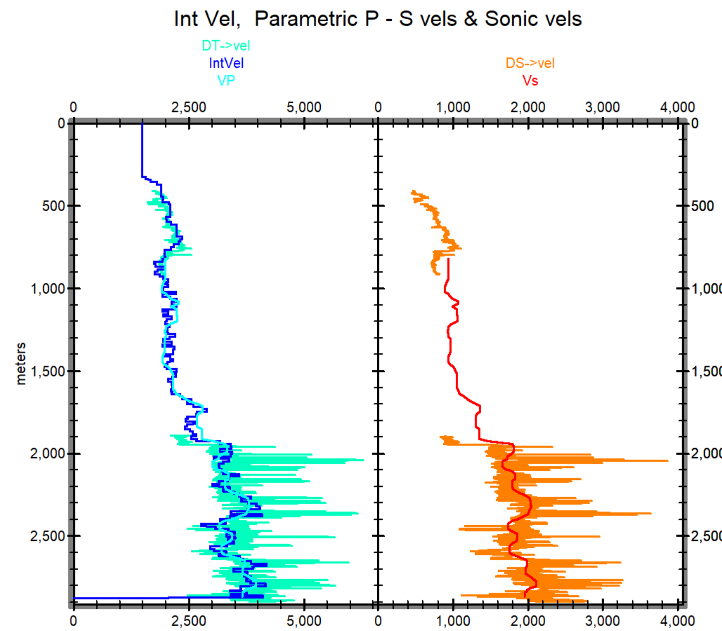
NORWEGIAN PETROLEUM DIRECTORATE
50 years

FORCE

NPD FORCE Geophysical Methods Group

Fundamentals of Borehole Seismic Technology



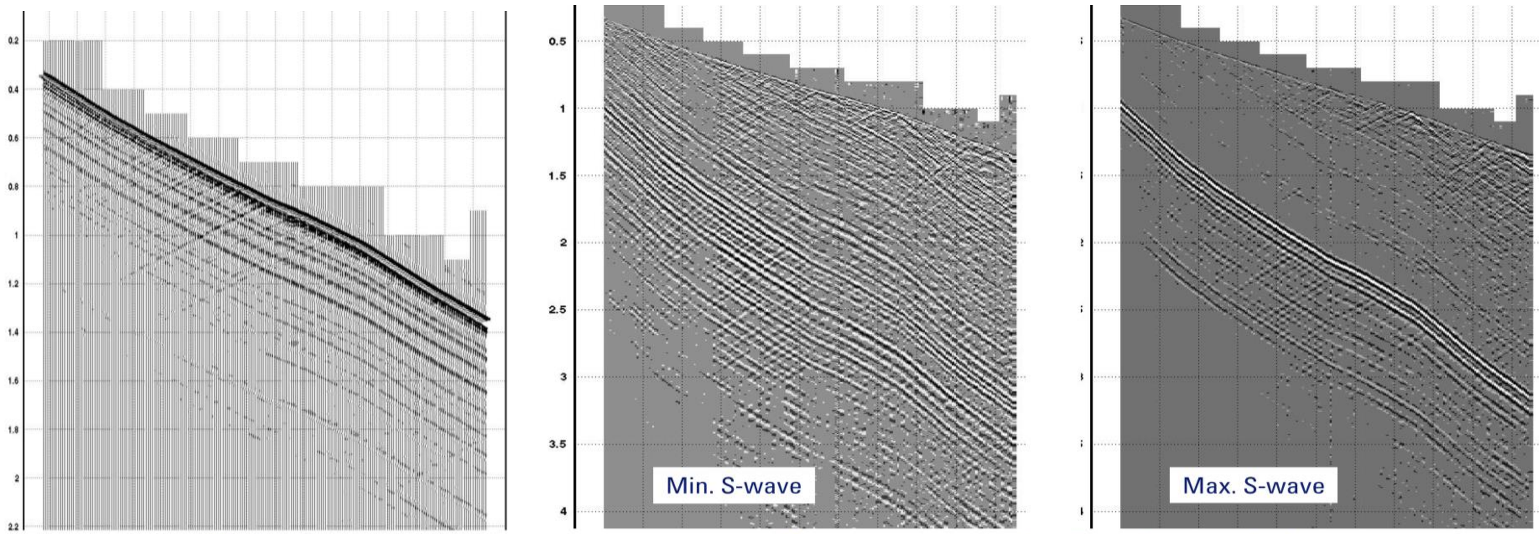


Armstrong et al 2001

VSP Shear Waves

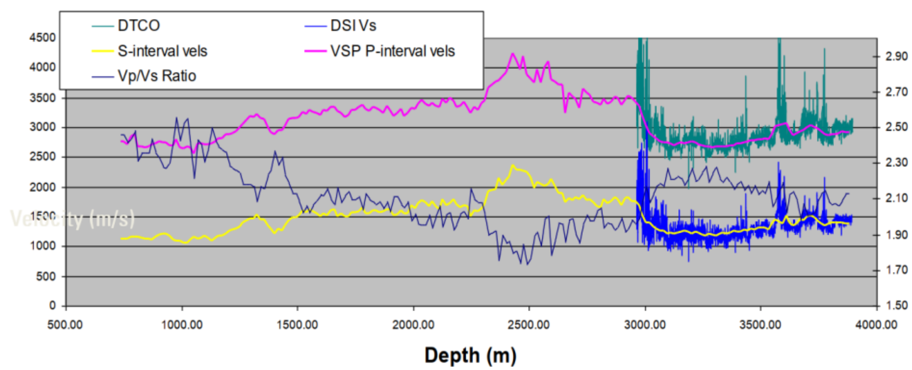
Stavanger, 04-Oct-2022

Land VSP P-Wave Source
Shear Waves & Sonic Calibration



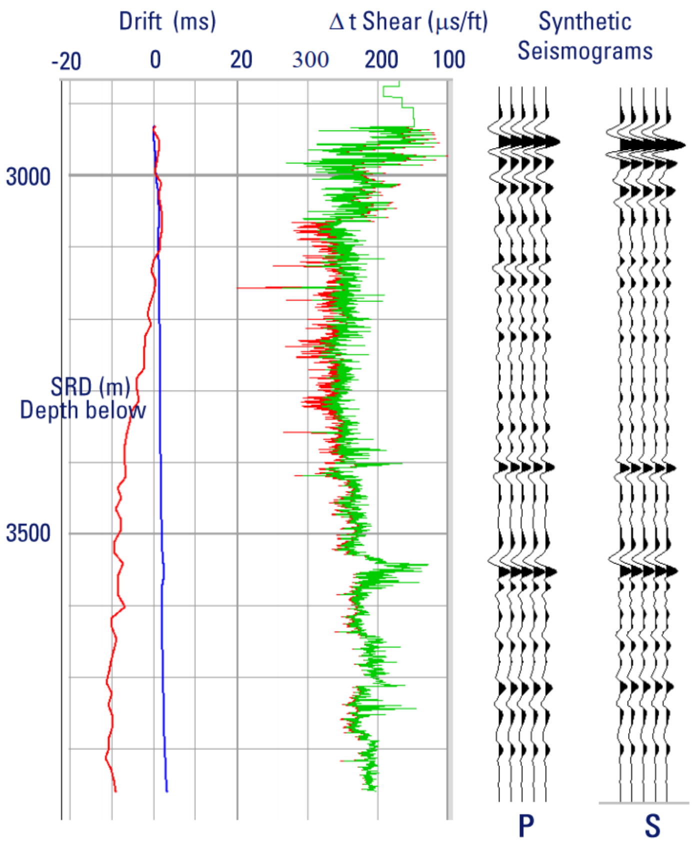
Z-component

H-components rotated on direct S-wave arrival

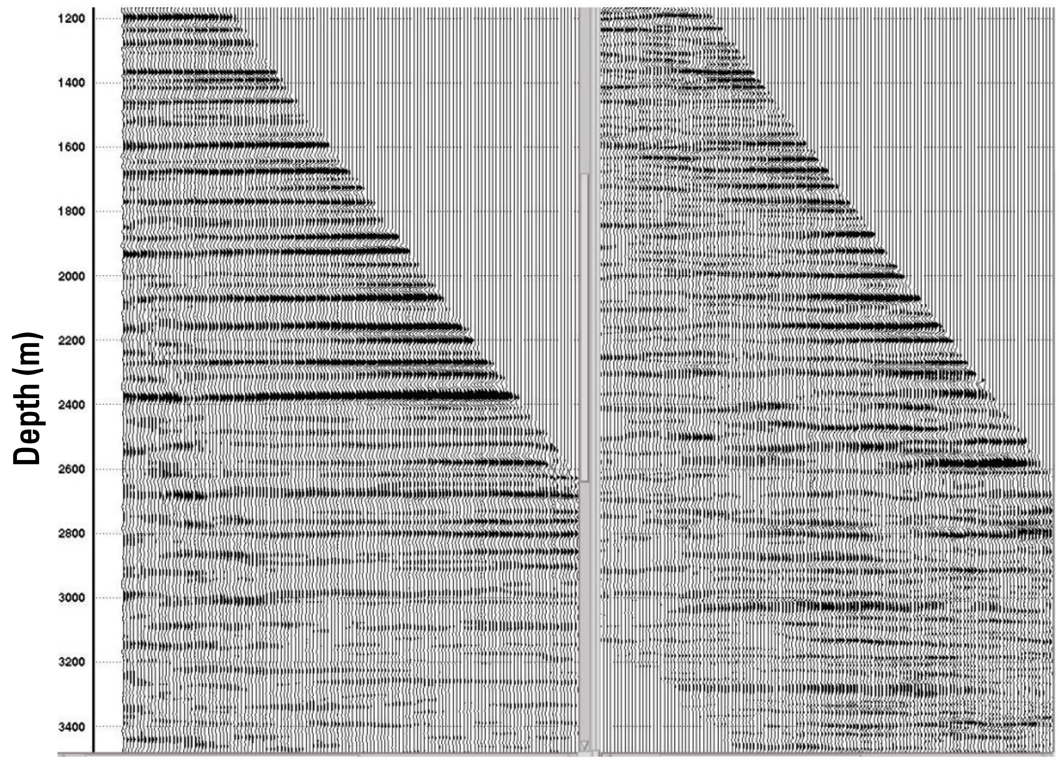


Armstrong et al 2001

Land VSP P-Wave Source
Shear Waves & Sonic Calibration



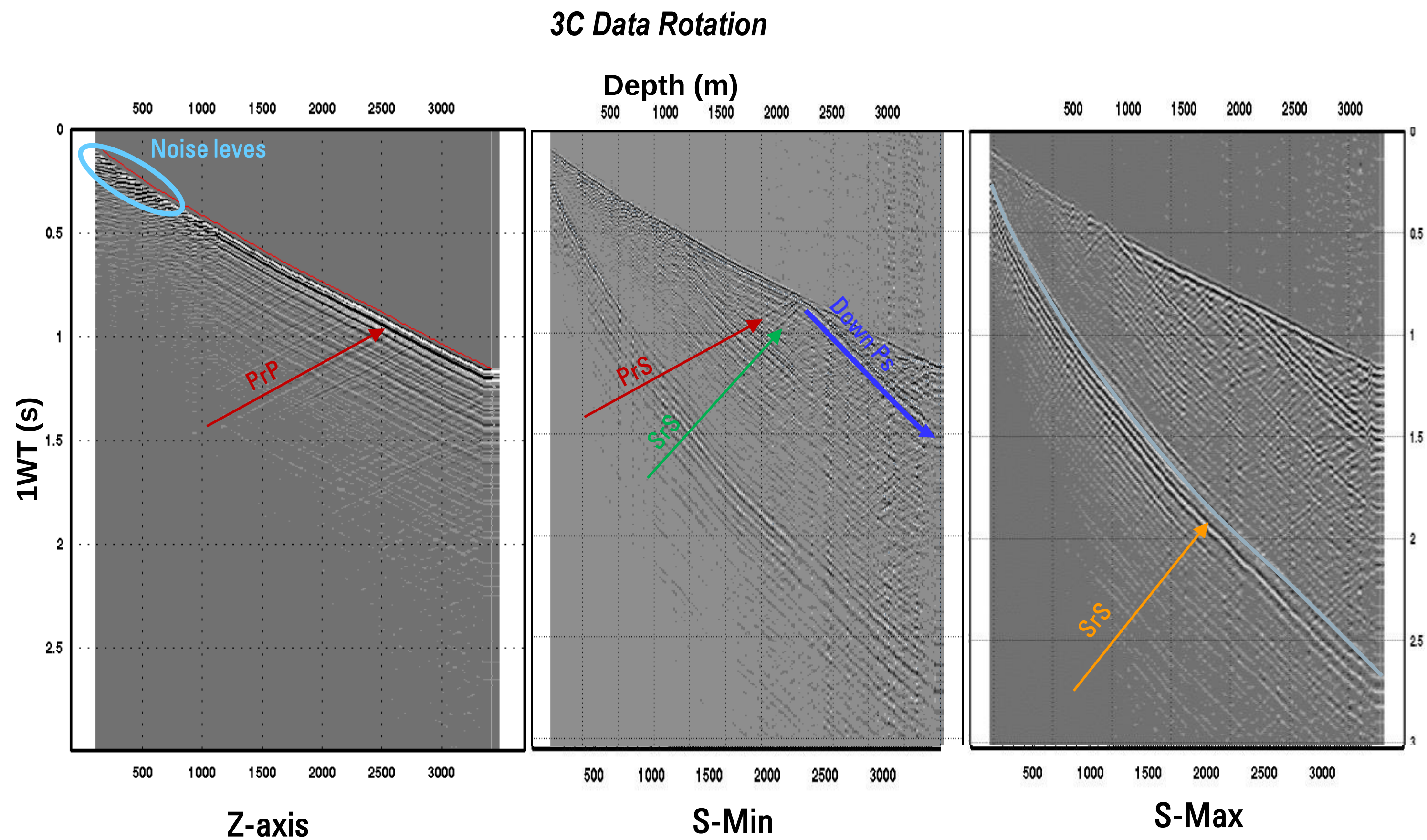
Synthetic Seismogram



P-VSP

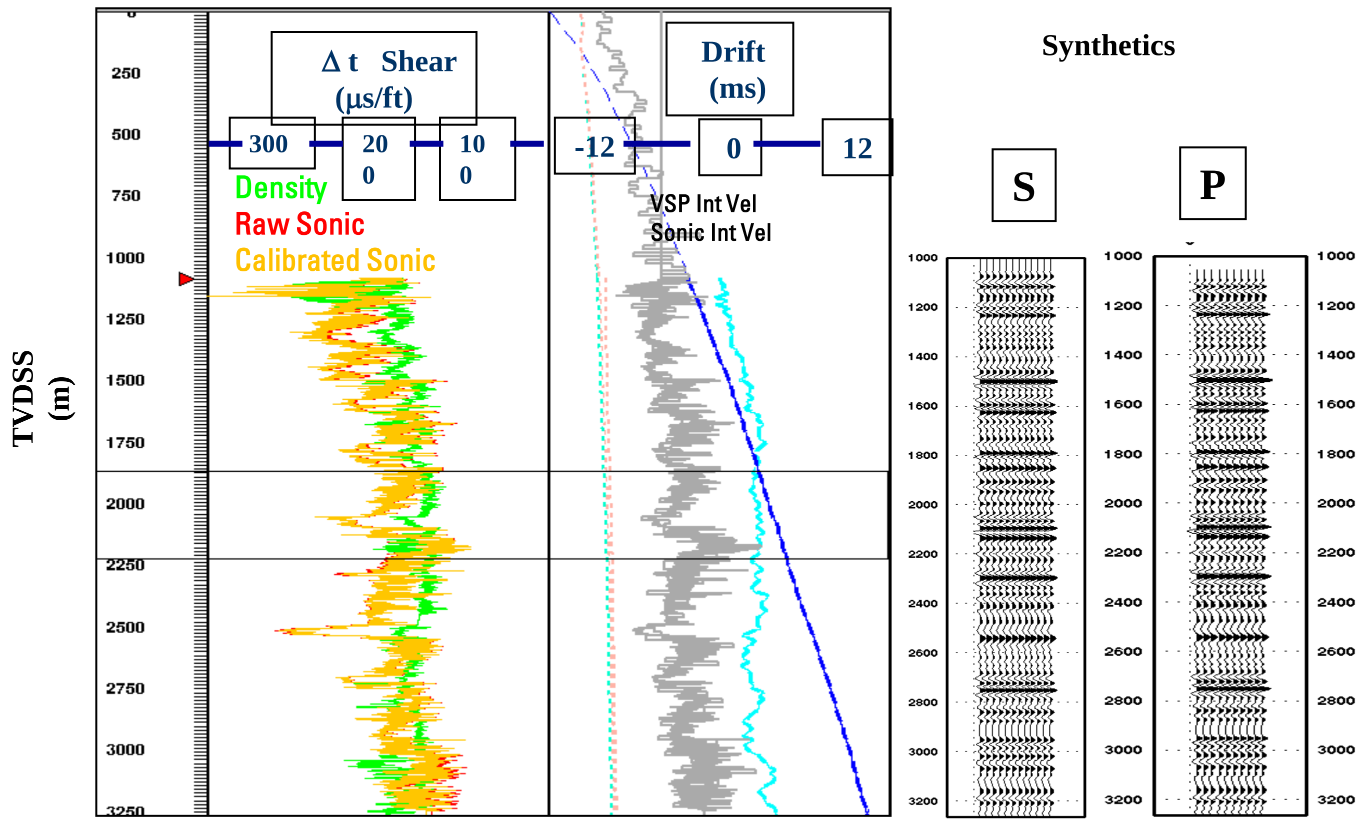
S-VSP

Land VSP P-Wave Source
Zero Offset VSP



Oilfield Review 2004

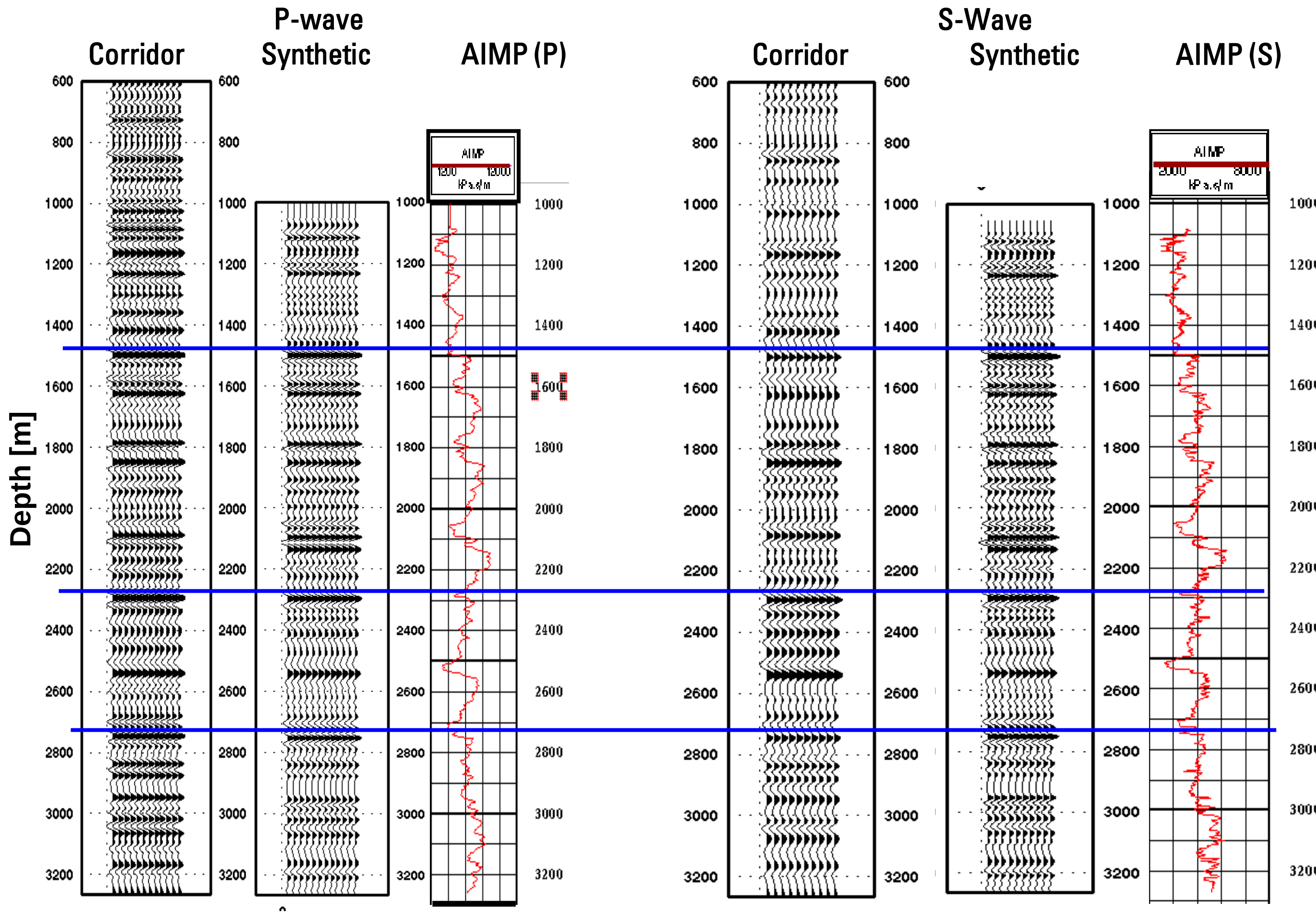
VSP Shear Waves & Sonic Calibration



Drift DTSM: 6ms

Oilfield Review 2004

ZVSP and Synthetics



Oilfield Review 2004

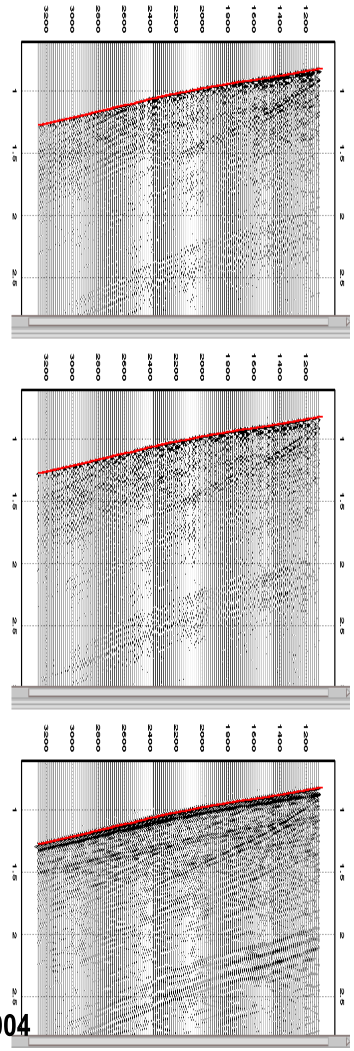
Offset VSP Processing

Raw Data

X-axis

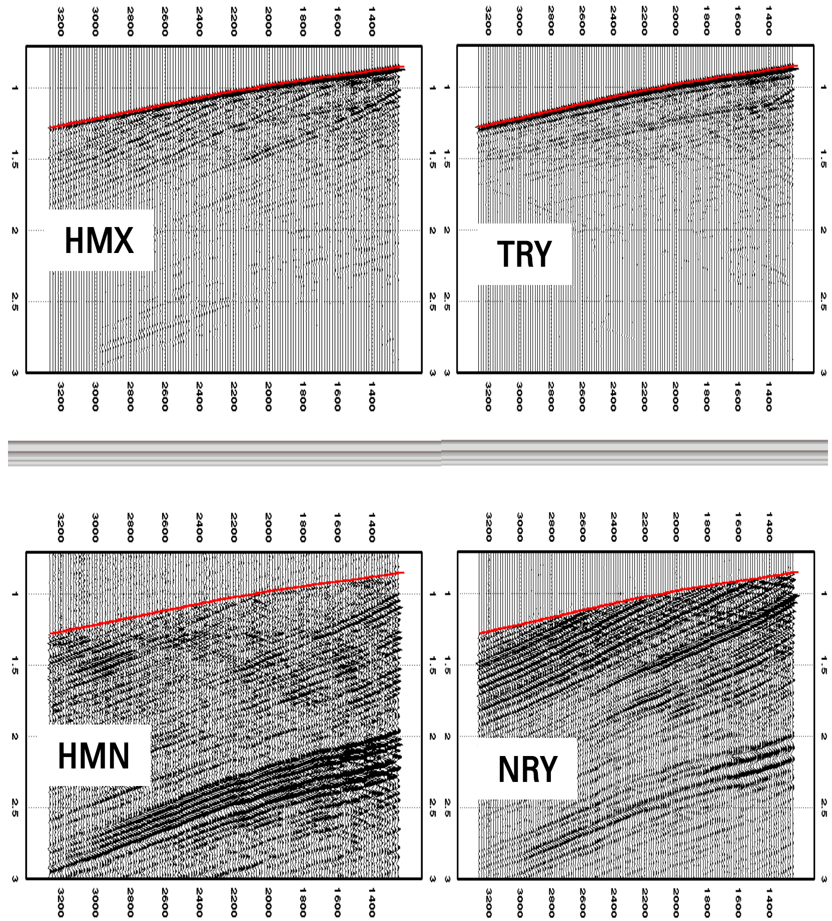
Y-axis

Z-axis



Oilfield Review 2004

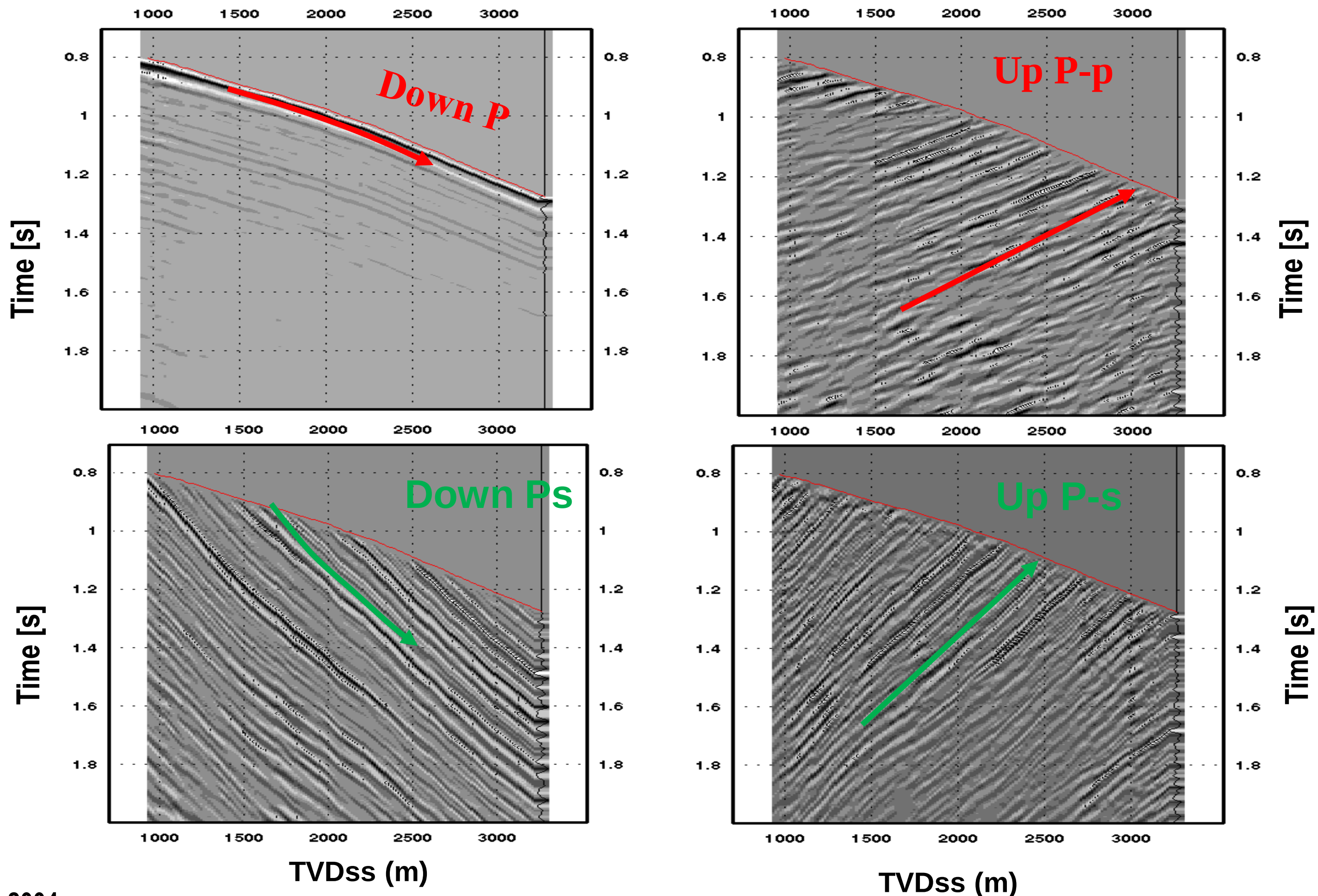
3C Rotated Data



Time [s]

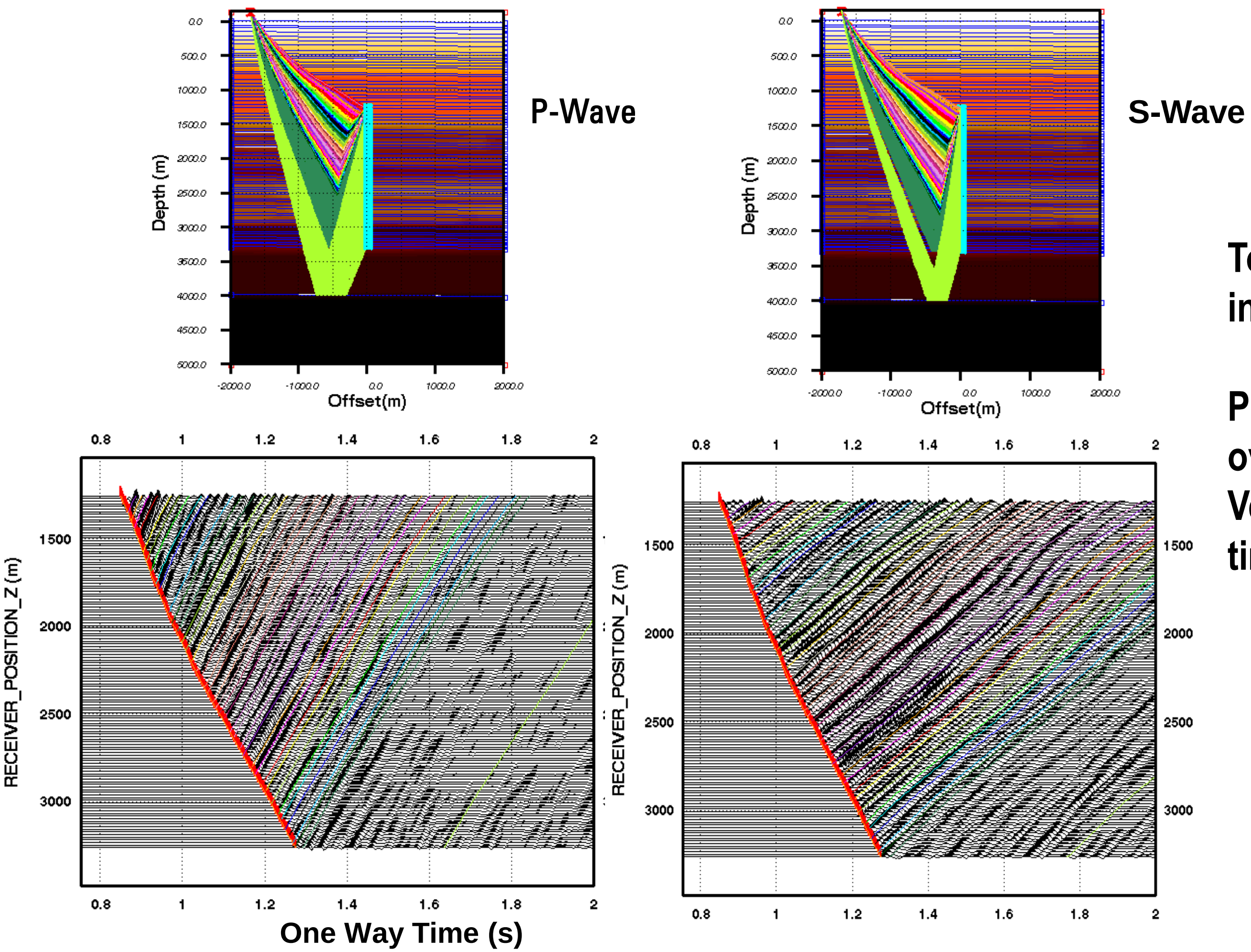
Time [s]

Offset VSP Processing



Oilfield Review 2004

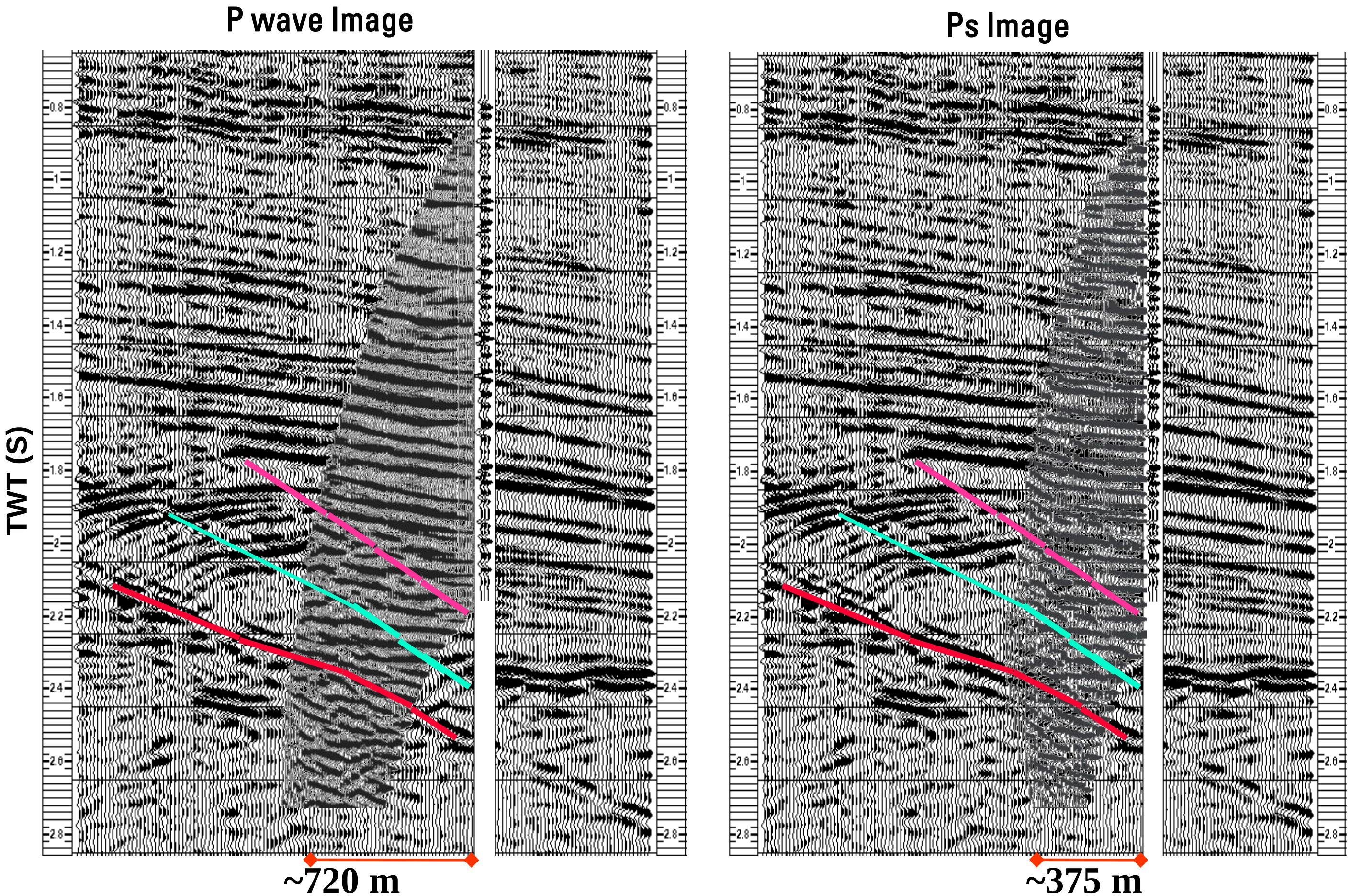
2D Elastic Model Calibration and Validation



Tomographic travel time inversion.

PrP and PrS colored events are overlaying the real data.
Velocity model fits arrival travel times and reflected waves.

Offset VSP PrP and PrS Images



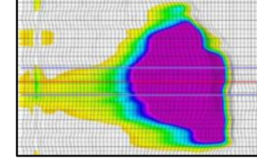
Oilfield Review 2004

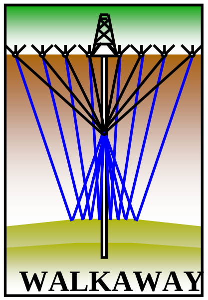
Benefits

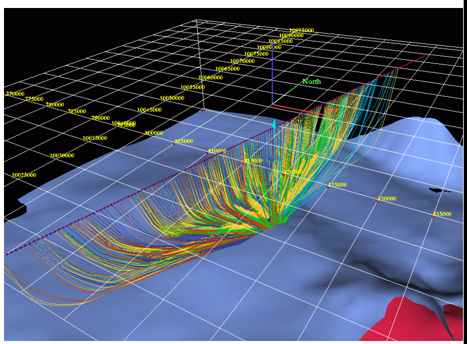
- Elastic Model
- Qp and Qs
- OVSP Fault Confirmation

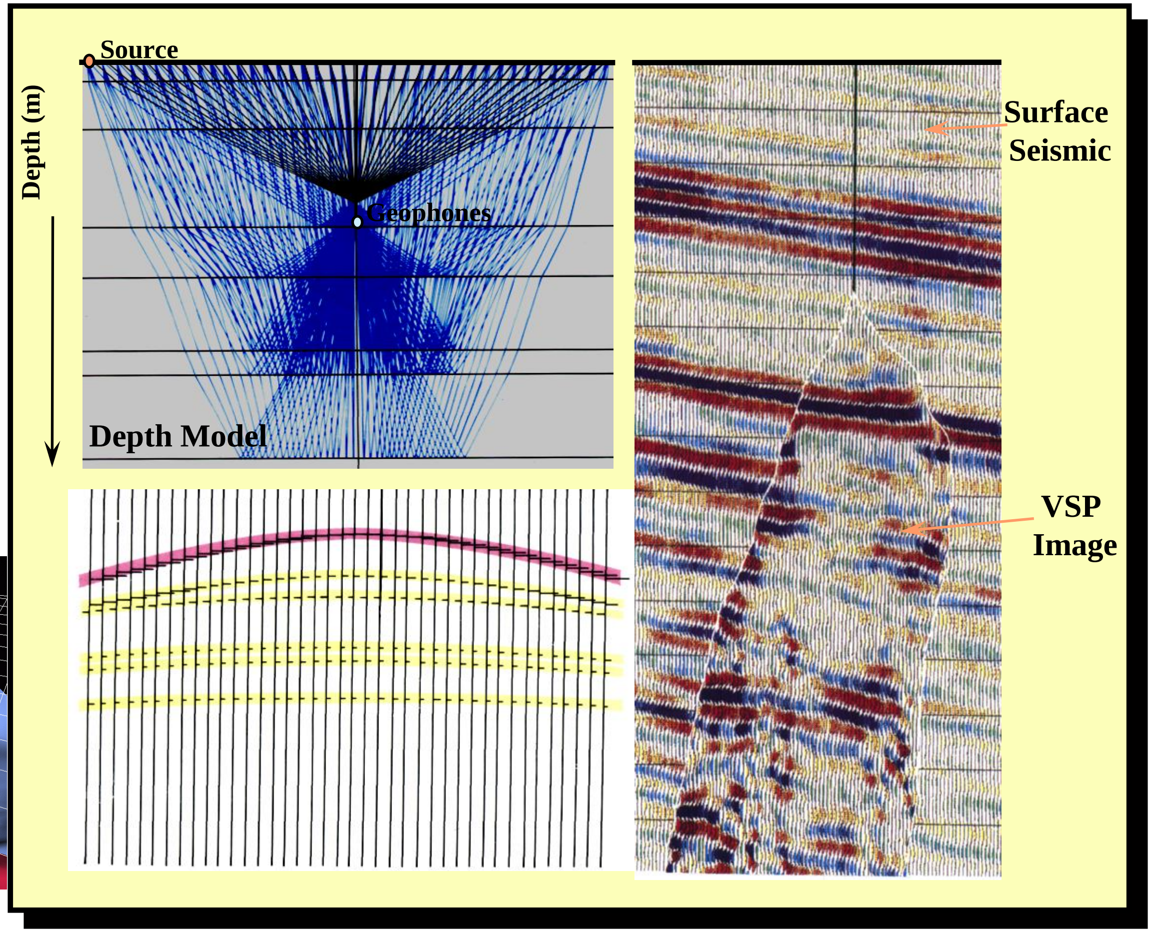
Aid on Surface Seismic Processing

- Multicomponent acquisition and processing.
- AVO calibration









Surface Seismic Correlation

Fault and Dip Identification

Anisotropy & AVO Analysis

Shear Wave Analysis

Surface Seismic Survey Design

Benefits of Walkaway VSP

- **Lateral reflection coverage under and away from the well:** *Walkaway VSP reflection points extend und and away from both sides of the well. The resulting image similar benefits of deconvolution and band width seen in the VSP.*

- **Shear velocity:** *Mode-converted down and up shear generated from the oblique ray-path can be used to determine shear velocity.*

- **PS & SS reflectivity:** *Mode-converted shear generated from the oblique ray-path can be used to observe where mode conversions occur and what the PS and SS wavefield is.*

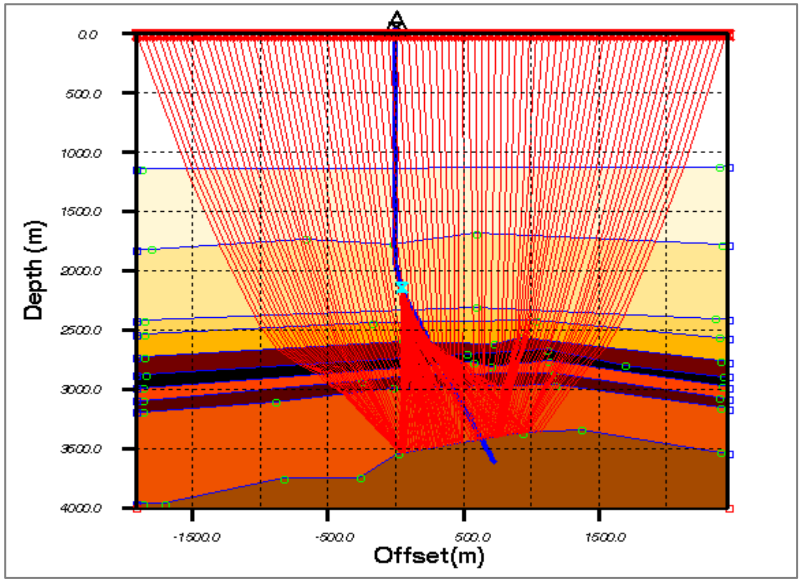
- **Direct measurement of AVO/AVA:** *A direct measurement of AVO/AVA of reflectors directly beneath the bottom of the receiver array can be made.*

- **Direct measurement of anisotropy:** *A direct measurement of polar anisotropy parameters can be made. Multiple walkaway lines can provide azimuthal anisotropy analysis.*

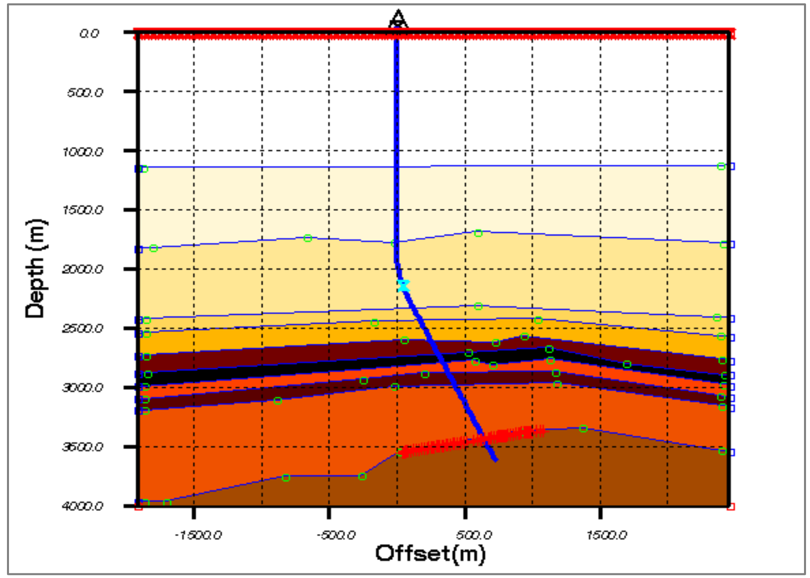
- **Oblique raypath multiples:** *Downgoing and upgoing multiples can be observed for all ray-paths and compared with the vertical incident survey multiples.*

- **Q filter determination:** *A Q filter more applicable to surface seismic can be determined using the downgoing wavefield from the walkaway.*

Walkaway Survey Design

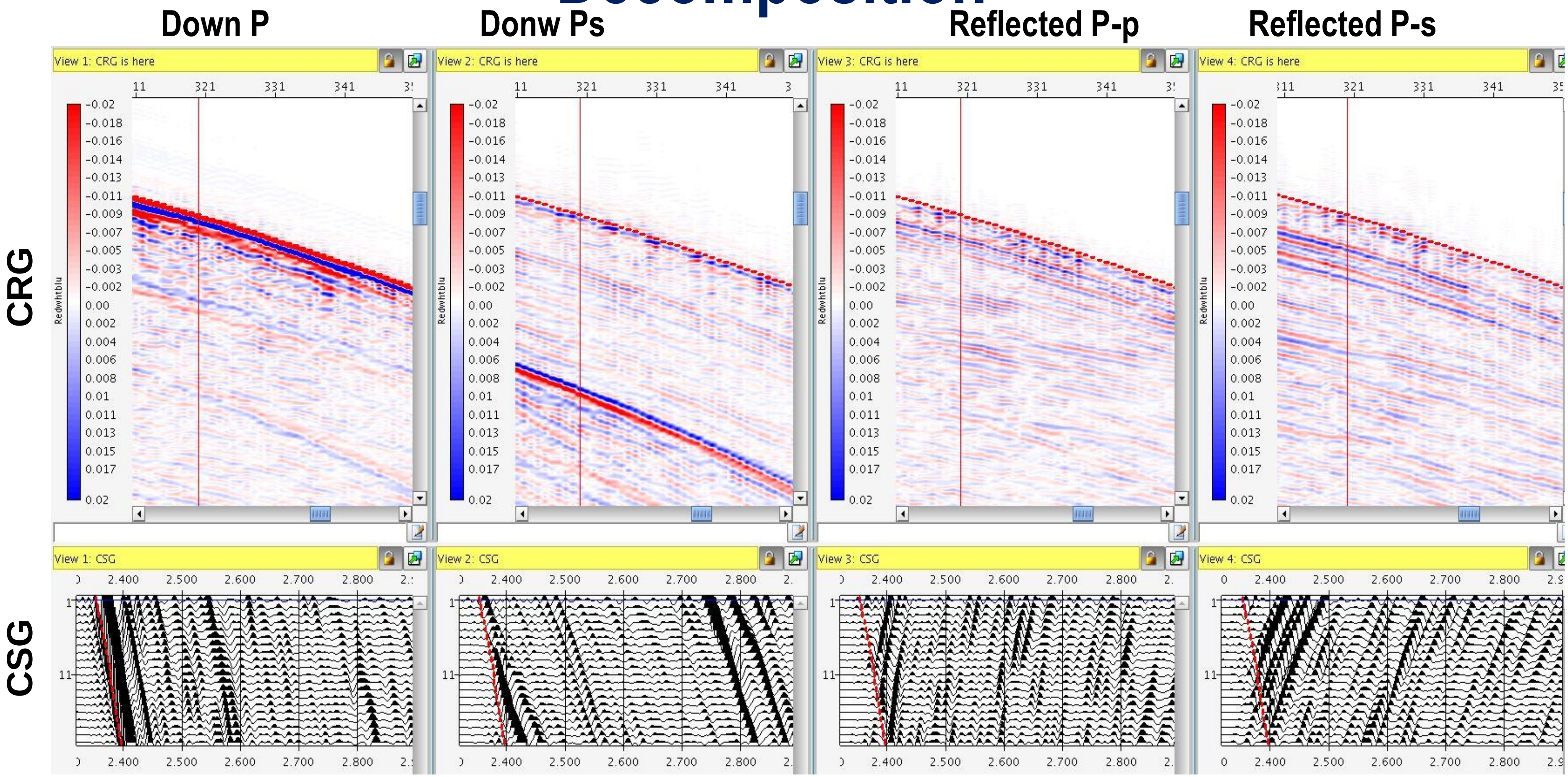


Ray Tracing

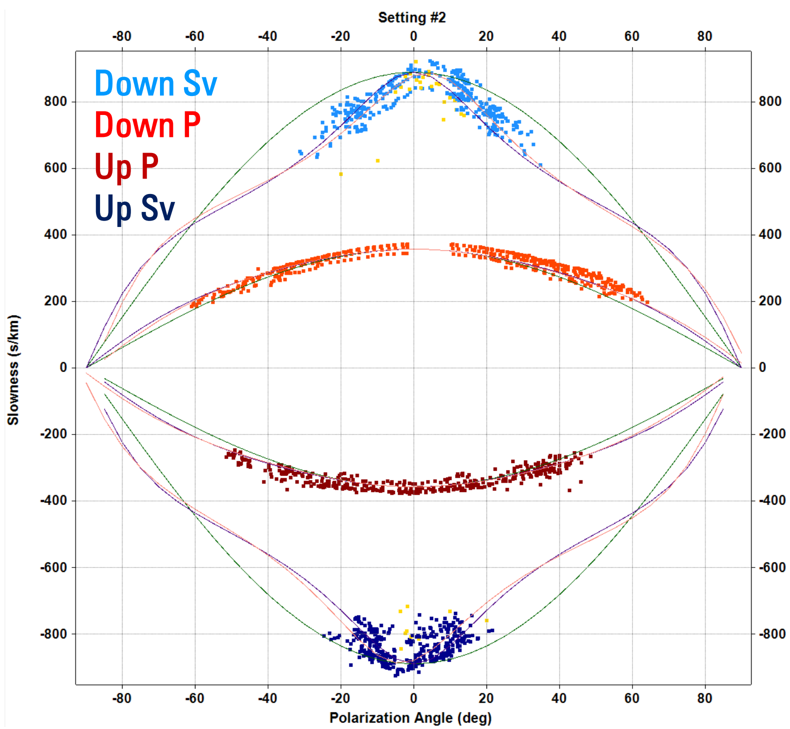


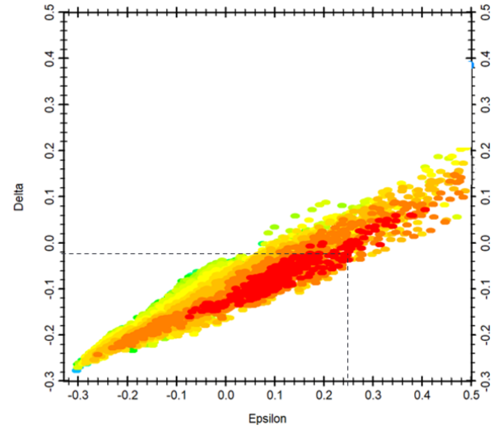
Reflection Points

Walkaway VSP for Imaging 3C Vector Wavefield Decomposition

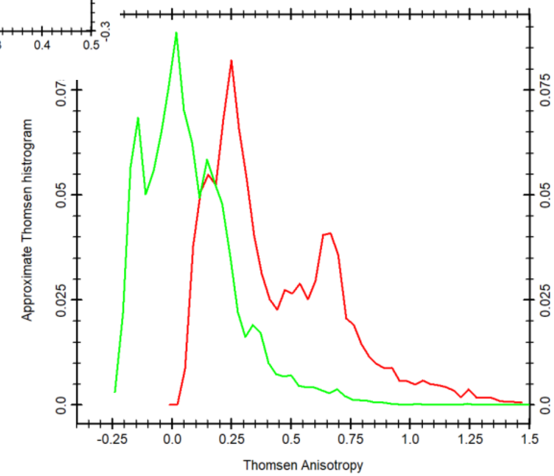


Anisotropy Estimation by Slowness and Polarization



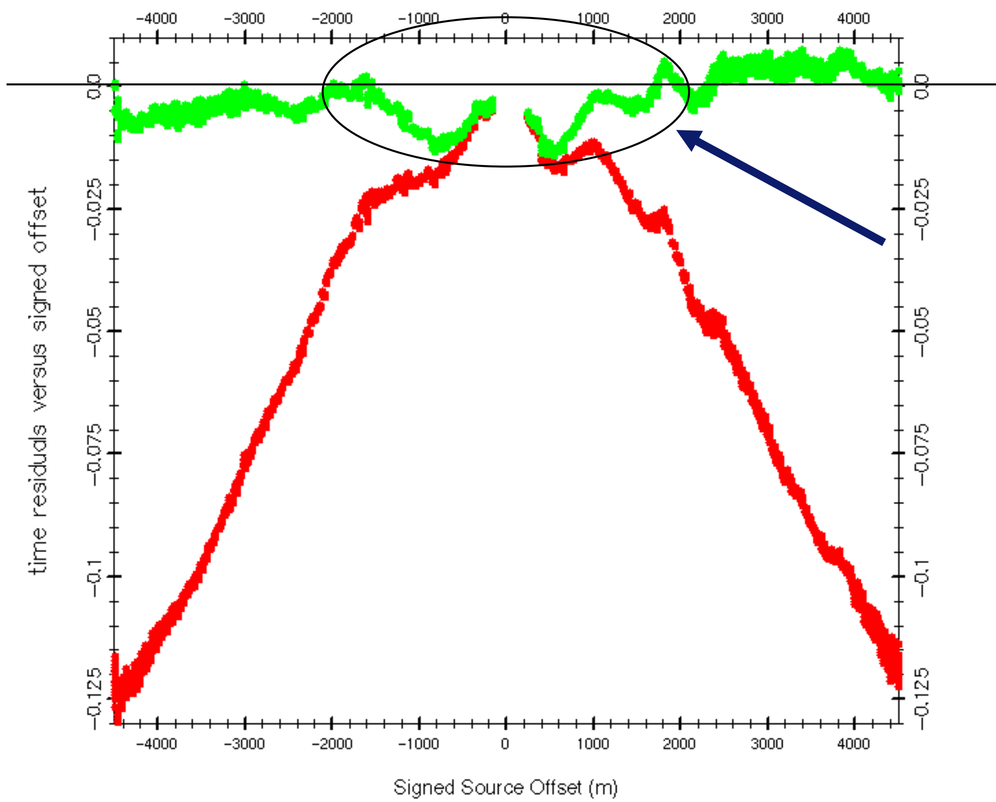


Monte Carlo



Anisotropic
Vp= 2855 m/s
Vs= 1269 m/s
Epsilon: 23%
Delta : -0.2%
Symmetry Axis : -5 deg

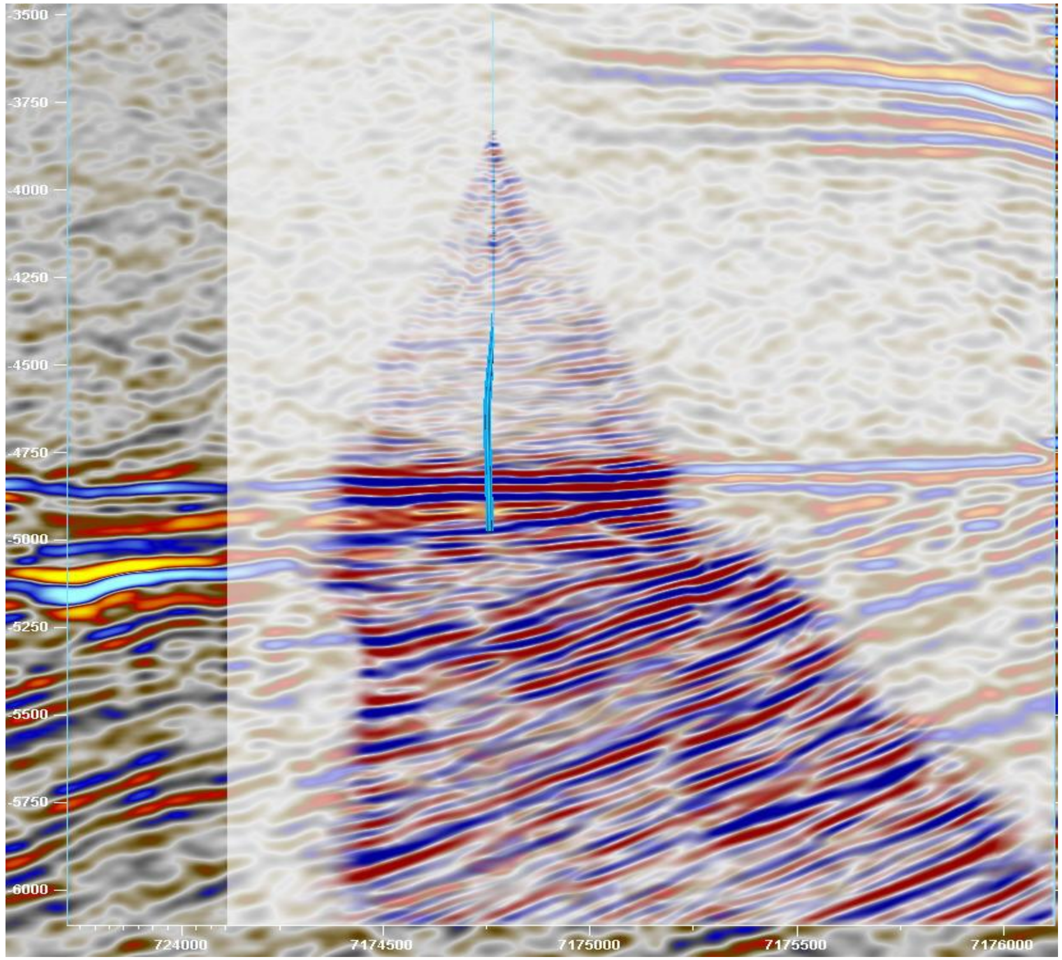
Isotropic & Anisotropic TT residuals



Diffraction related focusing of direct arrival causing TT picking ambiguity – near surface overburden effect?

Scott Dingwall, Jean-Claude Puech & Fraser Louden, EAGE 2003

Walkaway VSP to guide sidetrack - offshore



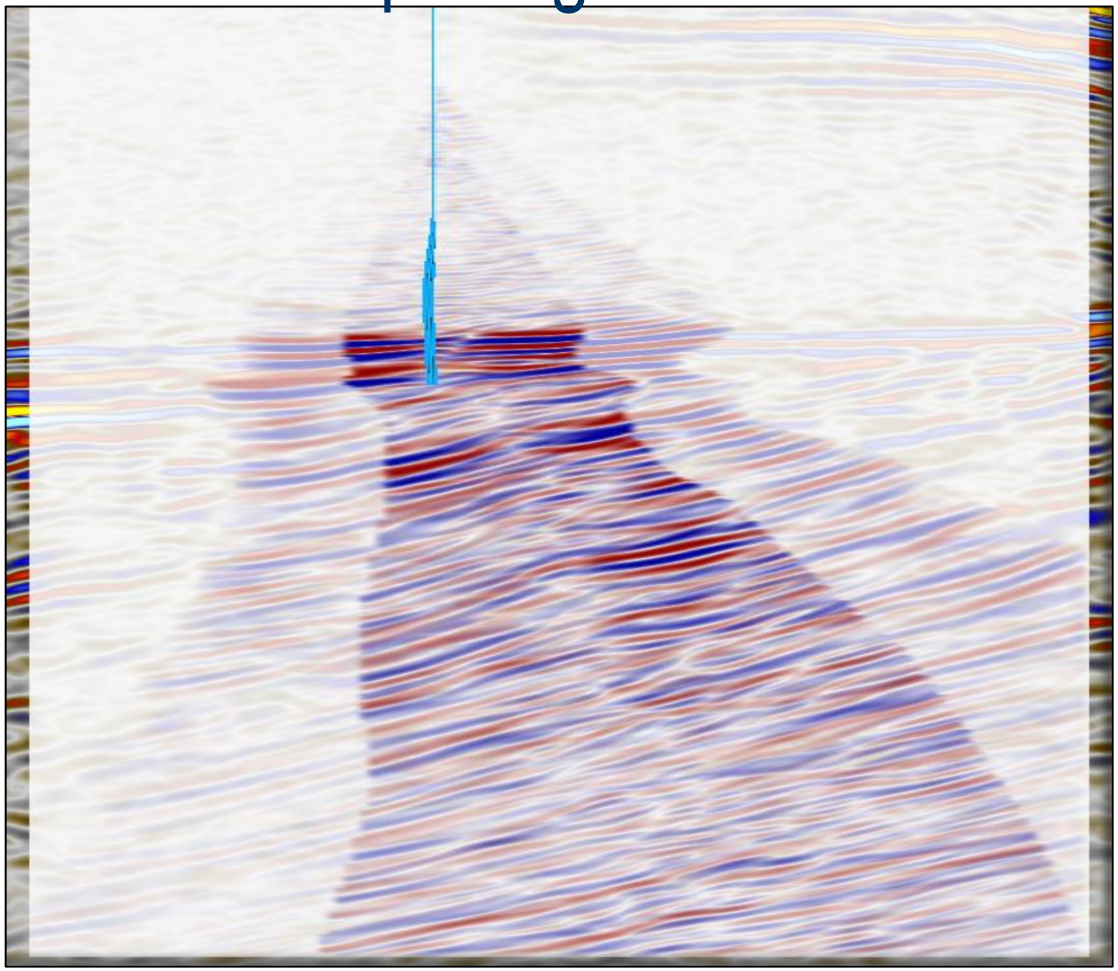
(5-90 Hz)

7

WVSP Imaging: Converted P->S, together with Pp image

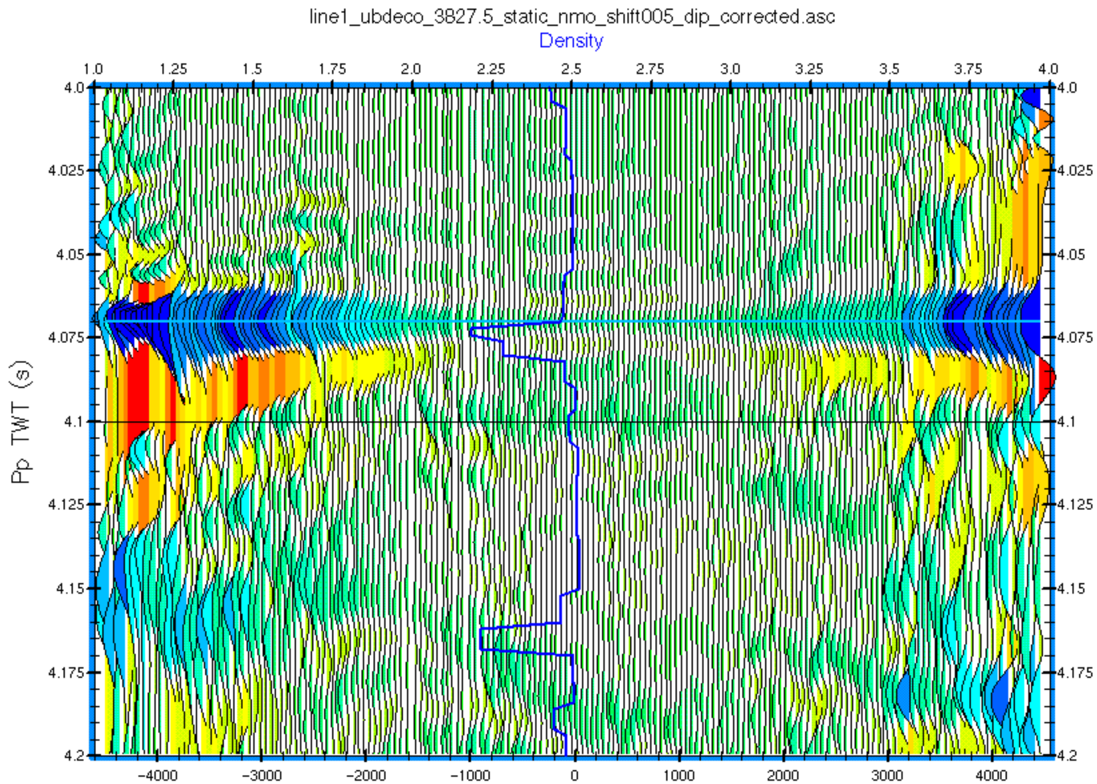
Benefits

- **Elastic Model**
- **Base of Salt confirmation**
- **Pinch-out mapping**
- **Help on 3DVSP design**



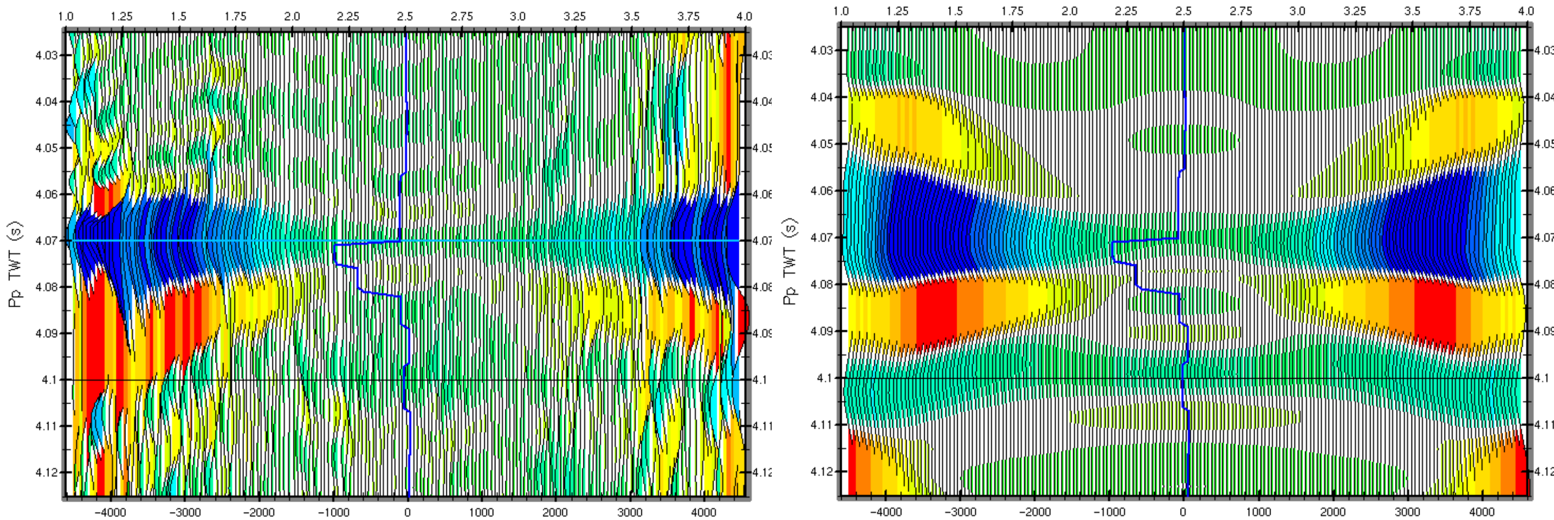
8

Zero Phase NMO corrected upgoing scalar compressional wavefield



Scott Dingwall, Jean-Claude Puech & Fraser Louden, EAGE 2003

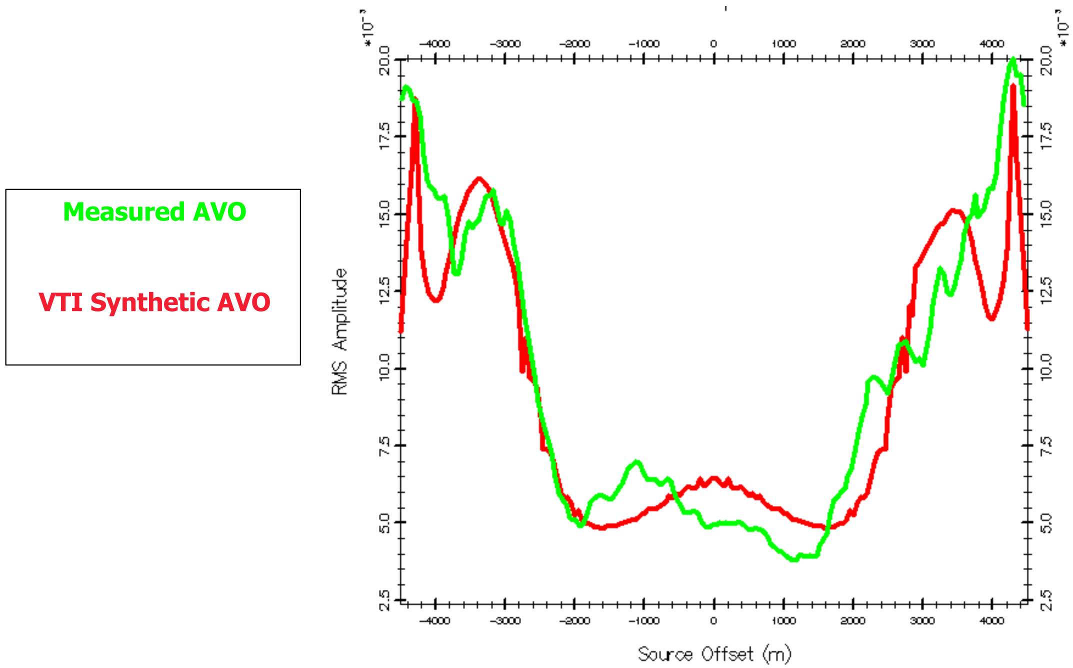
VTI Model Validation -2



Qualitative AVO comparison – VTI synthetic & measured

Scott Dingwall, Jean-Claude Puech & Fraser Louden, EAGE 2003

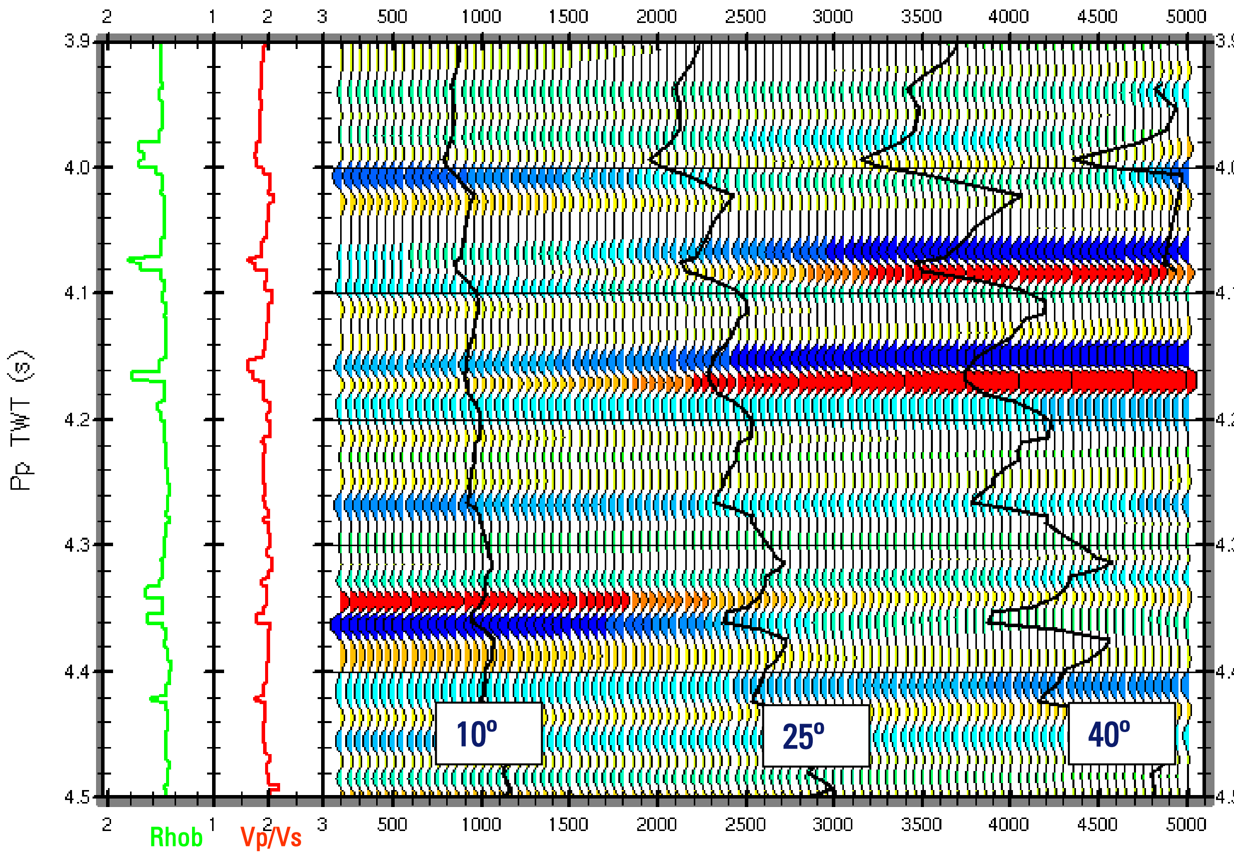
VTI Model Validation -3



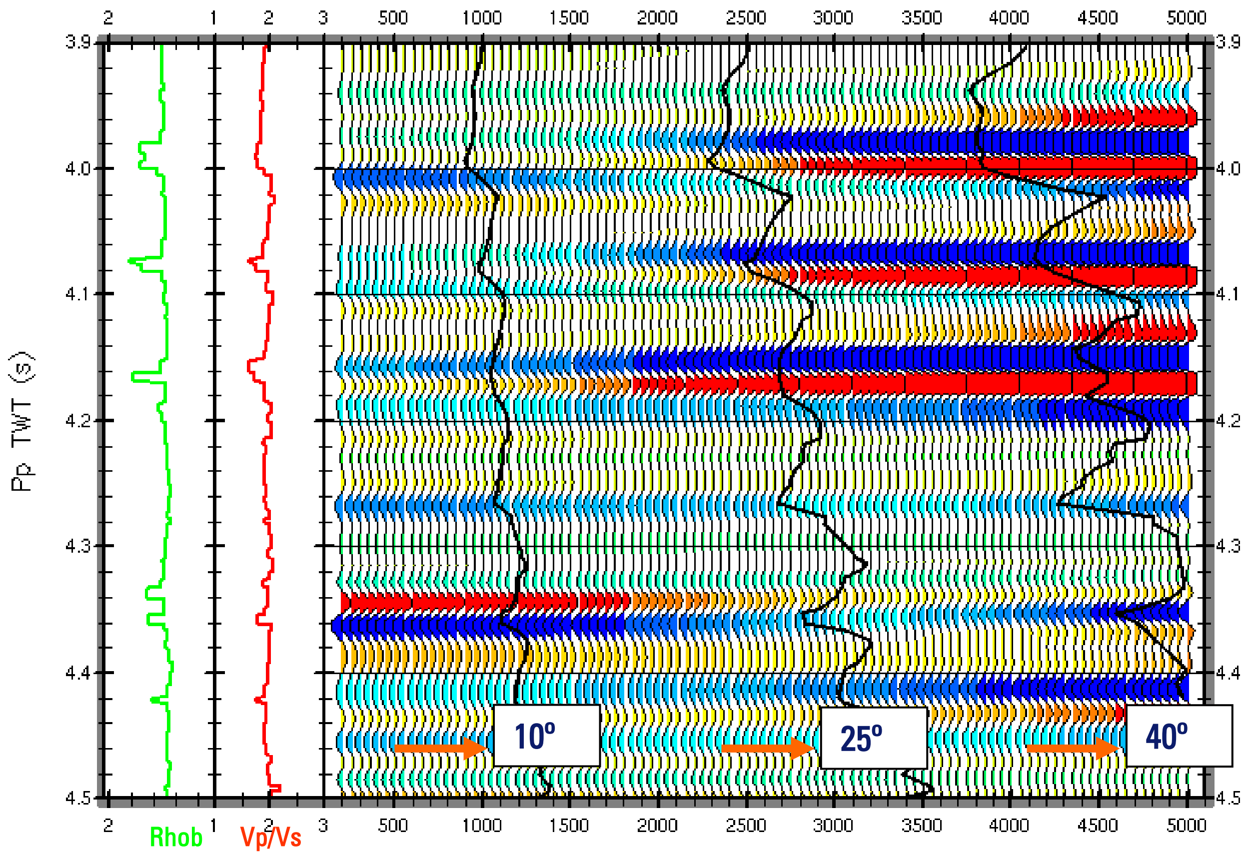
Quantitative AVO comparison – VTI synthetic & measured

Scott Dingwall, Jean-Claude Puech & Fraser Louden, EAGE 2003

Interpretation – CMP AVO Simulation (Isotropic)



Interpretation – CMP AVO Simulation (Anisotropic)



Summary

- Objective driven and integrated survey design, acquisition & interpretation key to success
- AVO ambiguity resolved via integration of full waveform sonic data and multi offset VSP
- Borehole calibration essential for long offset AVO

Additional Value

- **Calibrated 1D VTI model subsequently used for true amplitude pre-stack parameterisation of surface towed streamer volume**
- **Calibration of anisotropic pre stack time velocity model**
- **Entire 3D acquisition volume to be re-processed based on test borehole calibrated processing project**