RCP
RESERVOIR CHARACTERIZATION PROJECT

Midland Basin Project

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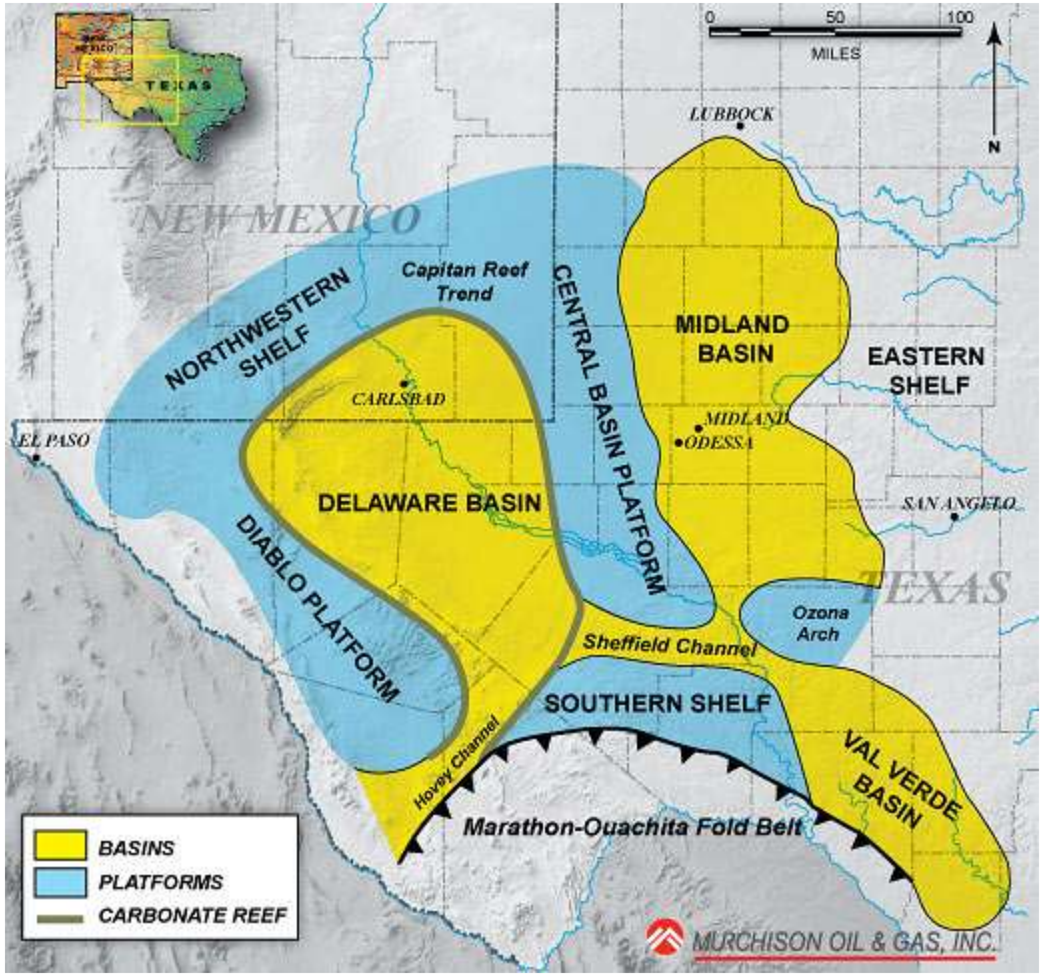
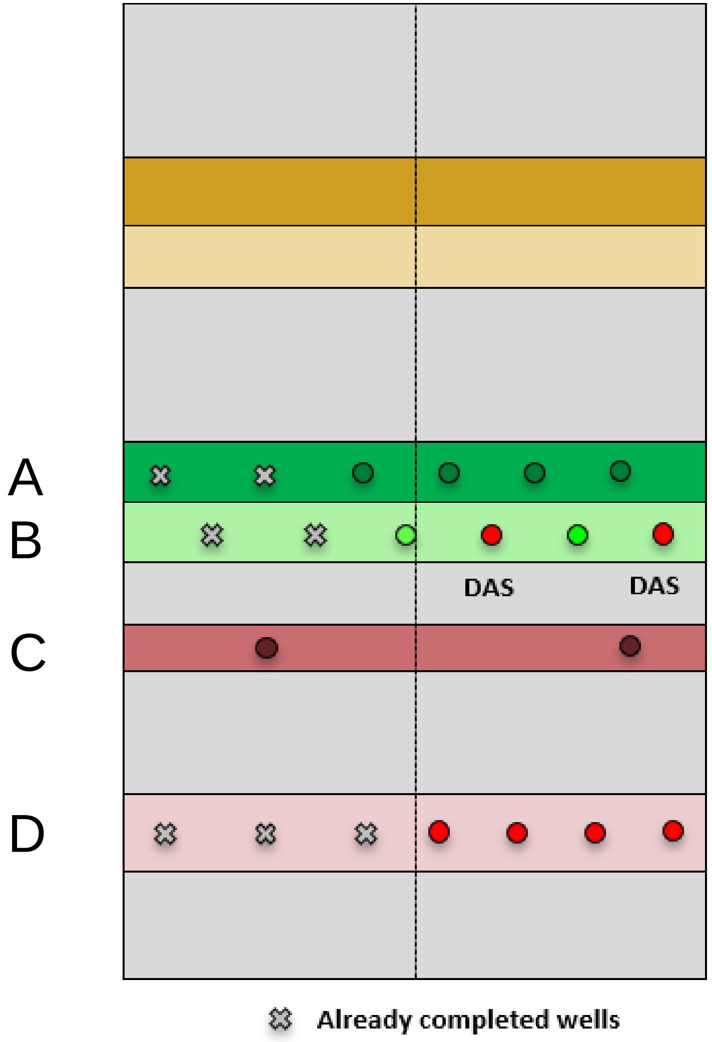
COLORADO SCHOOL OF MINES

Introduction

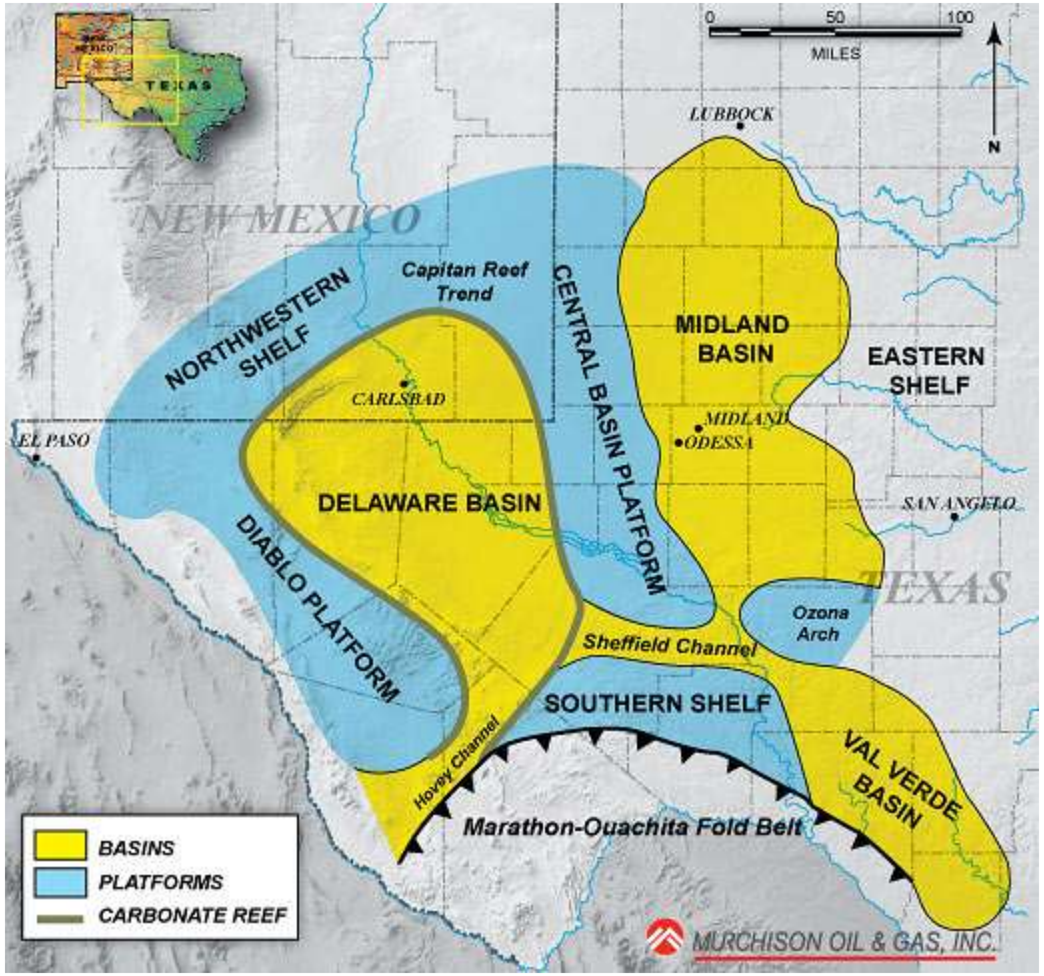
- In 2018, Apache monitored the stimulation of 13 horizontal wells in the Midland Basin using distributed acoustic sensing (DAS) in two of the wells

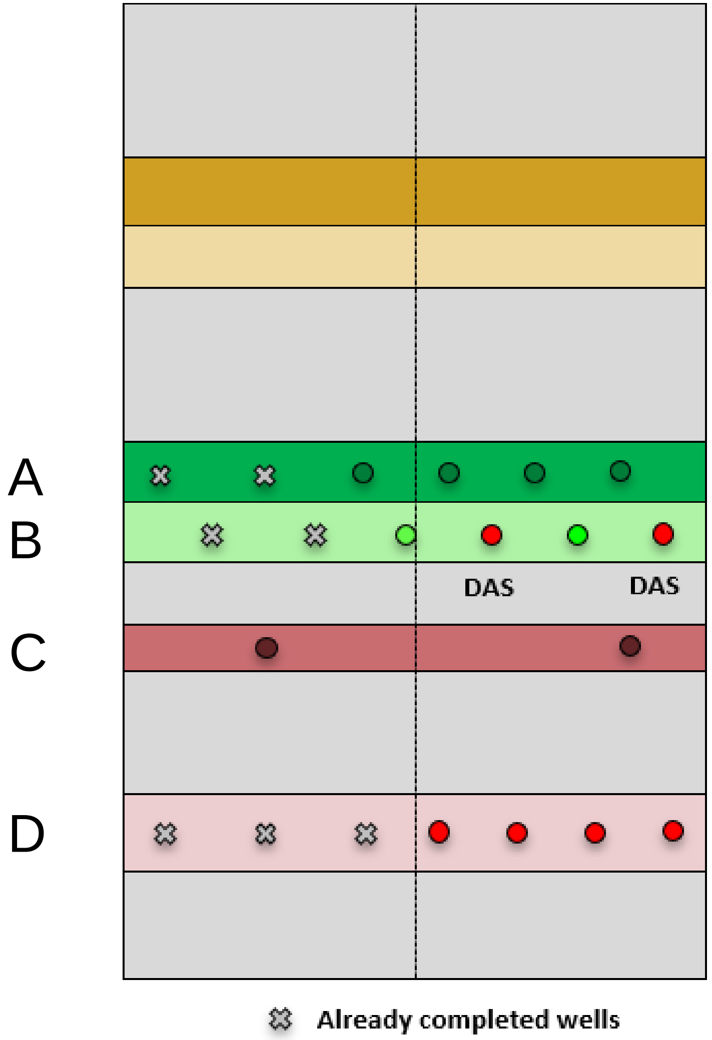




Introduction

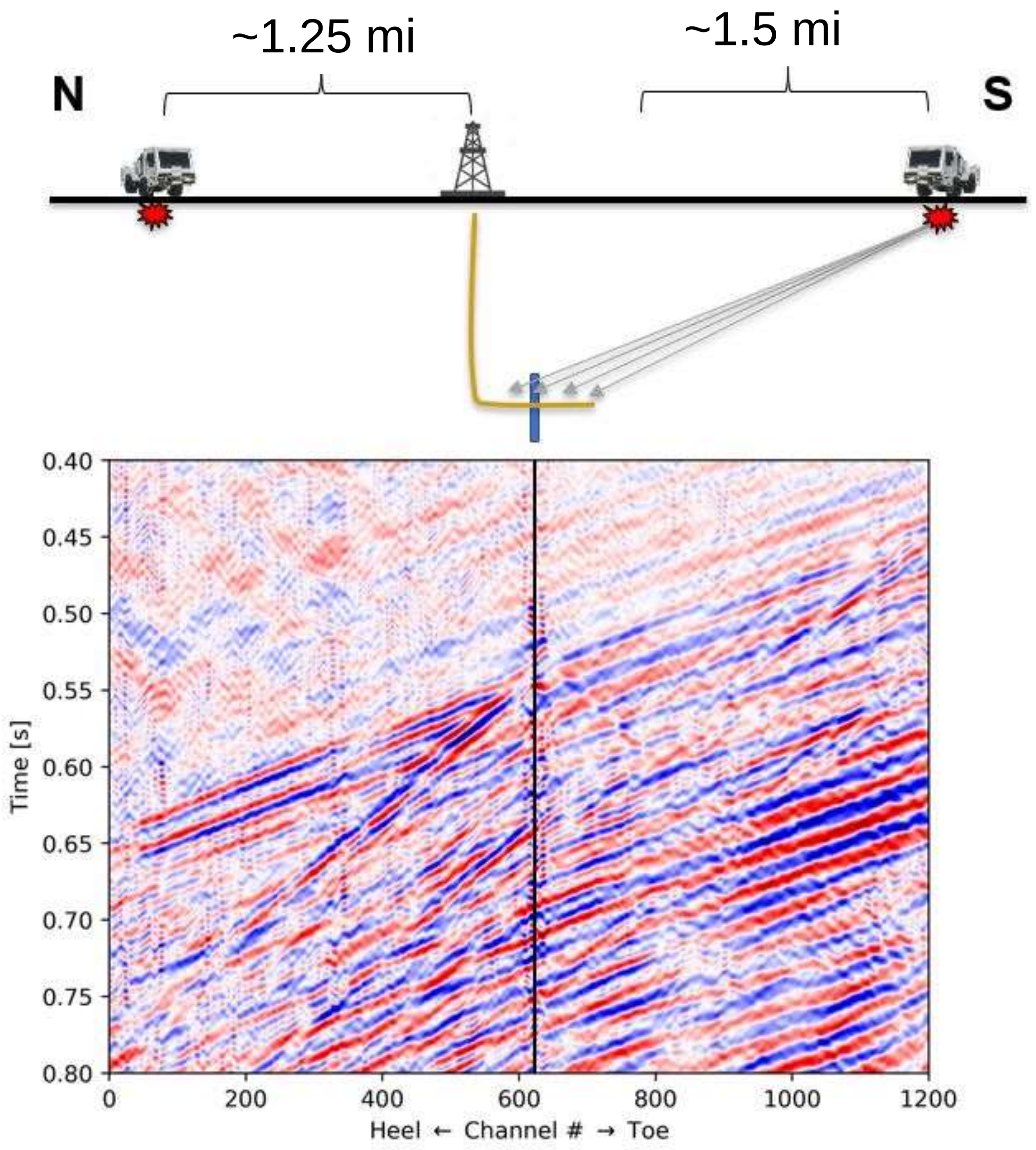
- 4 different landing zones were tested with variations in well spacing and stage design





Interstage DAS VSP Survey

- VSP surveys were conducted after every fracturing stage of the DAS wells
- Two vibroseis sources offset from the heel and toe of the fiber wells
- The use of permanent engineered fiber technology lead to substantial improvements in SNR
- Current observations
  - ~1 ms time shifts of the direct P-wave arrival
  - P to S scattered waves after nearly every stage



Project Objectives

- Analyze P and S-wave time shifts, amplitude changes, and scattering effects caused by each stage of hydraulic fracturing
- Use time-lapse response to characterize the geometry and dynamics of hydraulic fractures
- Characterize the interference of other zipper group wells in the time-lapse signal
- Associate time-lapse changes with variations in completion design parameters
- Use findings to design future acquisition geometries

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In pursuit of new ideas

RCP PHASE XVII: WOLFCAMP PROJECT RECAP

Recap: Interstage DAS VSP

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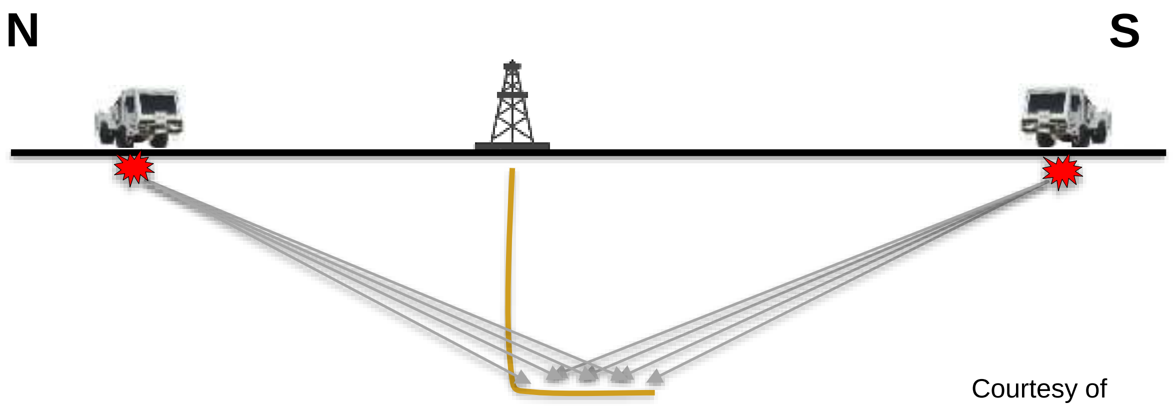
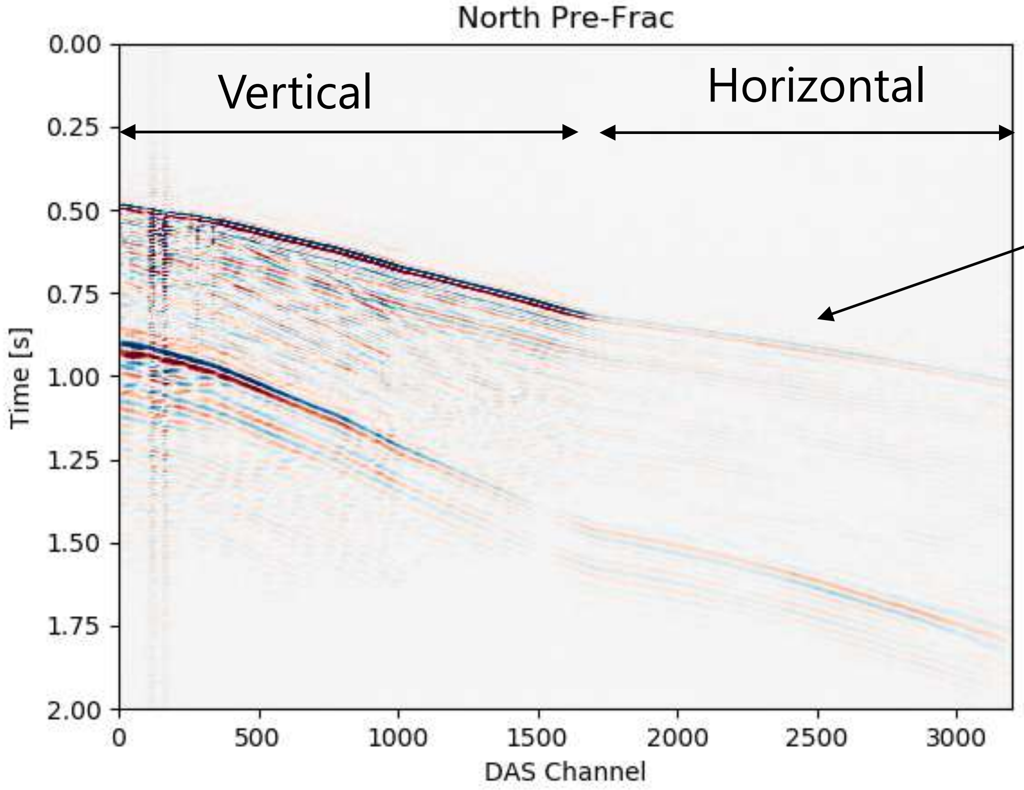
In pursuit of new ideas

This project is a follow-up to a previous interstage DAS VSP conducted by Apache in 2017

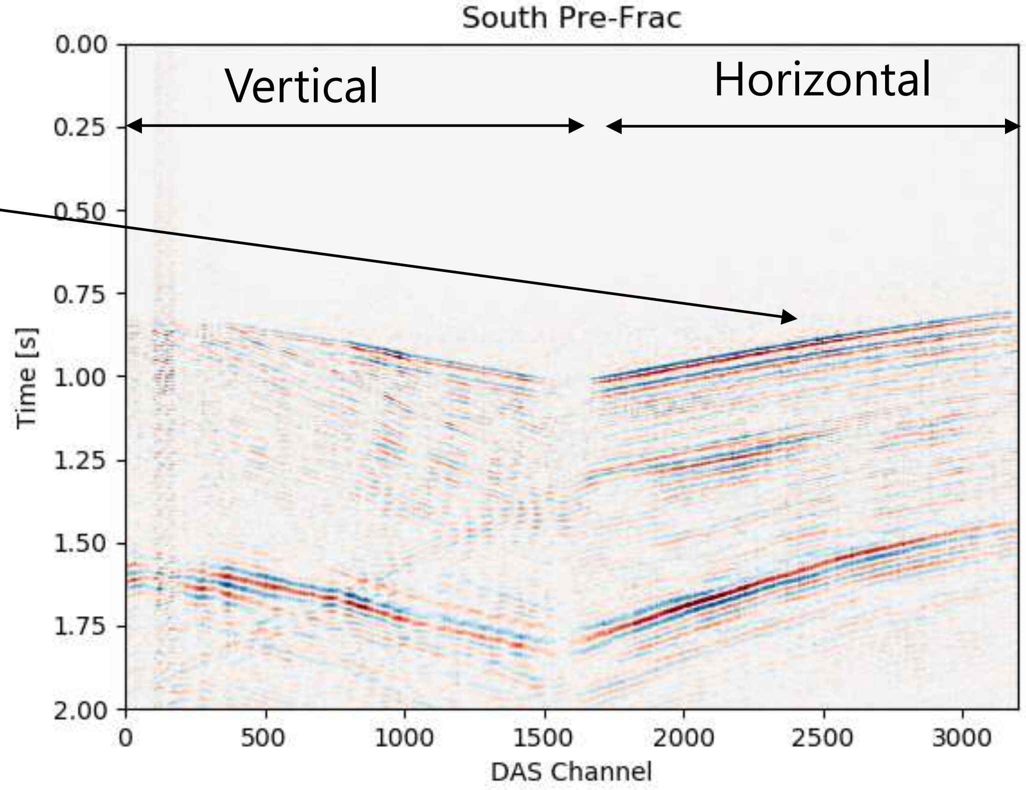


Courtesy of Apache

Byerley, G., et al. (2018). *The Leading Edge*, *37*(11), 802–810.



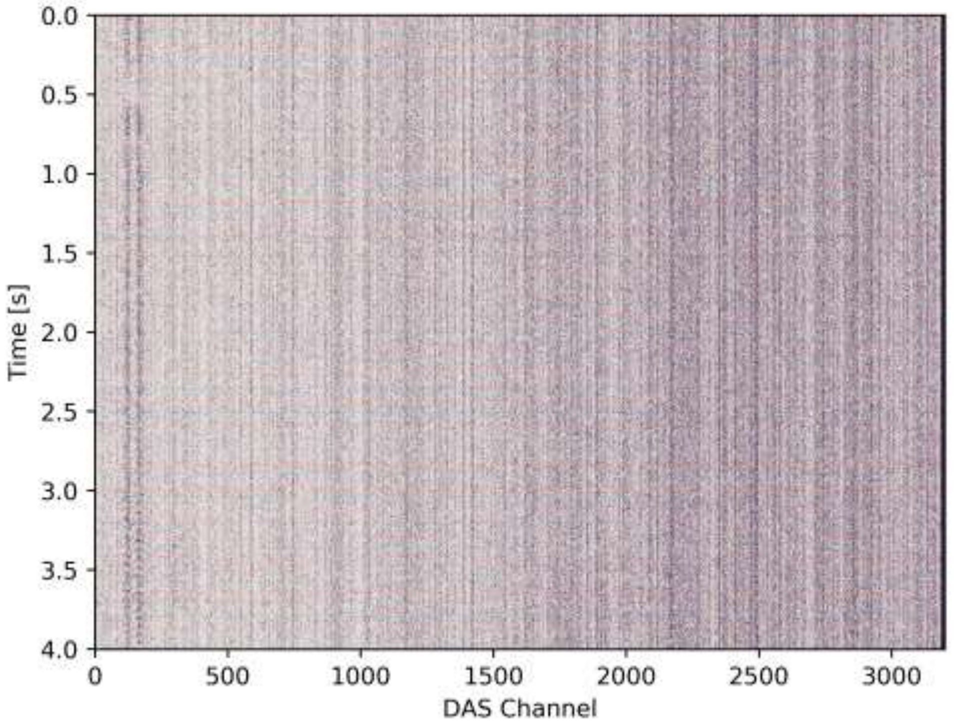
Time shifts observed along P-wave arrival



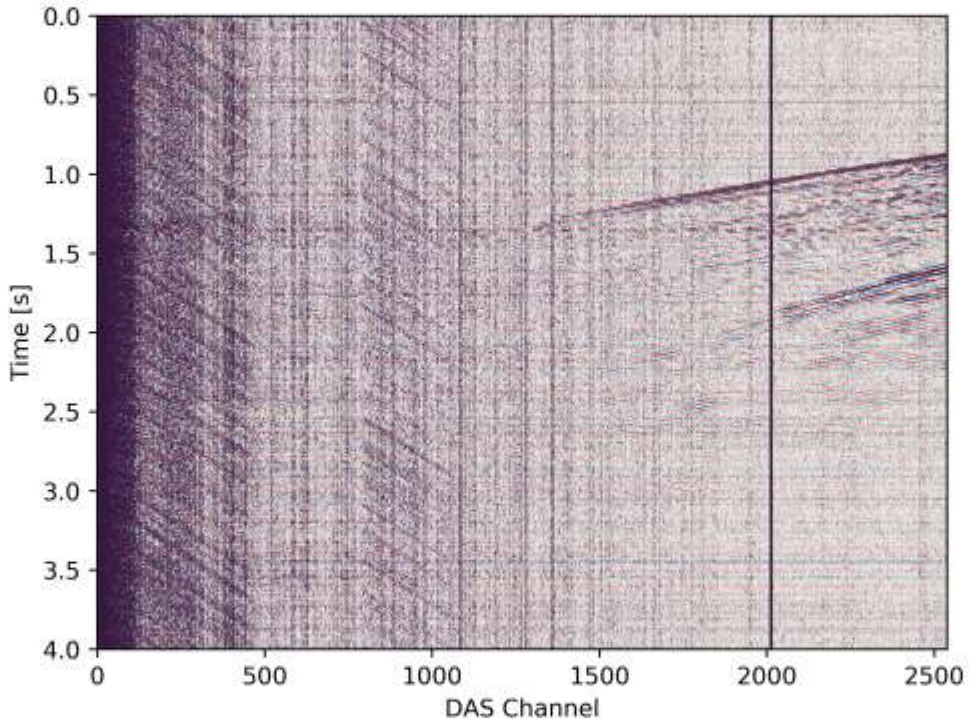
Recap: Data Quality

- Standard optical fiber was used in the previous survey
- Improved interrogator technology and the use of engineered optical fiber has lead to a factor ~100 improvement in SNR
- Comparison of single, raw correlated sweeps:

Previous: Standard Fiber

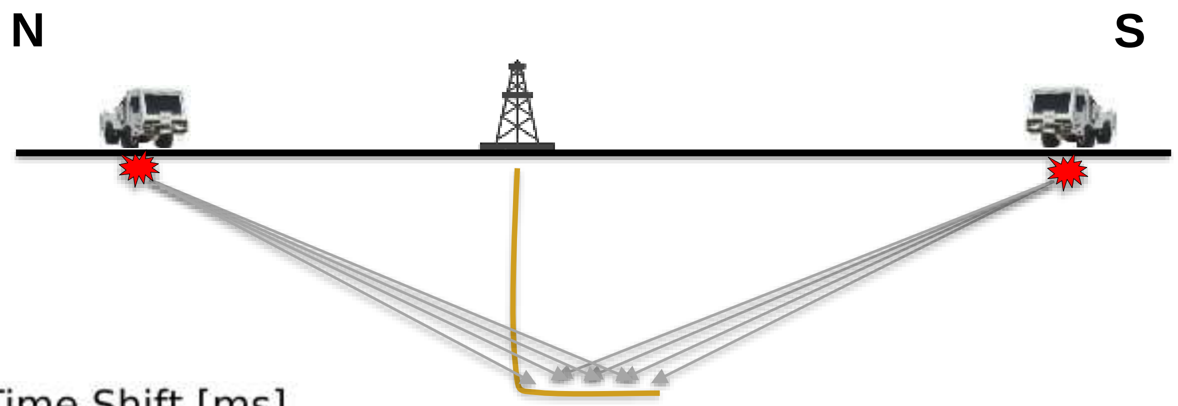


Now: Engineered Fiber



Recap: P-Wave Time Shifts

Time shifts observed after each stage moving from toe to heel



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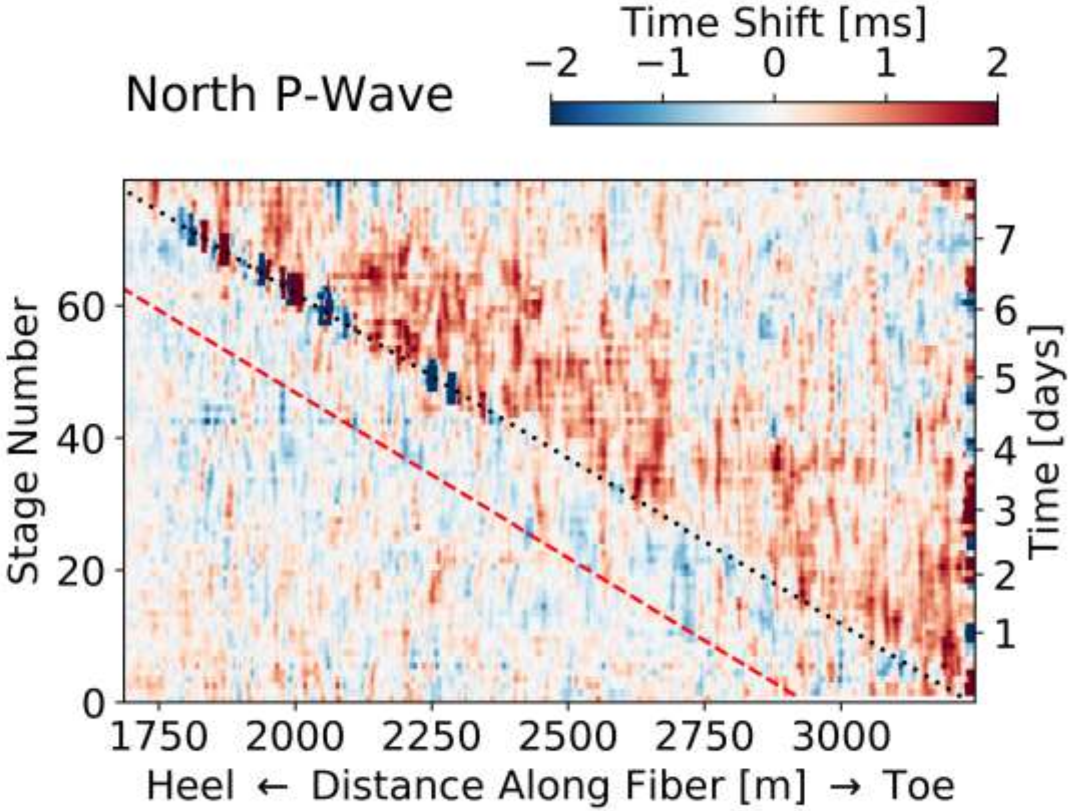
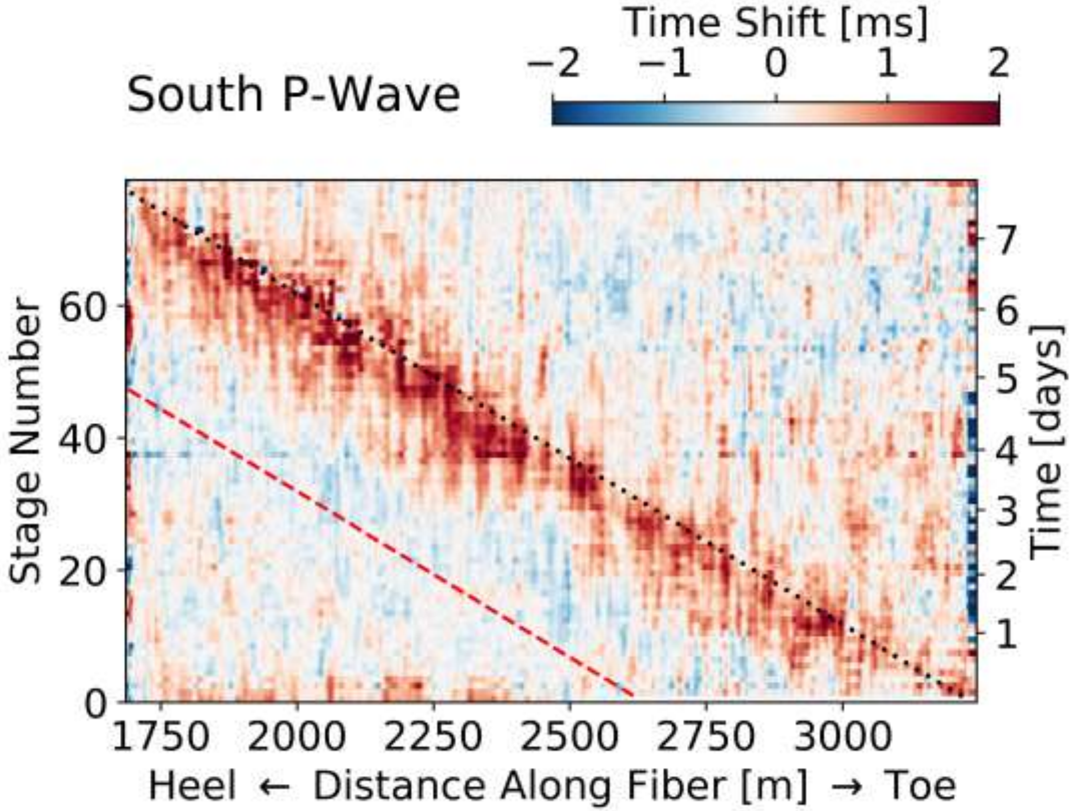
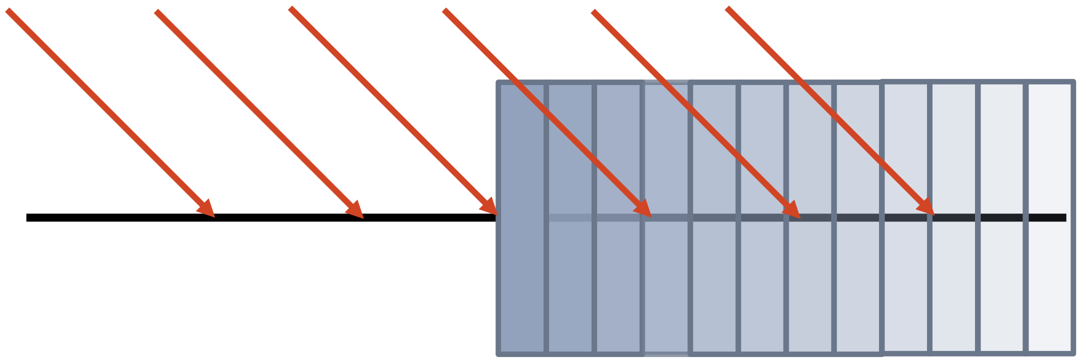
Speedup ← → Slowdown

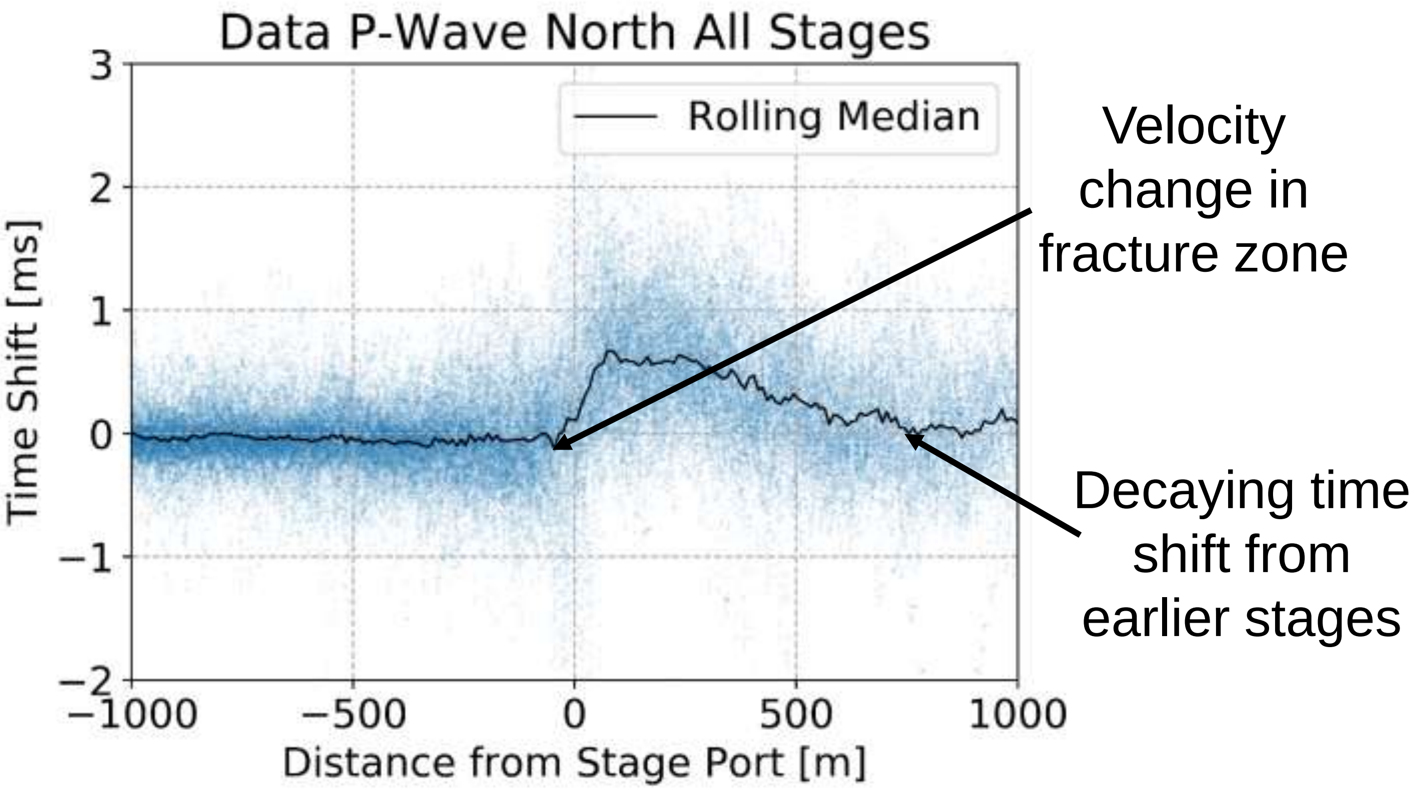




Recap: P-Wave Time Shifts for All Stages

Stack time shifts as a function distance from stage port to increase SNR

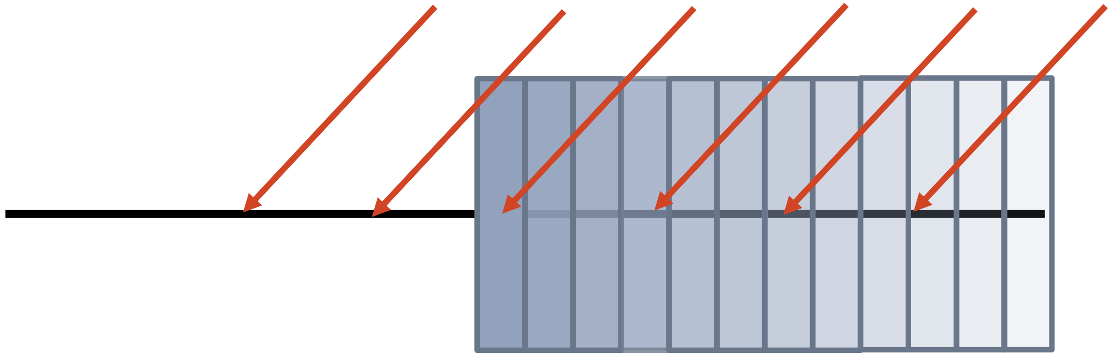


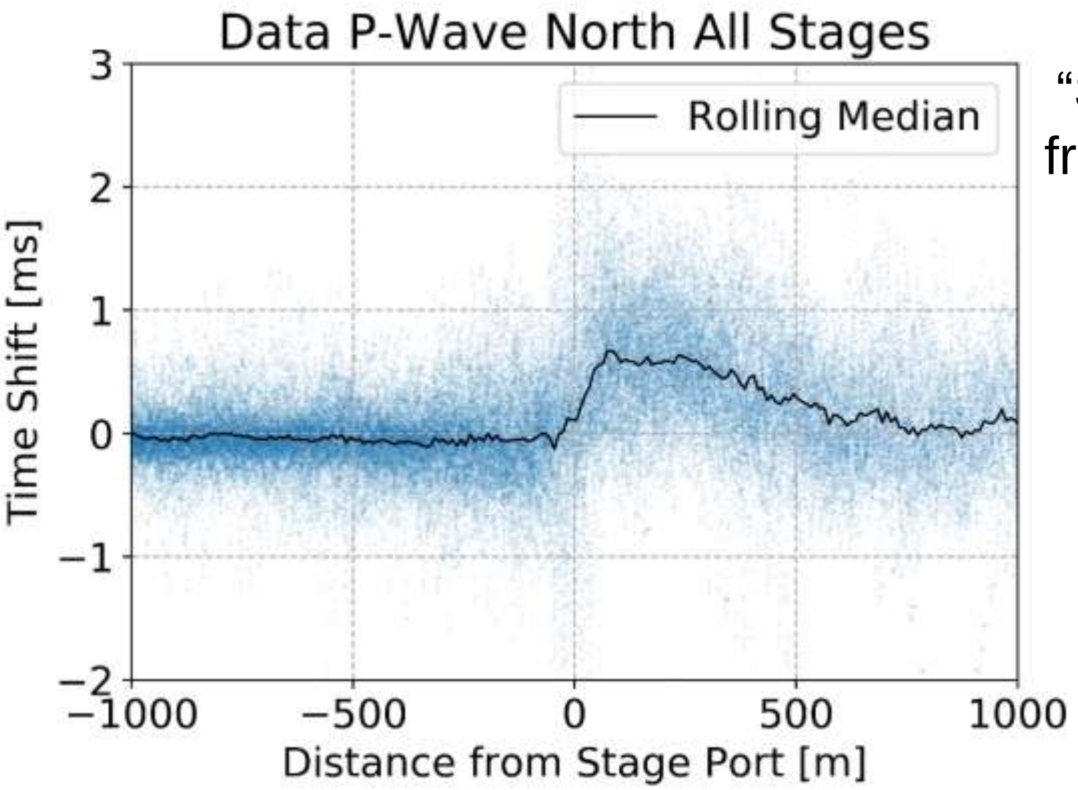


Stage-to-stage variations are comparable to the noise level

Recap: P-Wave Time Shifts for All Stages

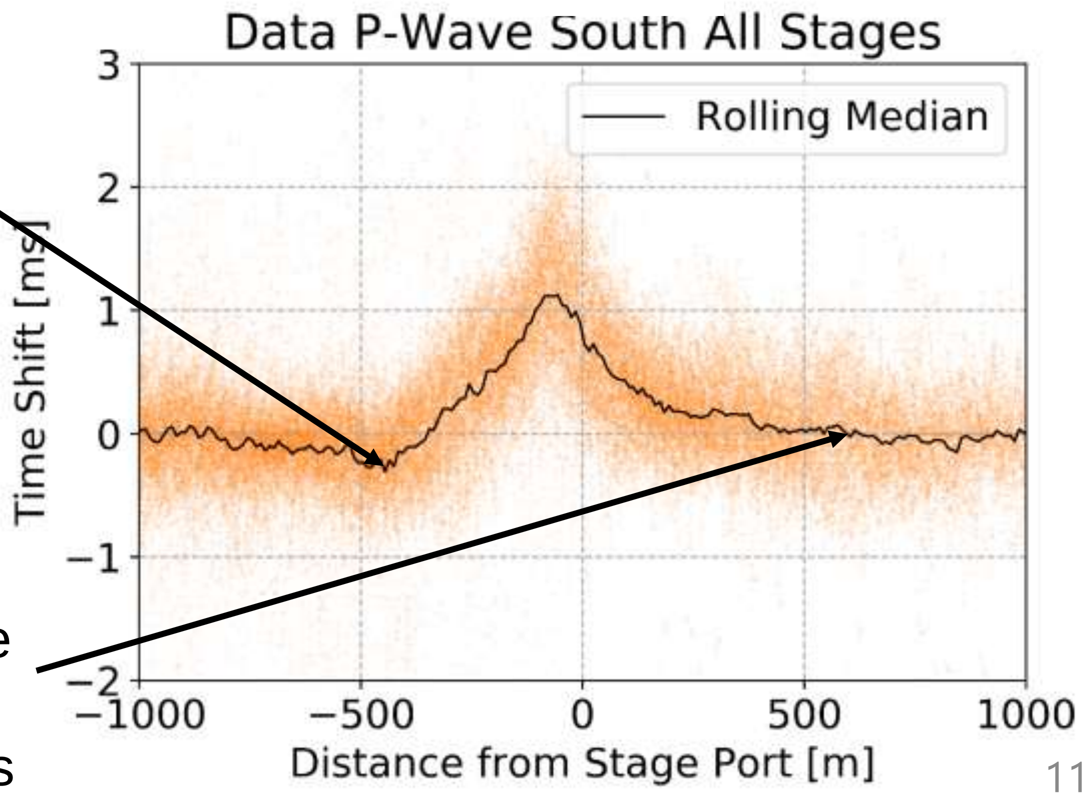
Stack time shifts as a function distance from stage port to increase SNR





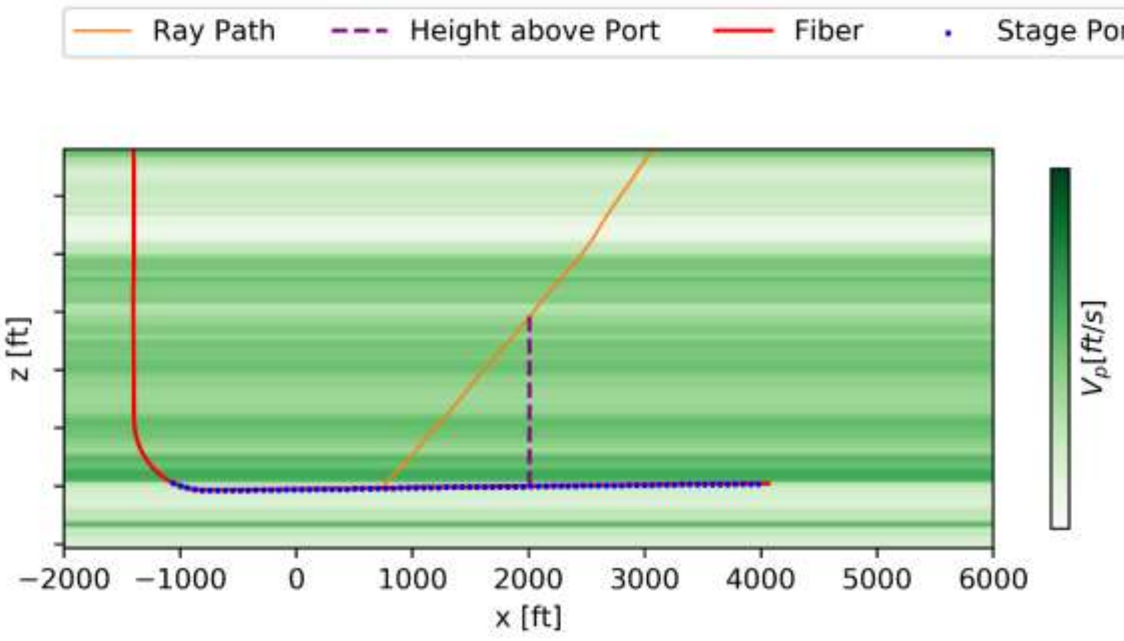
"Shadow" of fracture zone

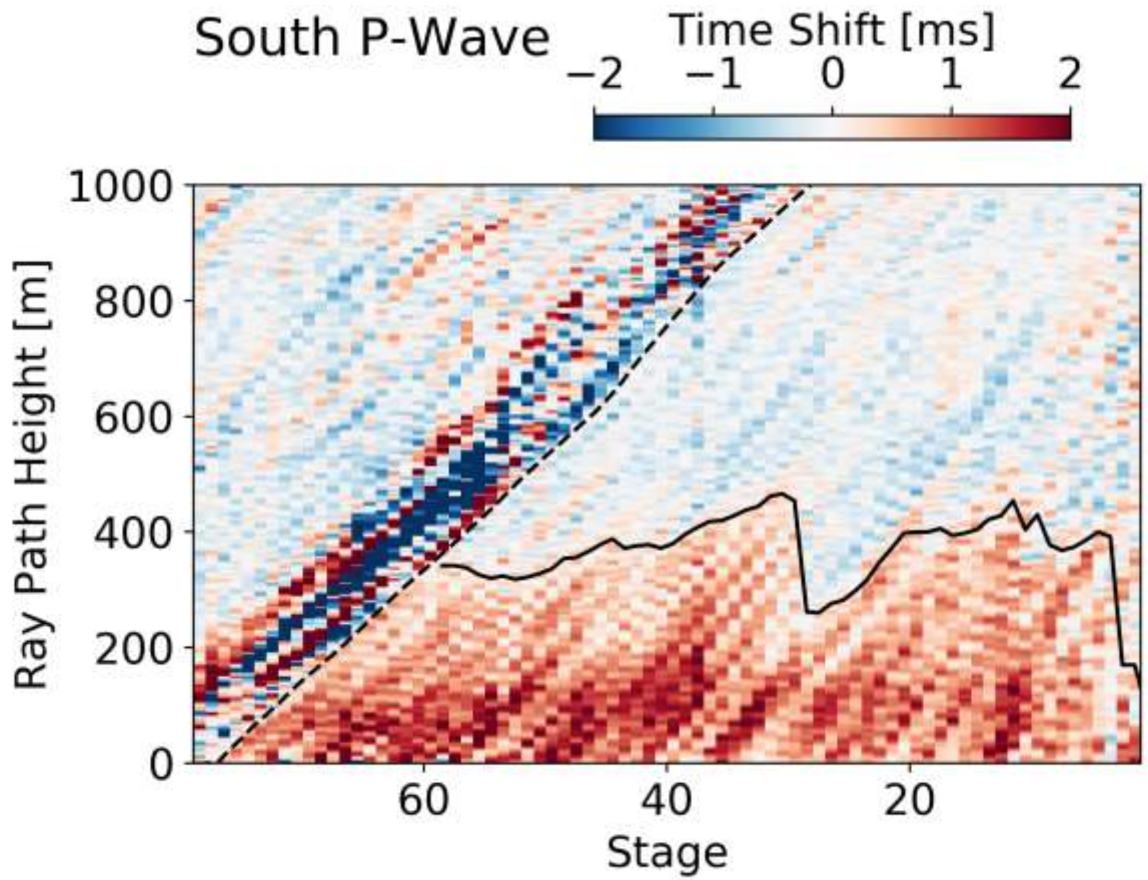
Exponential decay in time delay from earlier stages



Recap: Height Estimation

- Ray tracing can be used to map the shadow to the height of the SRV above the stage port

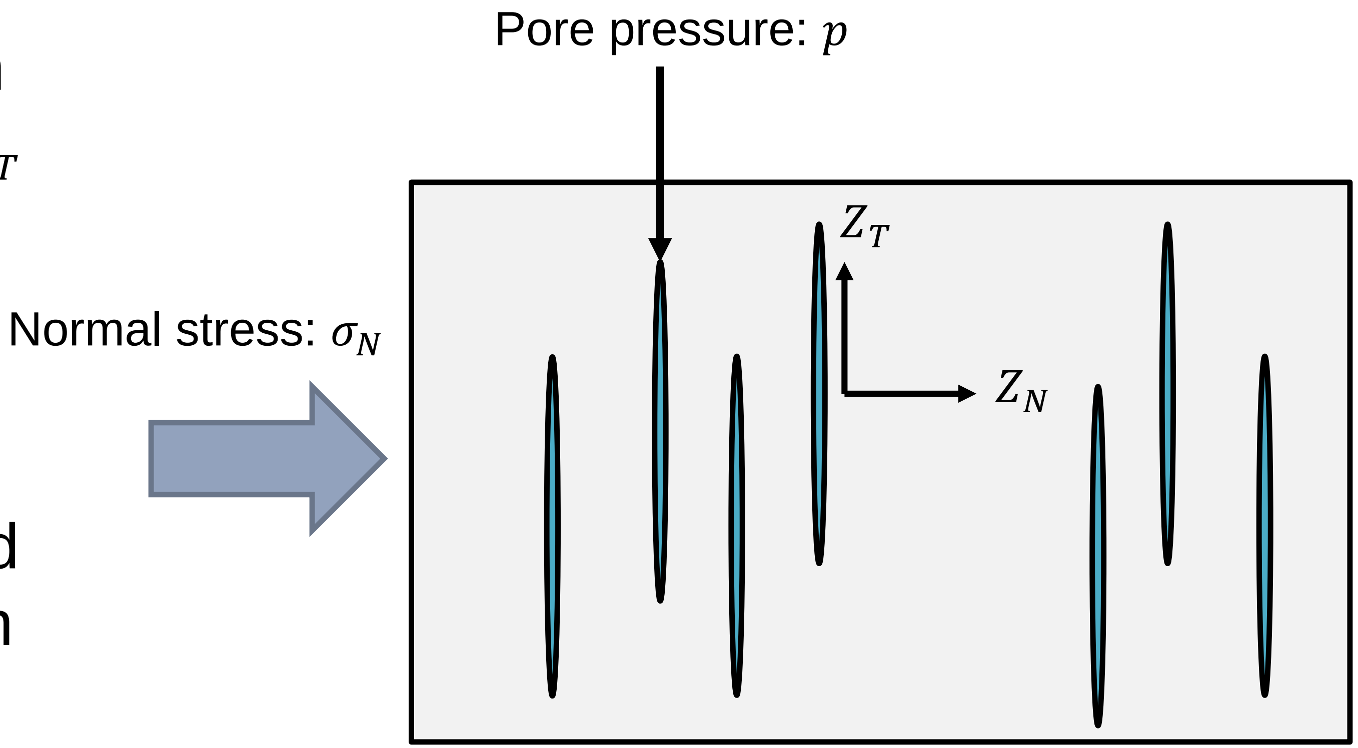




Recap: Mechanism of Time Shifts

- Natural or hydraulic fractures increase compliance of the medium
  - Normal/tangent to fracture plane, Z_N/Z_T
  - Z_N/Z_T is sensitive to fluid or proppant content
  - $Z_N/Z_T \rightarrow 0$ for fluid-filled fractures

- Fracture compliance often observed to have exponential dependence on effective stress in core studies:
  - $Z_N, Z_T \propto \exp\left(-\frac{\sigma_N - p(t)}{\sigma_c}\right)$



Sayers, C. M., and M. Kachanov, 1991, International Journal of Solids and Structures, **27**, 671–680.

Zhang, Y., C. M. Sayers, and J. I. Adachi, 2009, Geophysical Journal International, **177**, 205–221.

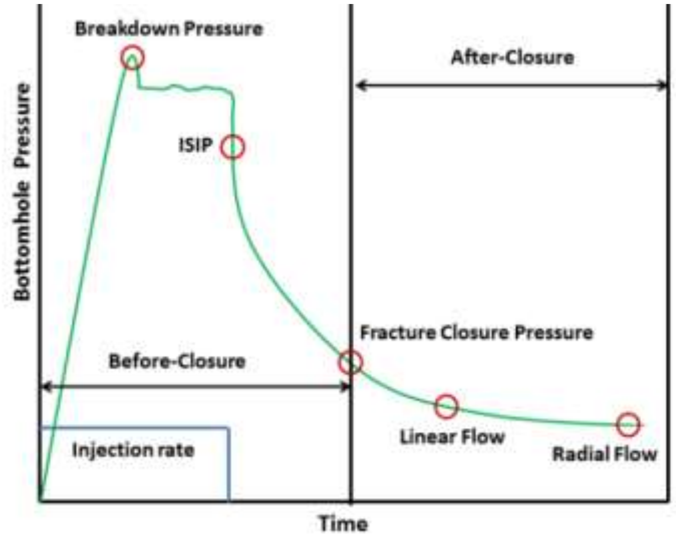
Recap: Decay of Time Shifts

- ≈ Linear pressure decline due to leak off leads to an exponential decay in time shifts

$$Z_N, Z_T \propto \exp\left(-\frac{\sigma_N - p(t)}{\sigma_c}\right) \propto \exp\left(-\frac{t}{\tau}\right)$$

- Decay constant sensitive to permeability and several other formation, fluid, pumping and fracture parameters

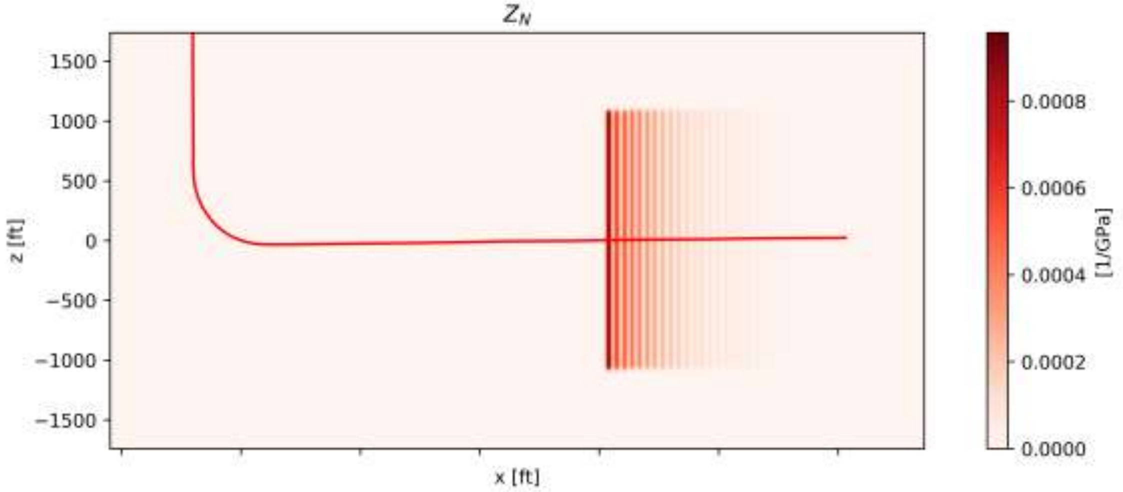
$$\tau \propto \frac{\sigma_c}{S_f(ISIP - p_0)}\sqrt{\frac{\mu K_f t_p}{k\phi}}$$

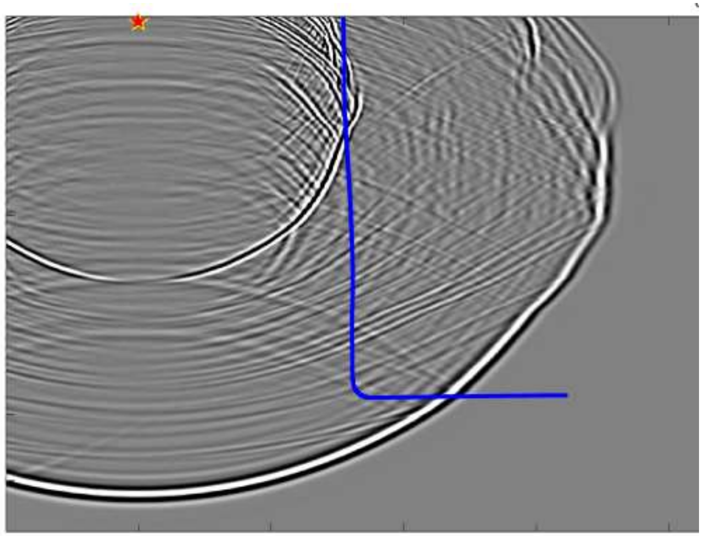


	Parameter
Formation	k, permeability
	ϕ, porosity
	p_0, pore pressure
Fluid	K_f, fluid bulk modulus
	μ, viscosity
Pumping	$ISIP$, shut-in pressure
	t_p, pumping time
Fracture	S_f, fracture stiffness

Recap: Modeling

- A simple model of exponentially decaying fracture compliance was fit to the data
- 2D elastic full wavefield finite difference modeling was conducted to predict time shifts
- Software available to RCP sponsors

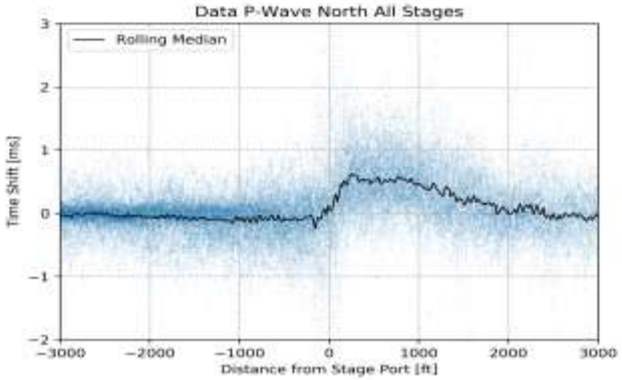
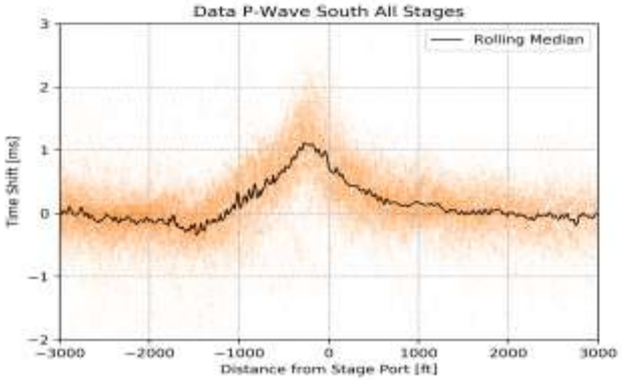
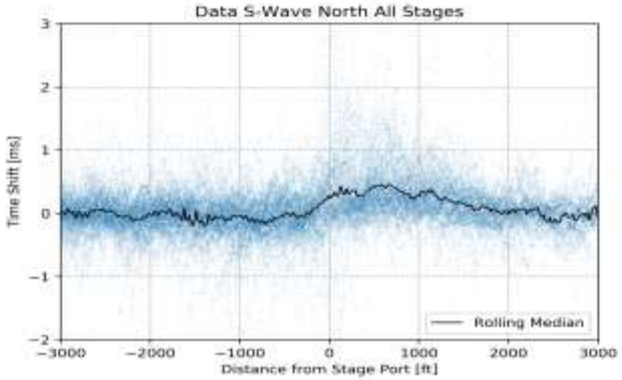
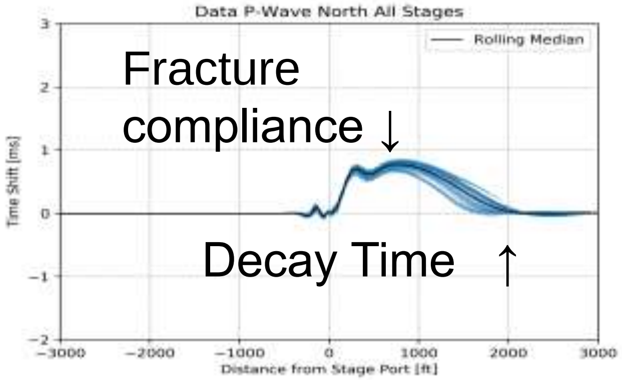
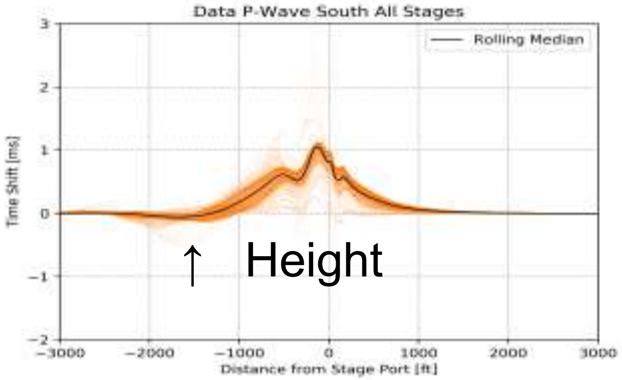
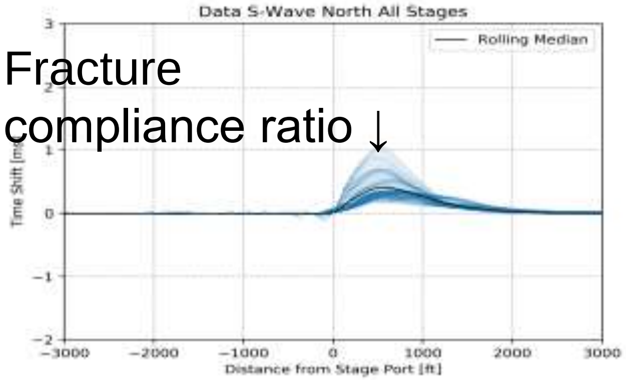




Parameter	Value
h, half-height	1100 ft
w, half-width	16 ft
τ, leak-off decay time	0.65 days
Z_N, normal fracture compliance	1.2×10^{-11} m/Pa
Z_N/Z_T, compliance ratio	0.1

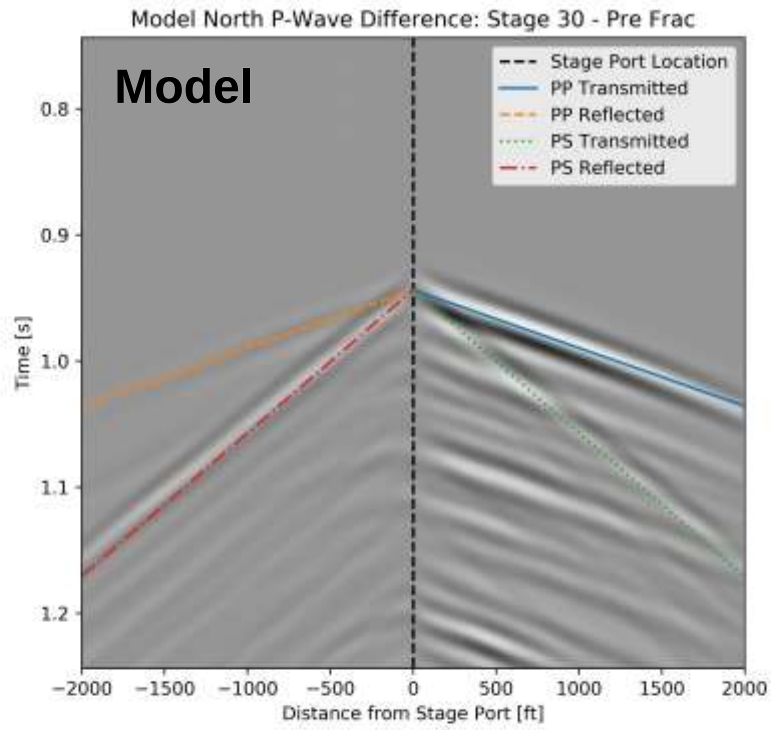
Recap: Model vs. Data

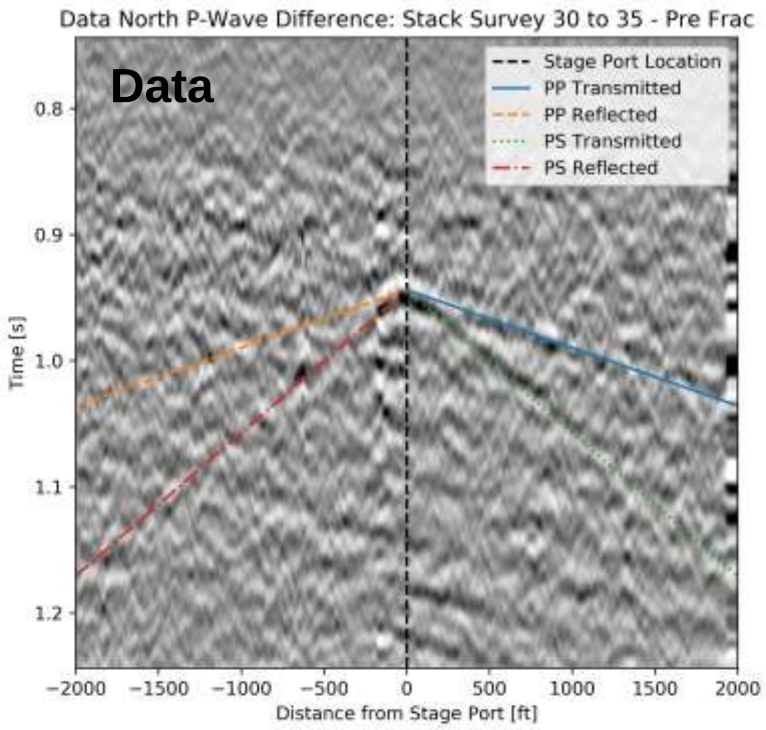
- The model matches distribution of both P and S-wave time shifts

	North P-Wave	South P-Wave	North S- Wave
Data			
Model			

Recap: Scattered Waves

- Modeling also confirms PS converted waves that were seen weakly for a few stages





Recap: Project Summary

- Time shifts and scattered waves are visible, but decay quickly over ~1 day

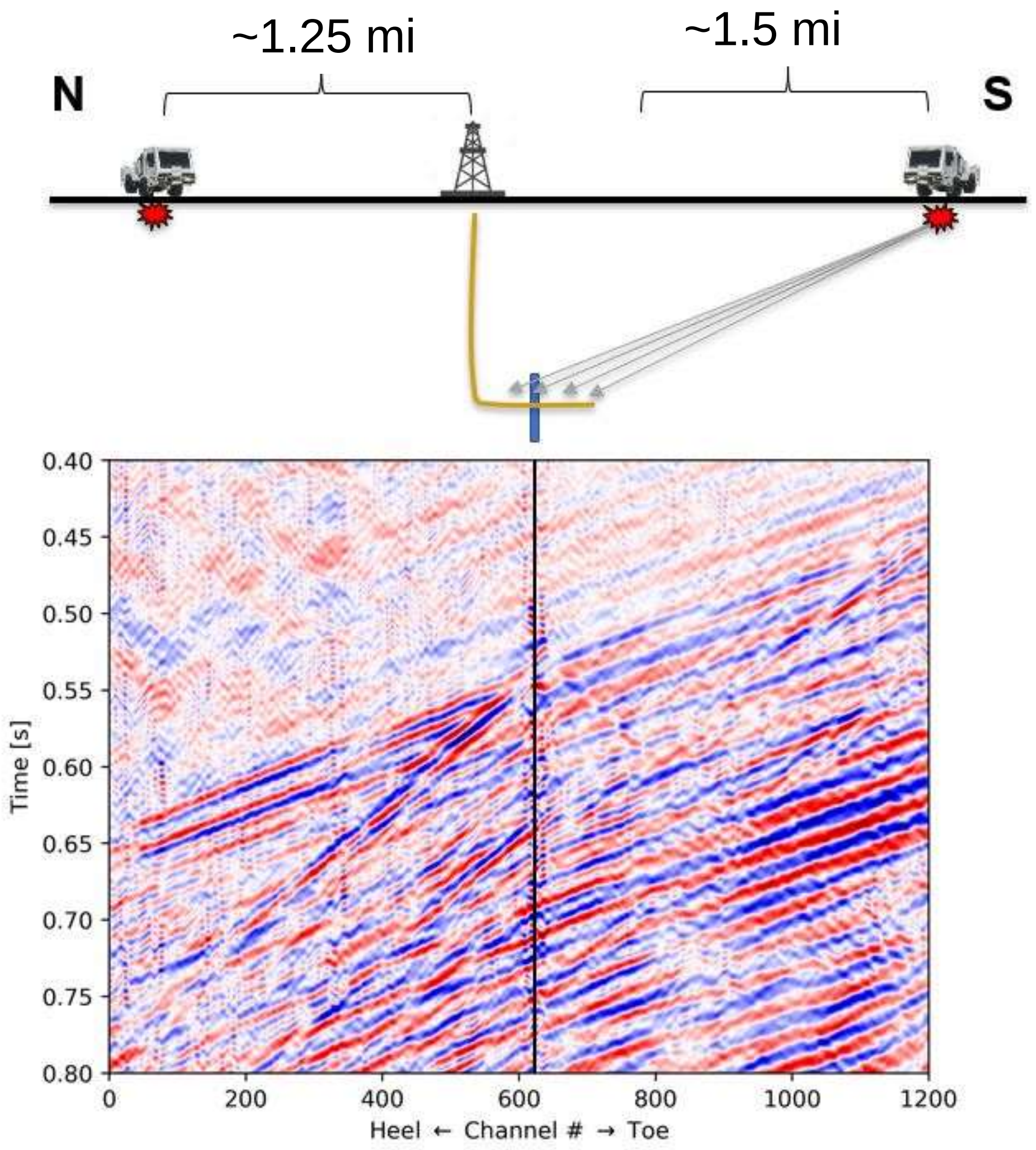
- SRV height can be estimated from a “shadow” effect in time shifts

- Finite difference modeling in an effective medium with vertical fractures closing exponentially with time matches the data well

- Fracture compliances, height, and leak-off decay time can be estimated from the data

Questions for New Survey

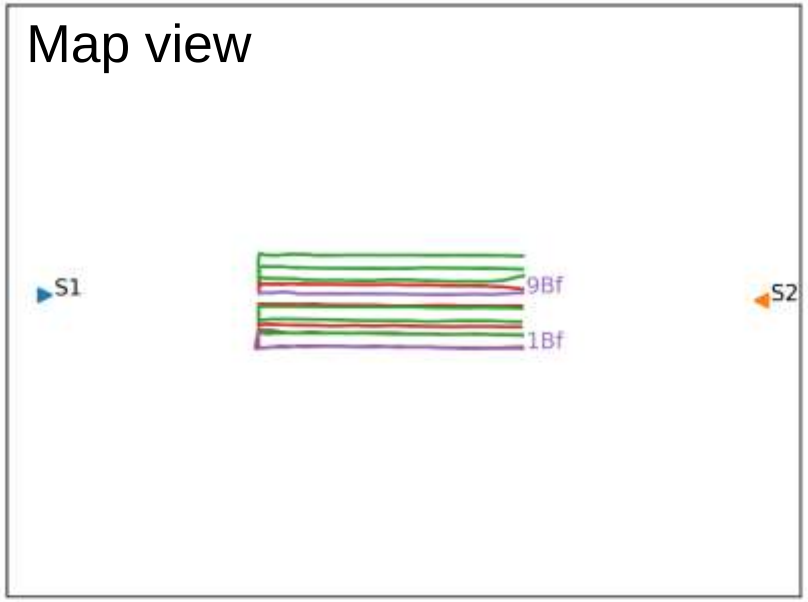
- Time-shifts and scattered waves visible after nearly every stage
- Can height, decay time and fracture compliance attributes be estimated stage by stage?
- Can these attributes be associated with changes in completion and geology?
- How do other zipper group wells influence the signal?

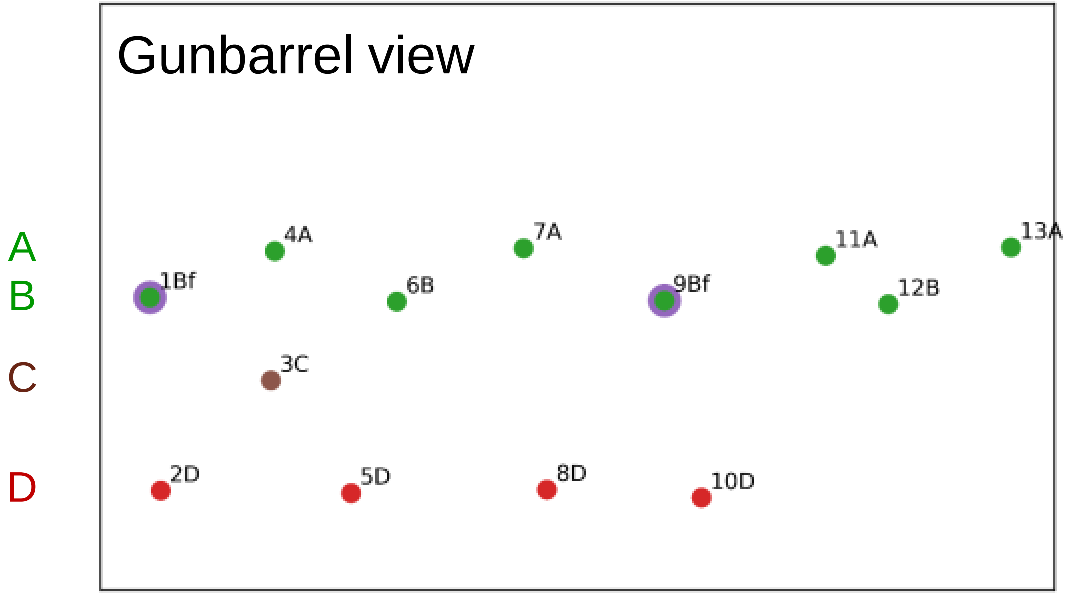


Data Acquisition

- Two wells, 1Bf and 9Bf, with engineered fiber cemented behind casing
- Same source locations used for both wells with two vibroseis trucks each

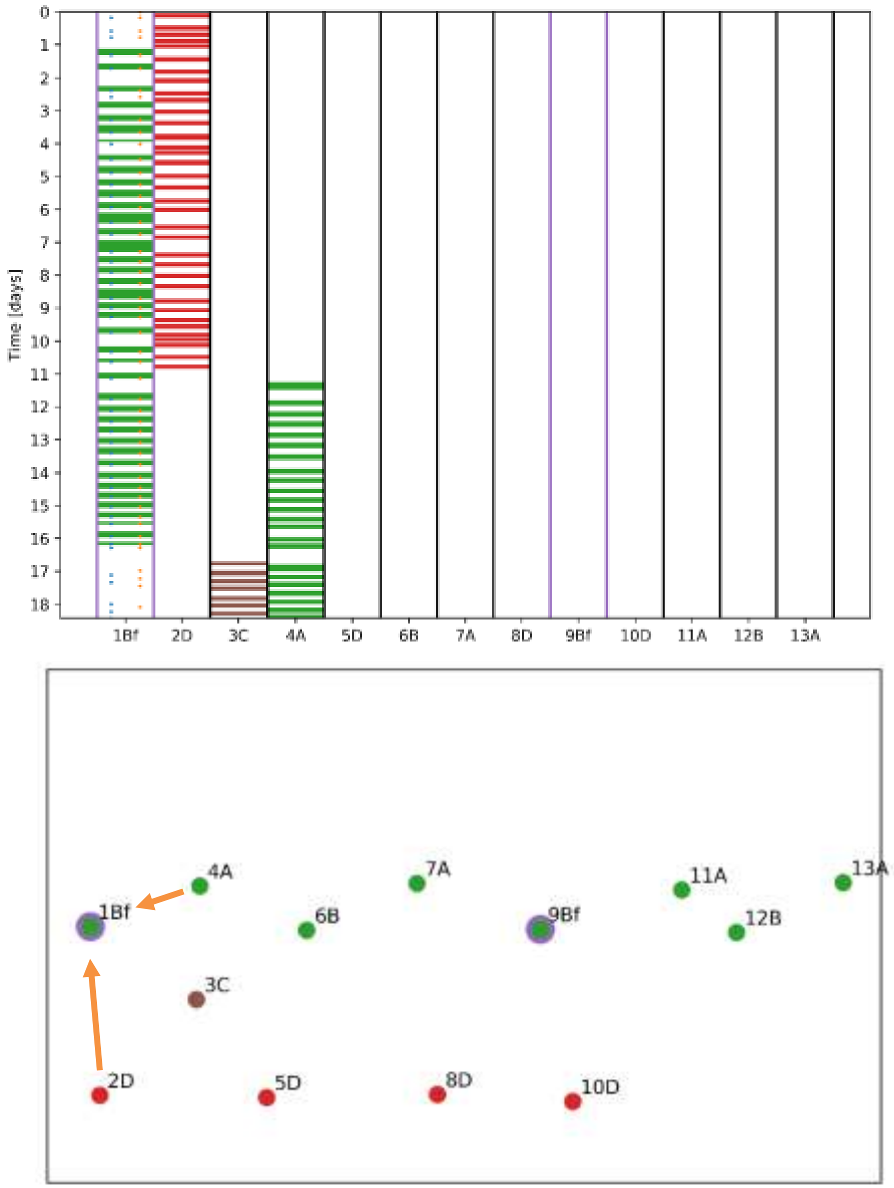
- Sweep parameters:
  - 20 sec sweep, 4 sec listen
  - 6 – 96 Hz
  - At least ~20 sweeps after each stage





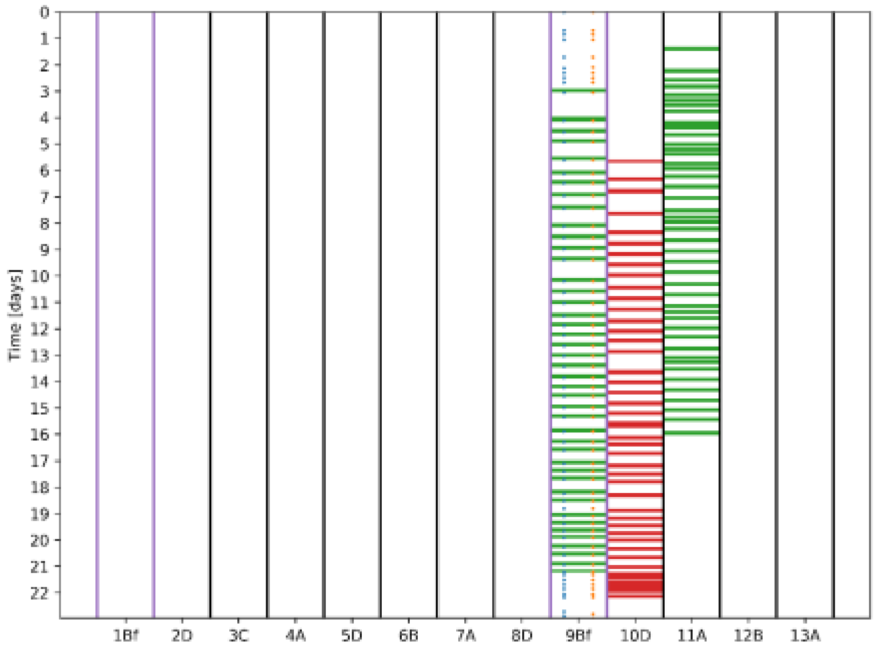
1Bf: Timeline

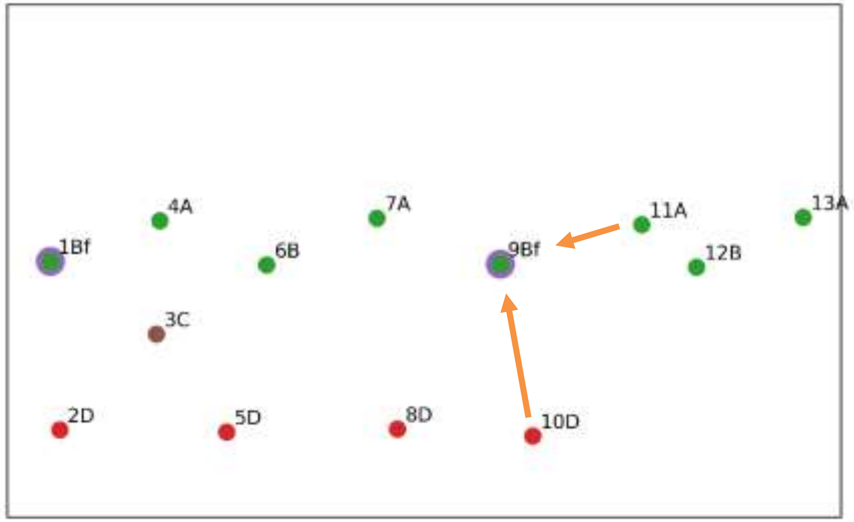
- Survey timeline:
  - 3 baseline surveys
  - 41 interstage surveys
  - 5 “leak-off” surveys
- Other wells were zippered during survey
- Opportunity to observe signals from 4A and 2D wells
- Fiber break occurred during stage 22



9Bf: Timeline

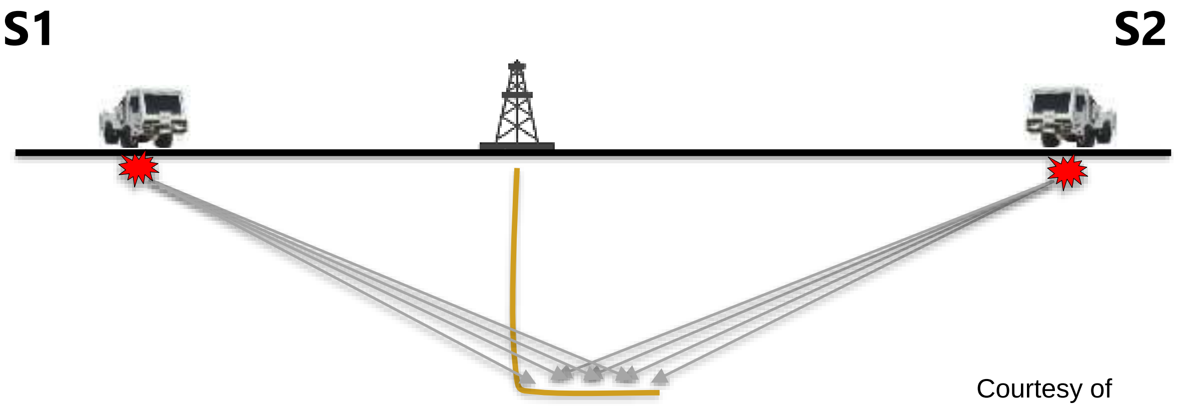
- Survey timeline:
  - 9 baseline surveys
  - 44 interstage surveys
  - 8 “leak-off” surveys
- Other wells were zippered during survey
- Opportunity to observe frac hits from 11A and 10D wells



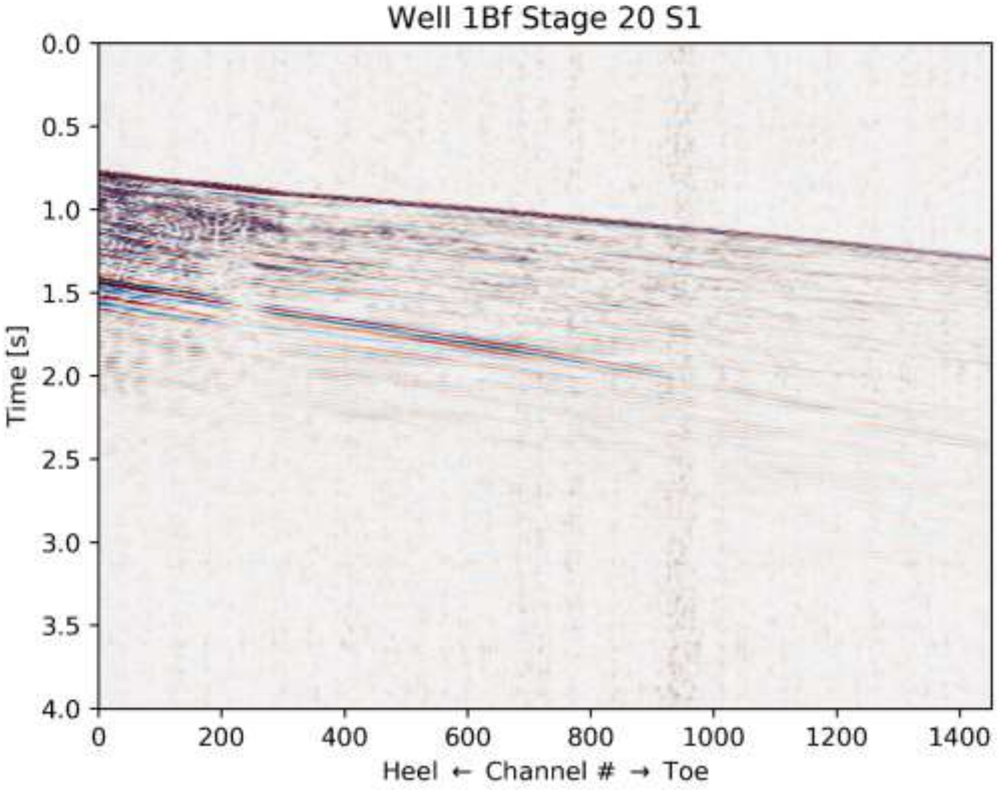


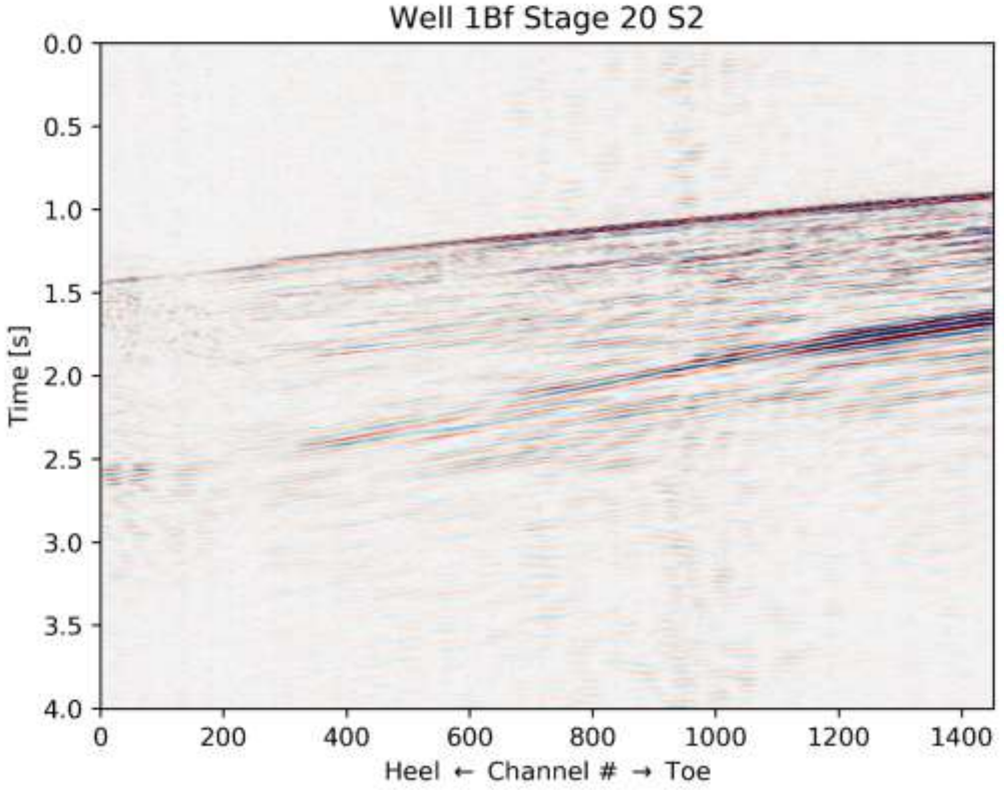
1Bf: Shot Records

Stacked, processed shot records along lateral after stage 20



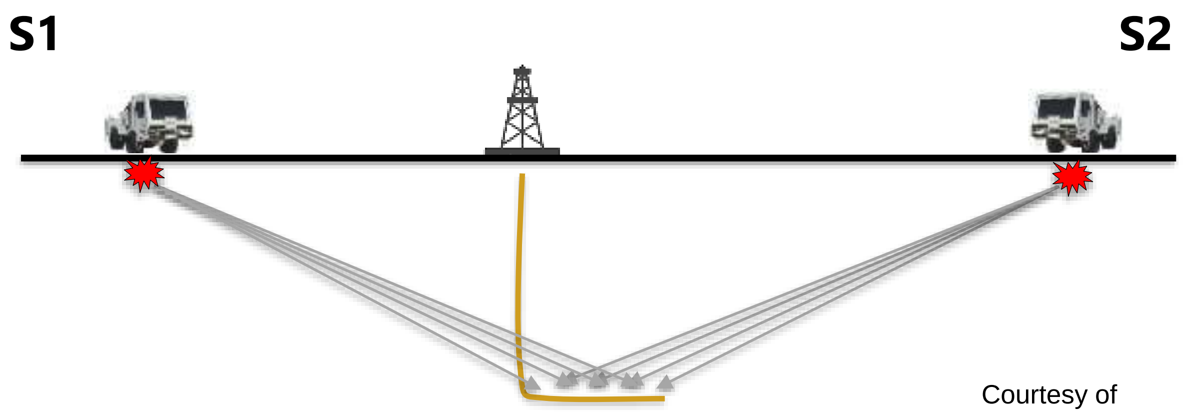
Courtesy of Apache





9Bf: Shot Records

Stacked, processed shot records along lateral after stage 20



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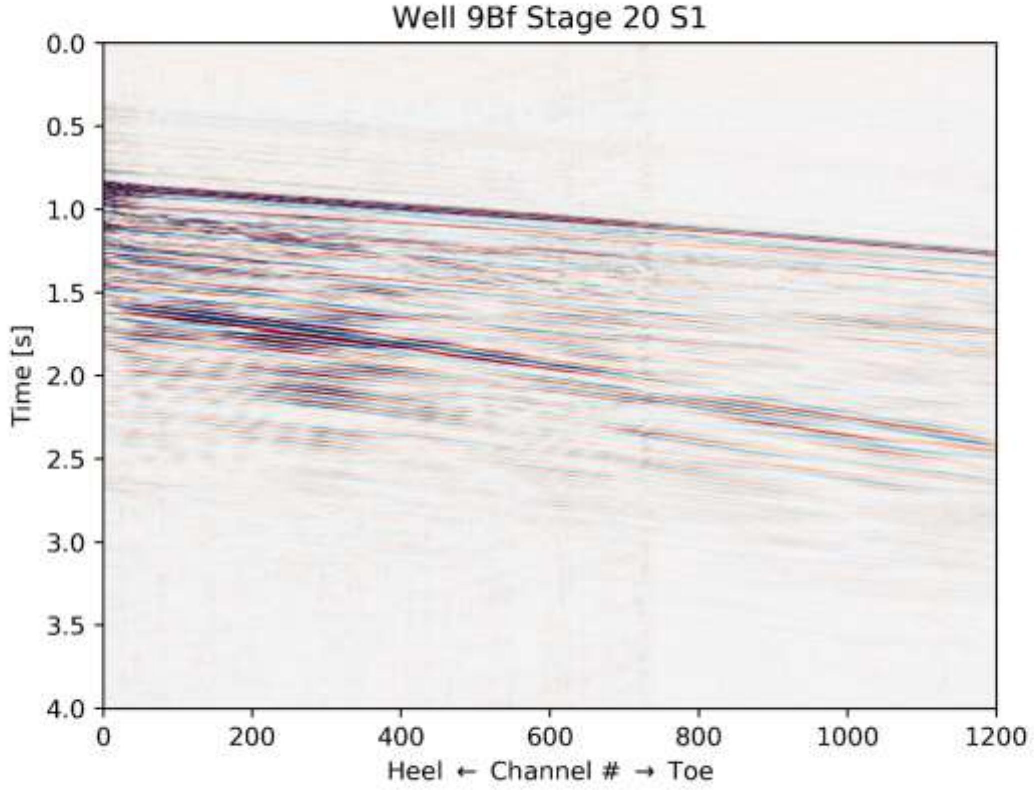
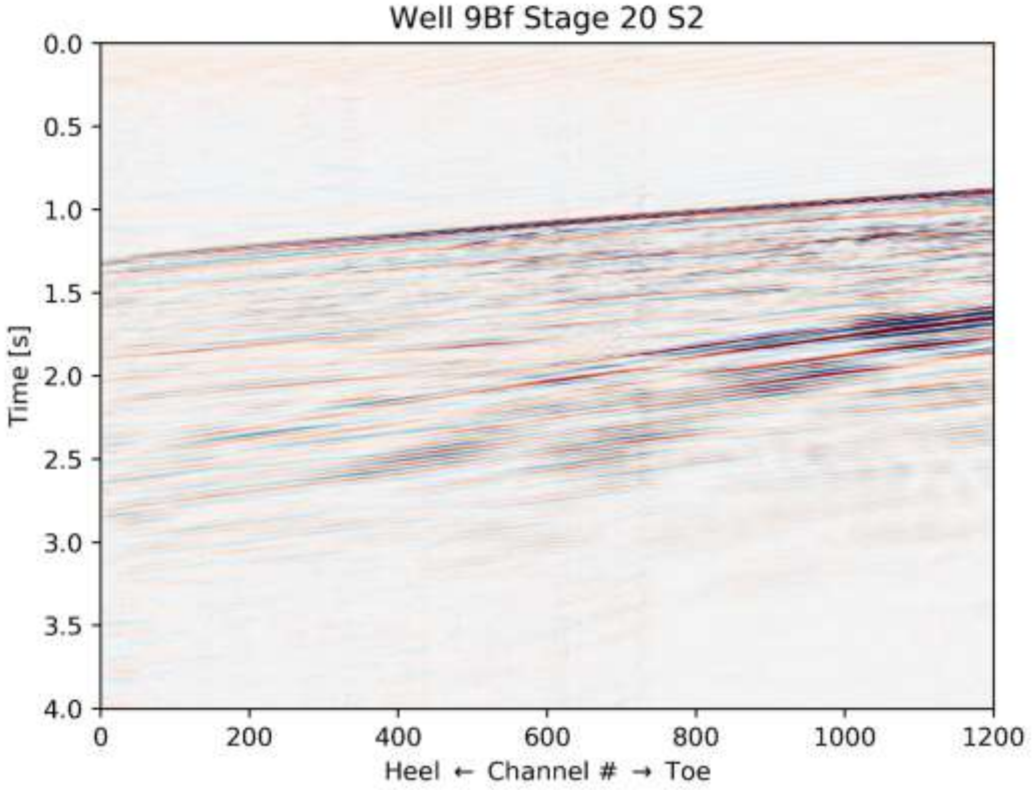
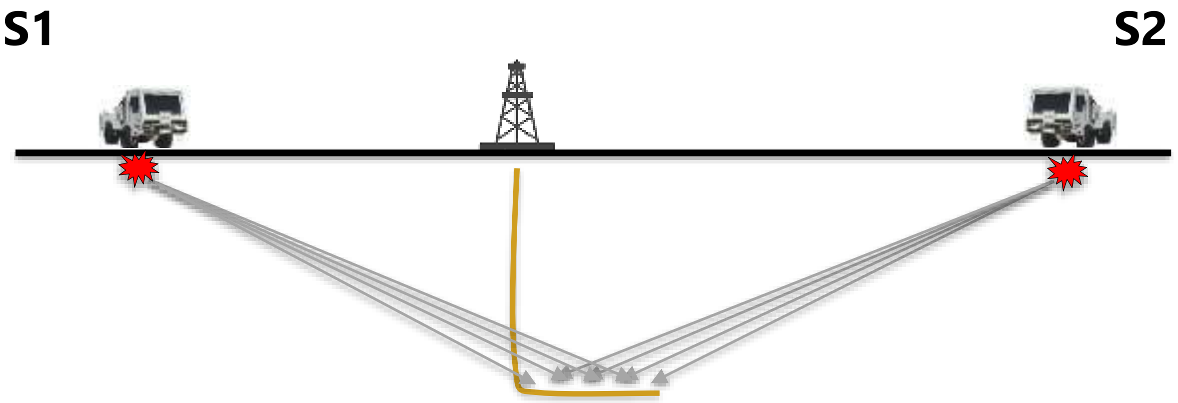


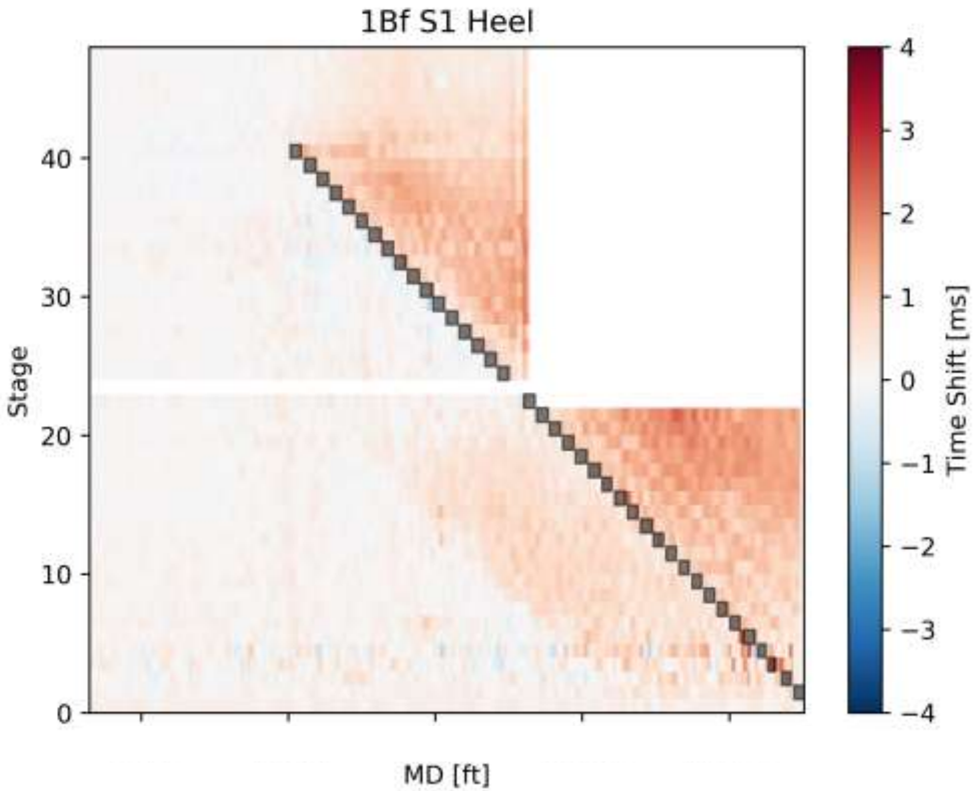


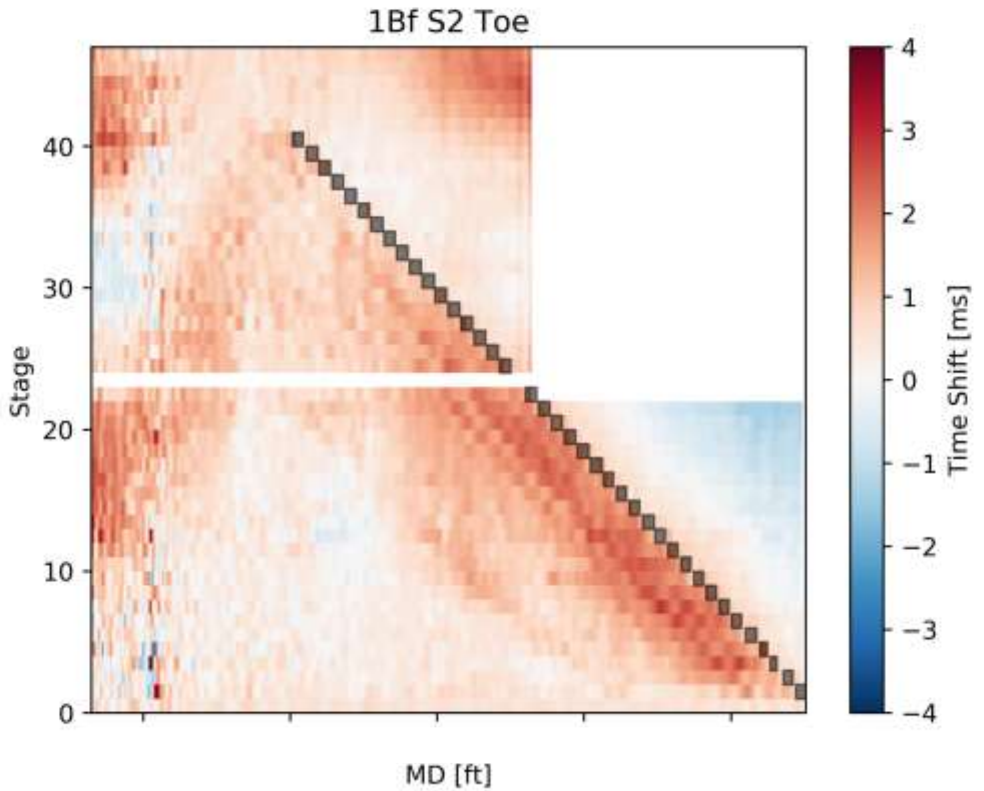
1Bf: P-Wave Time Shifts

Time shifts up to ~2 ms follow stage intervals



Speedup ← → Slowdown





1Bf: P-Wave Time Shifts

RCP
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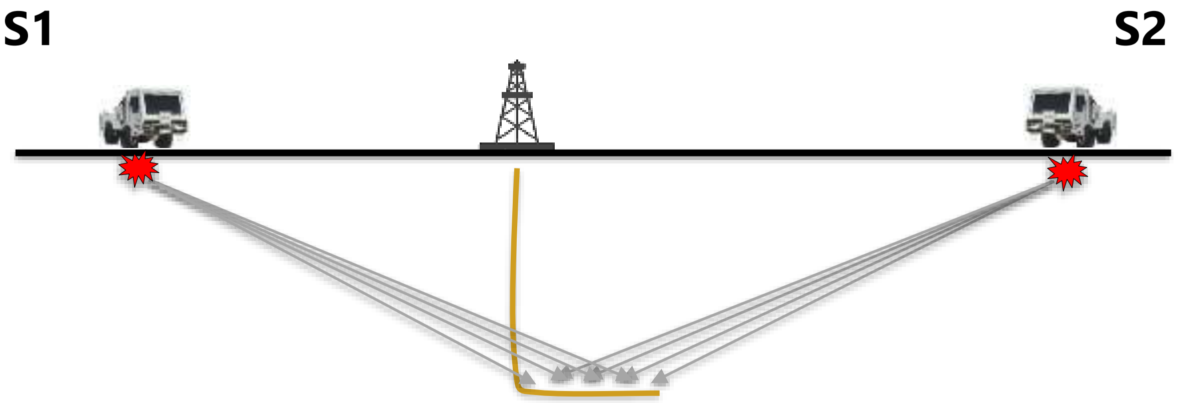
Time shifts up to ~2 ms follow stage intervals



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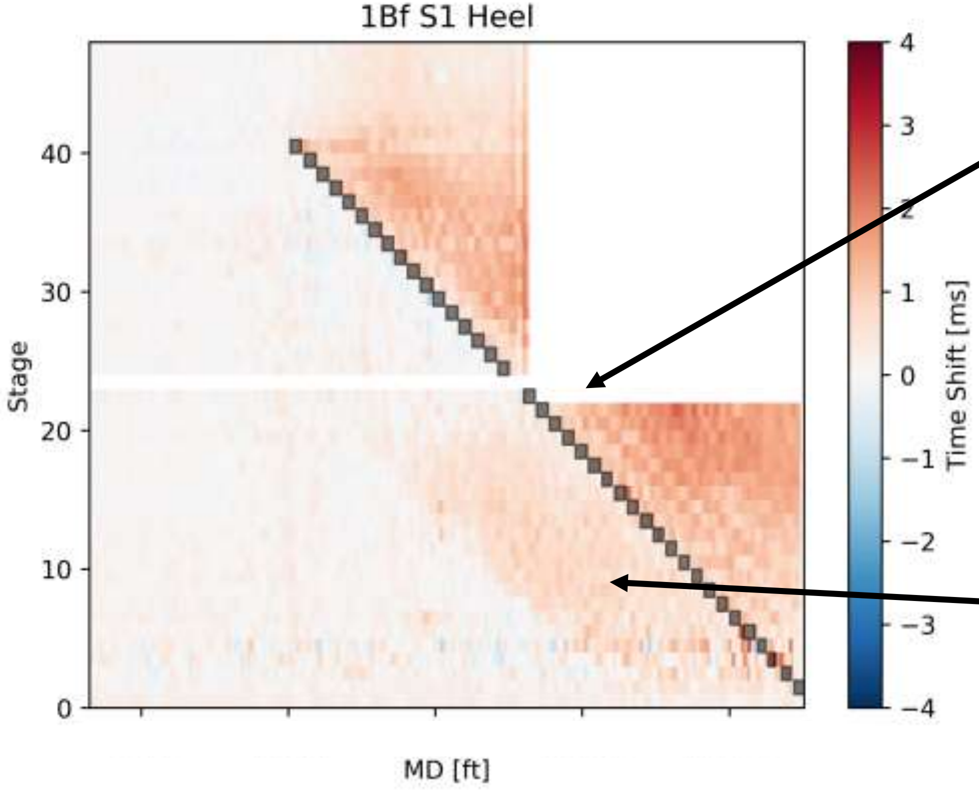
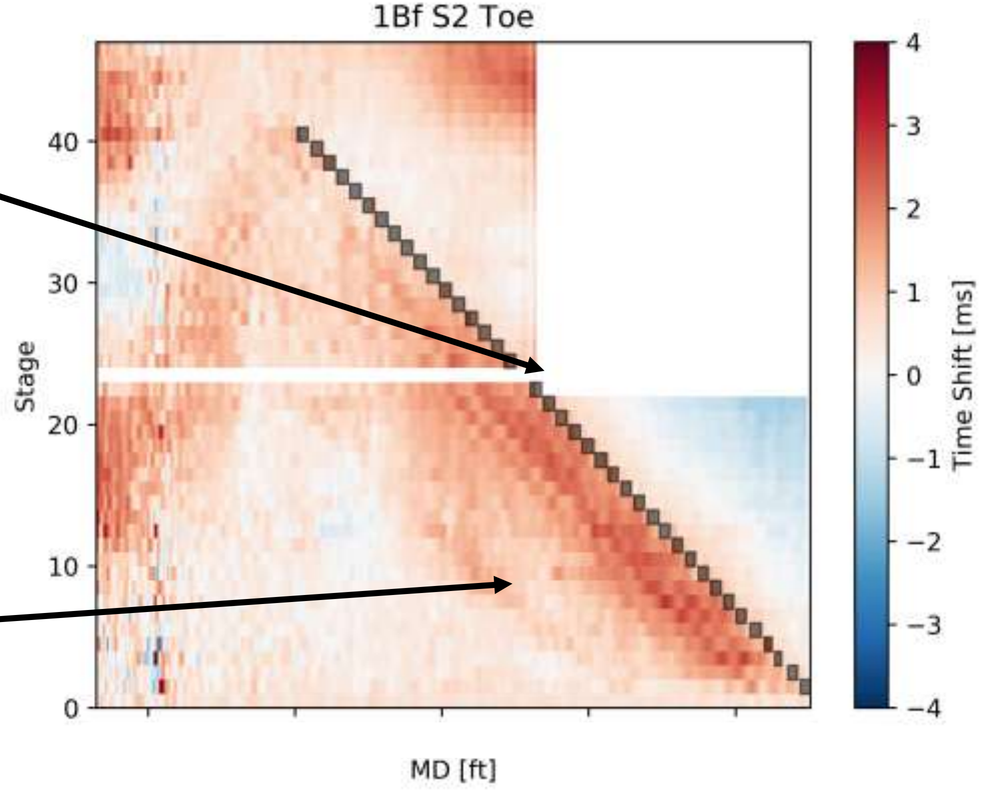


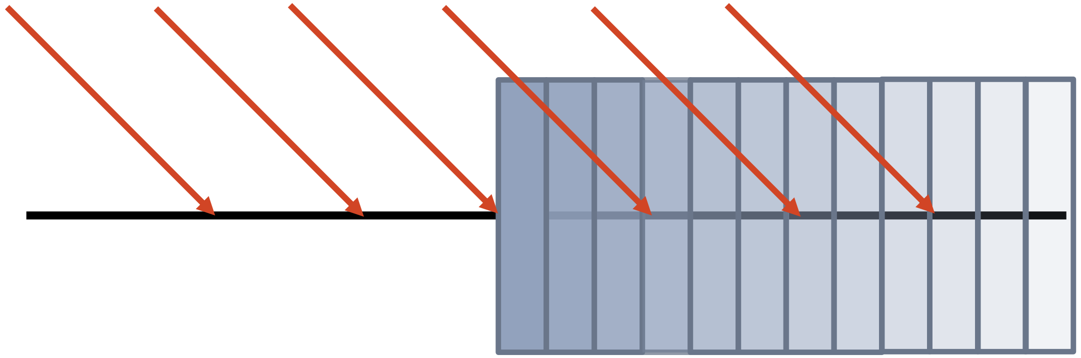
Fiber break occurred during stage 22

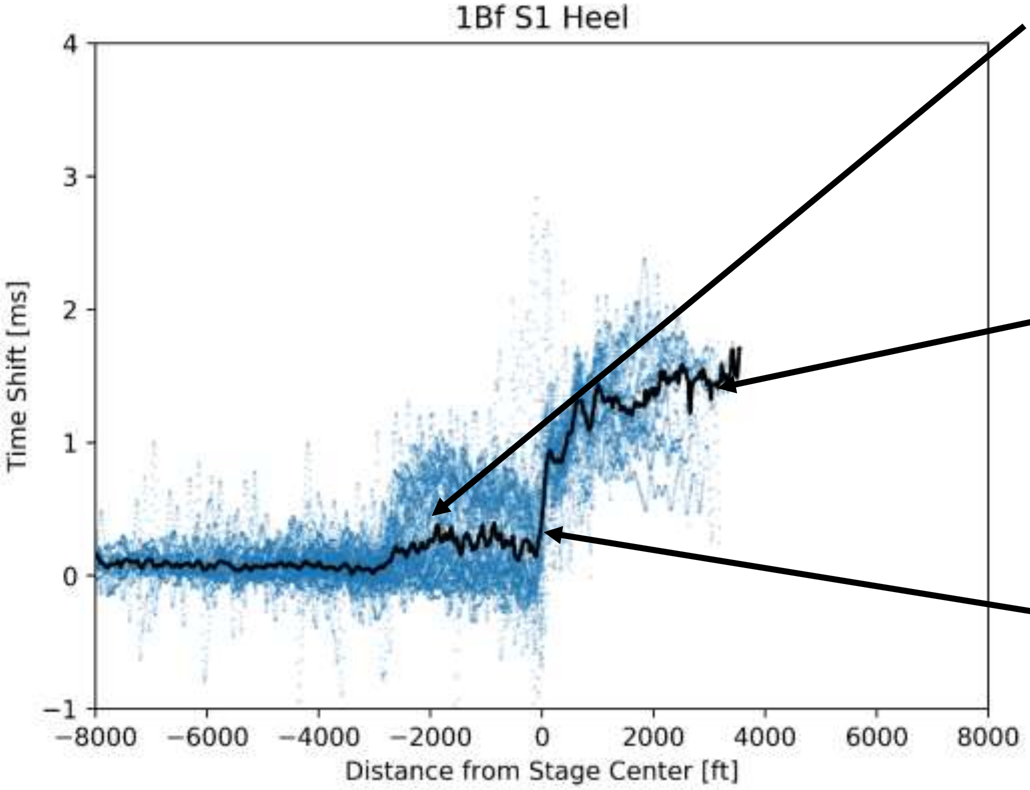
Secondary bands from another well?



1Bf: P-Wave Shifts for All Stages

Stack time shifts as a function distance from stage port





Time shifts before stage from another well?

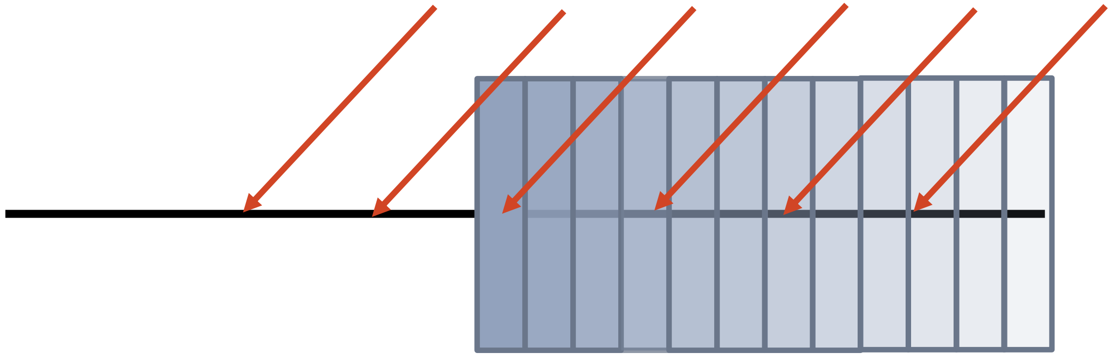
Time shifts don't entirely decay?

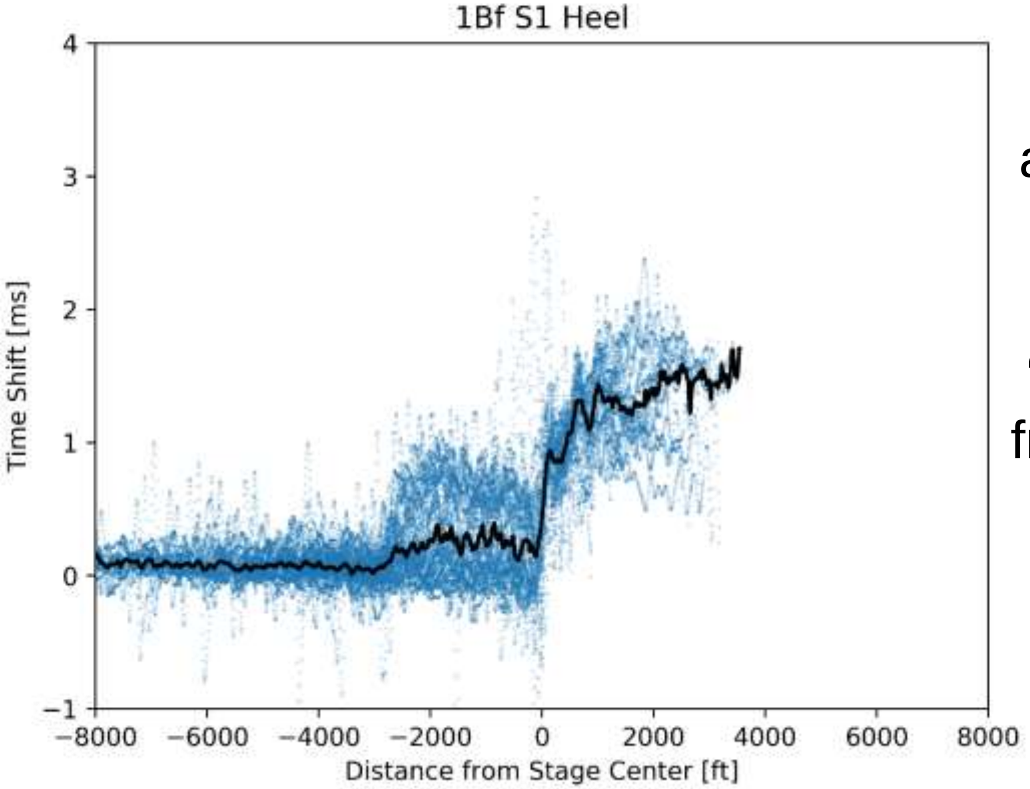
Velocity change in fracture zone

Stage-to-stage variations are above noise level

1Bf: P-Wave Time Shifts for All Stages

Stack time shifts as a function distance from stage port

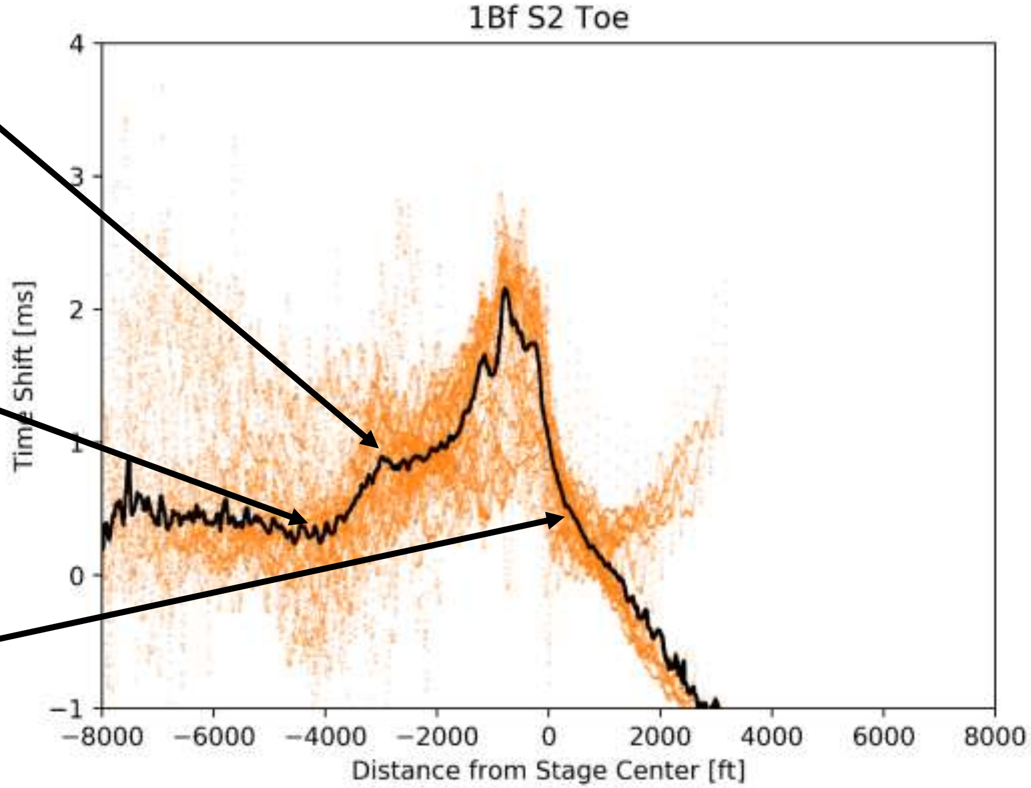




Secondary peak from another well?

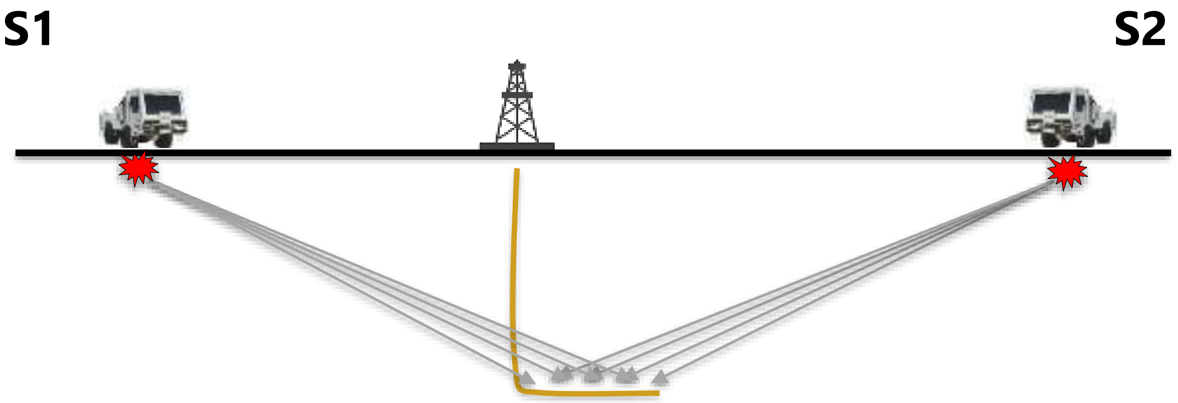
~4000 ft “shadow” of fracture zone

Time shifts rapidly decay

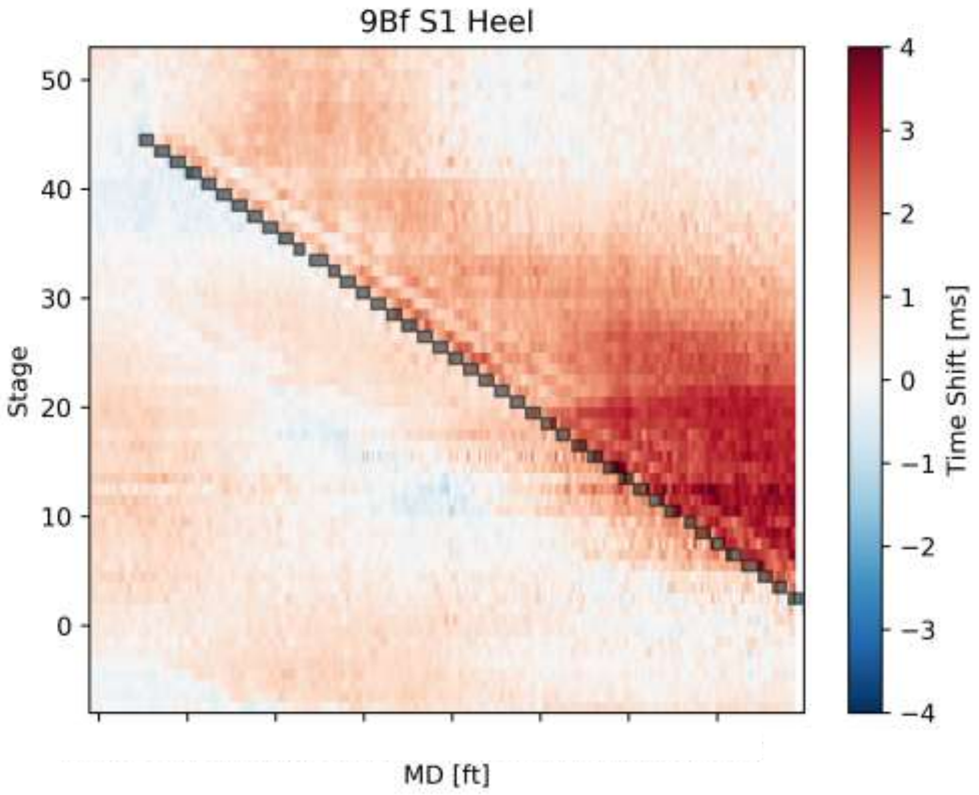


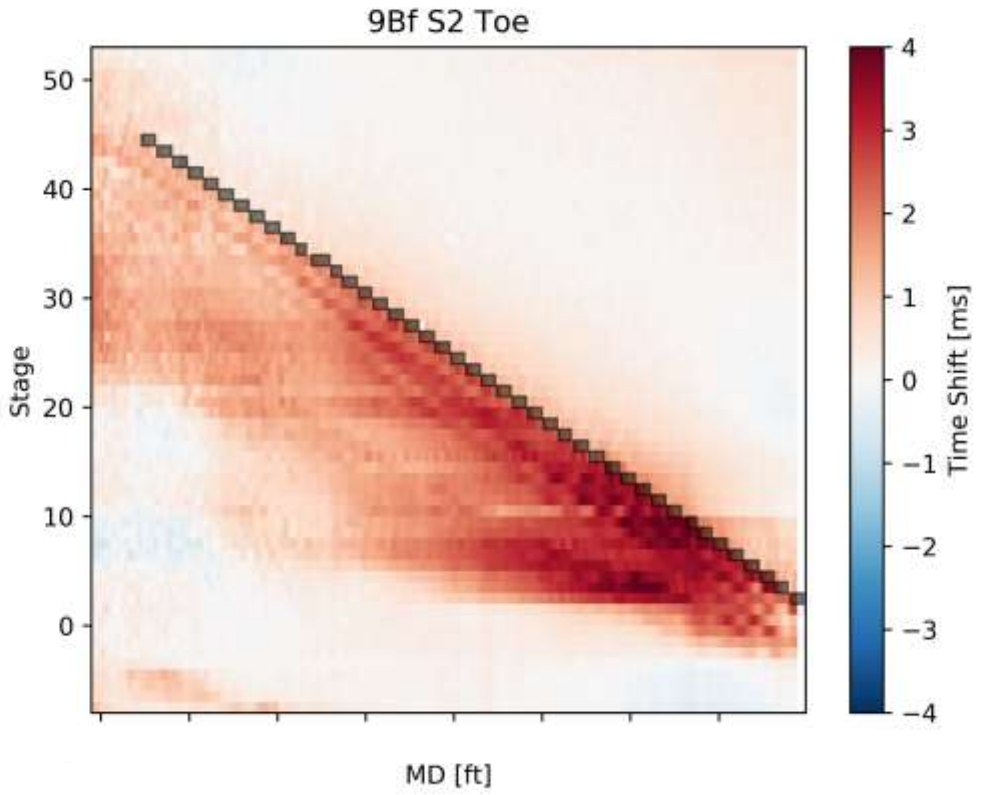
9Bf: P-Wave Time Shifts

Time shifts up to ~4 ms follow stage intervals



Speedup ← → Slowdown





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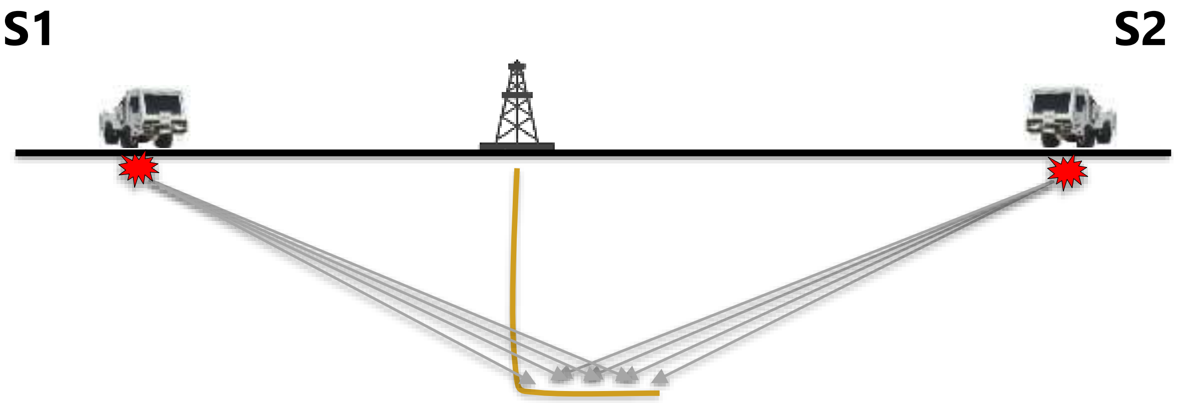
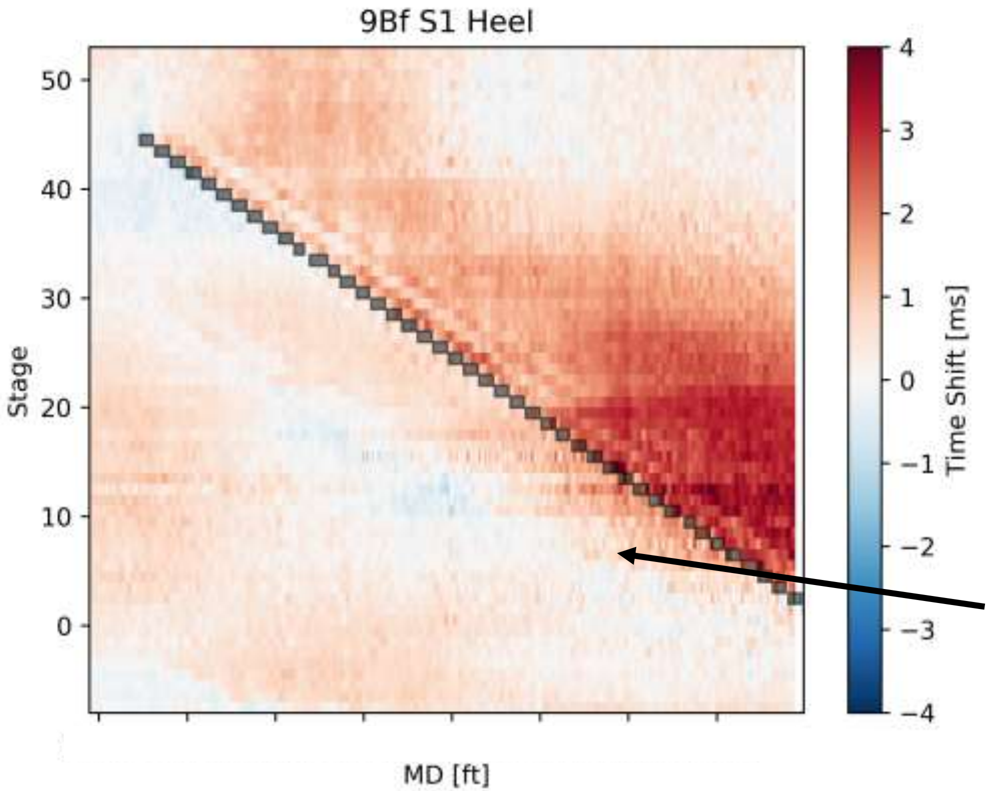
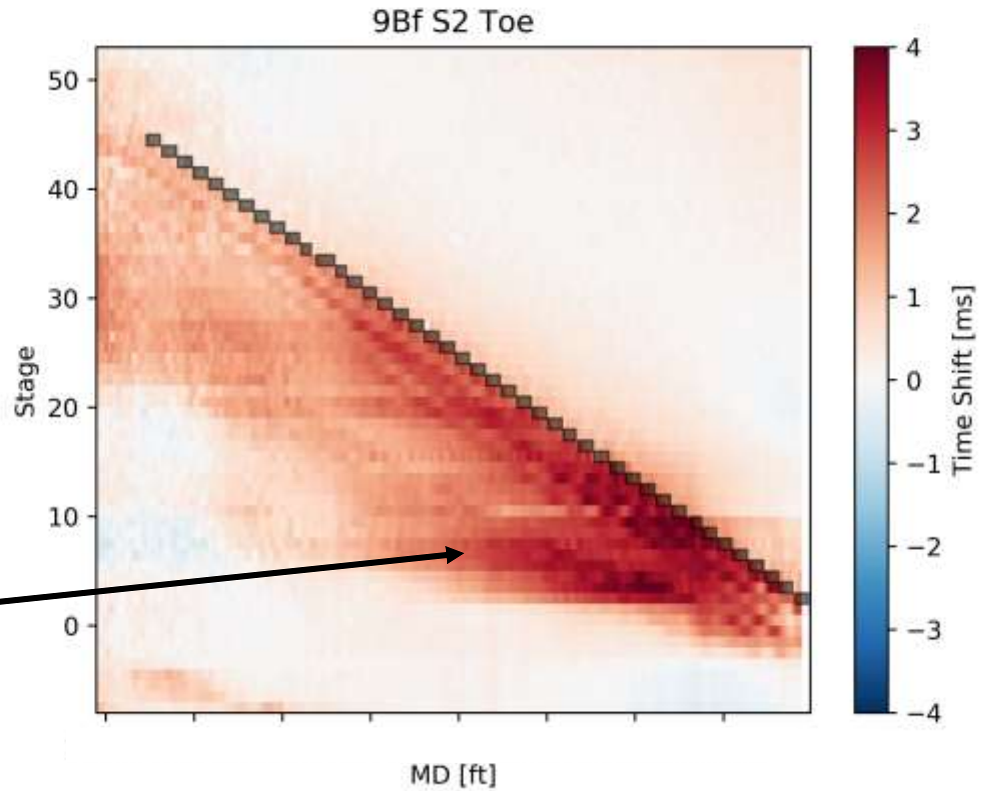


Speedup ← → Slowdown

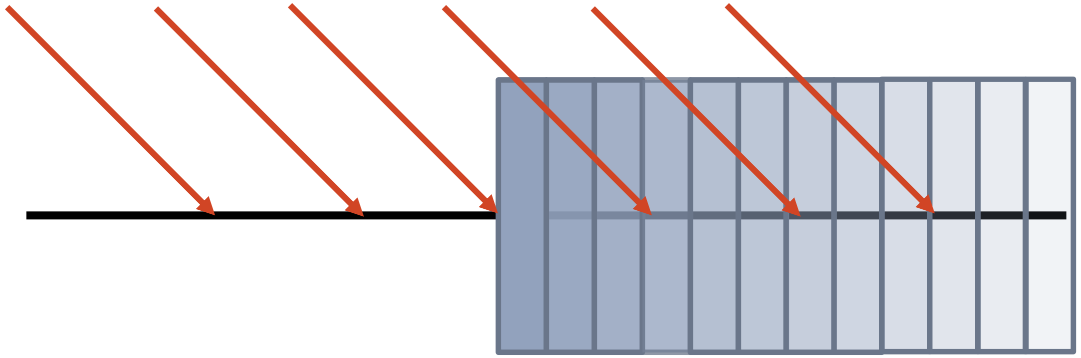


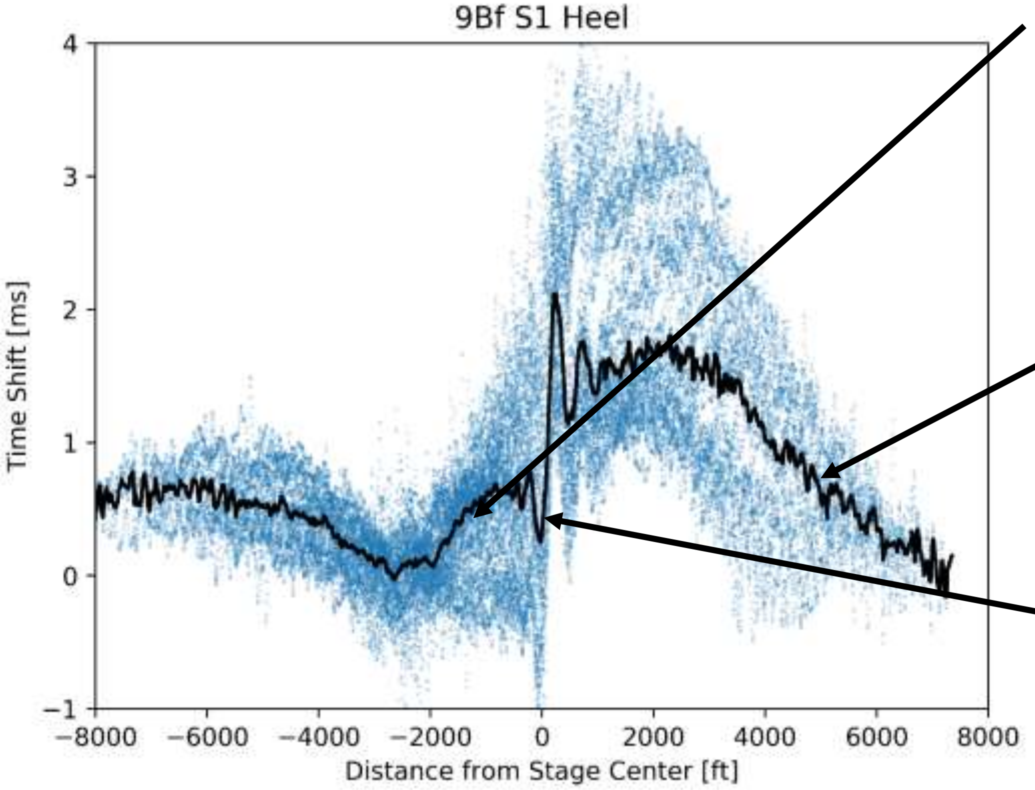


Secondary bands from another well?

9Bf: P-Wave Shifts for All Stages

Stack time shifts as a function distance from stage port





Time shifts before stage from another well?

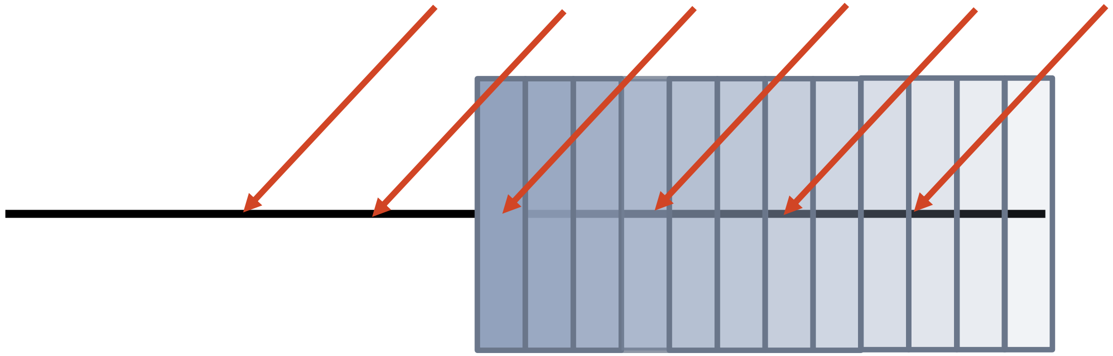
Time shifts decay

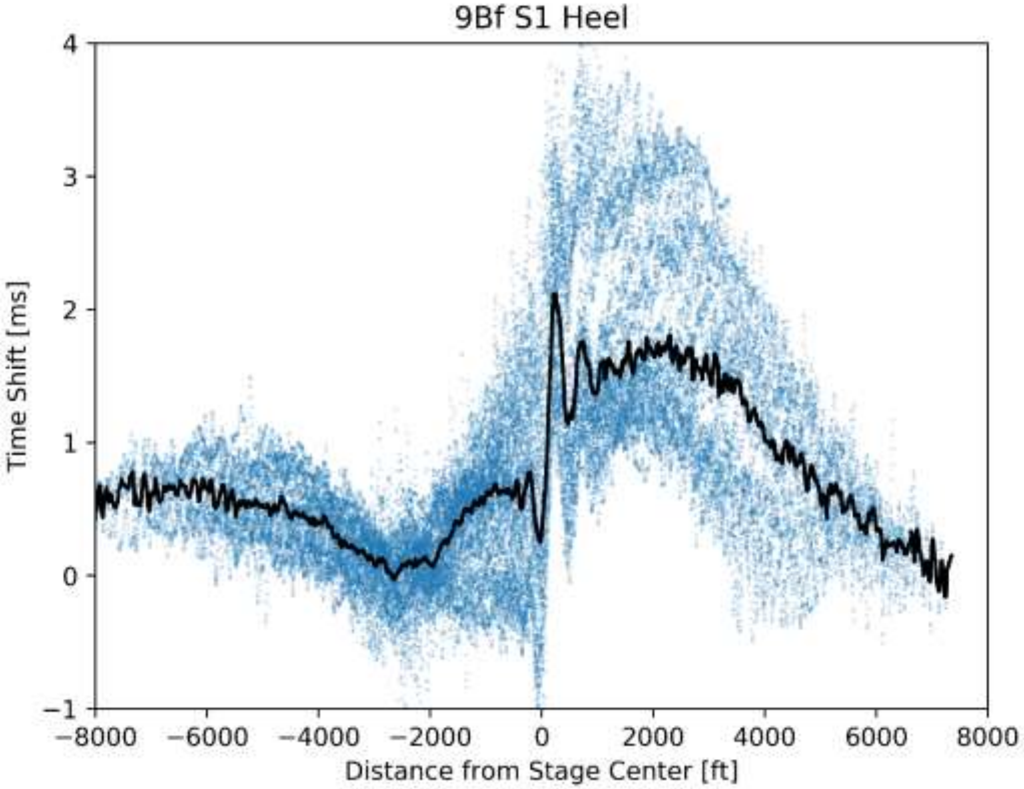
Velocity change in fracture zone

Clear stage-to-stage variations above noise level

9Bf: P-Wave Time Shifts for All Stages

Stack time shifts as a function distance from stage port

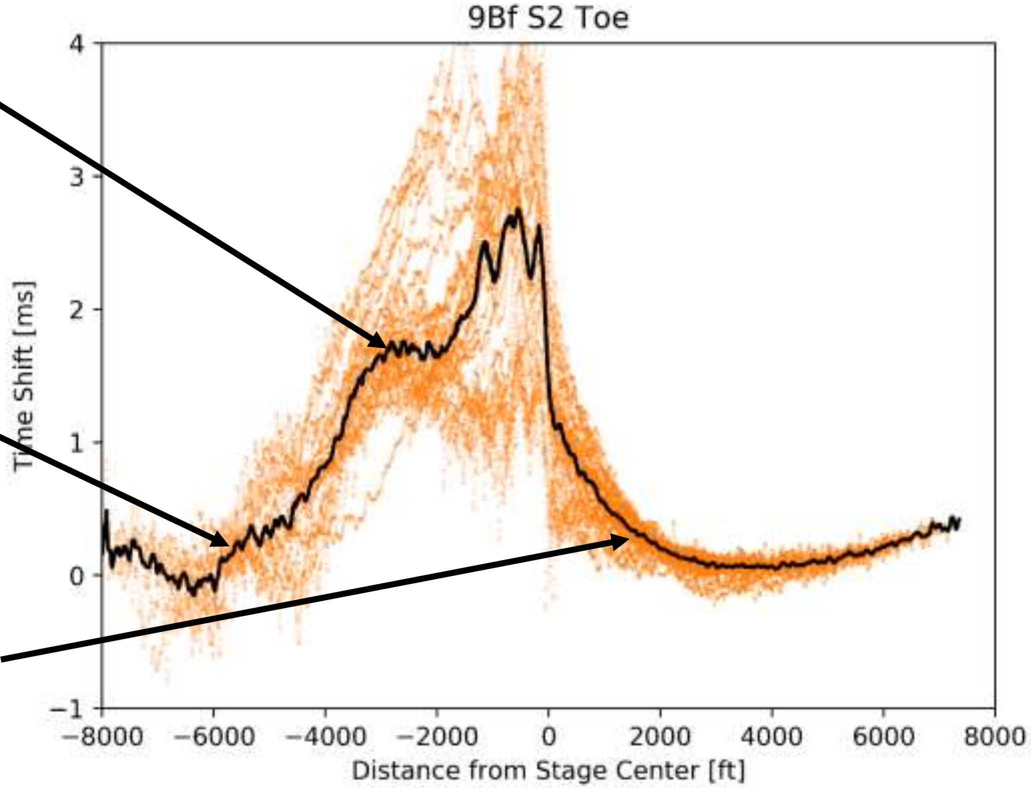




Secondary peak from another well?

~6000 ft "shadow" of fracture zone

Time shifts rapidly decay



P-wave Time Shift Observations

- P-wave time shifts follow a very different pattern than previous data
  - A primary component follows expected stage locations and decays quickly
  - Signs of secondary bands from other wells

- SRV height cannot be estimated based on the size of the time shift shadow alone

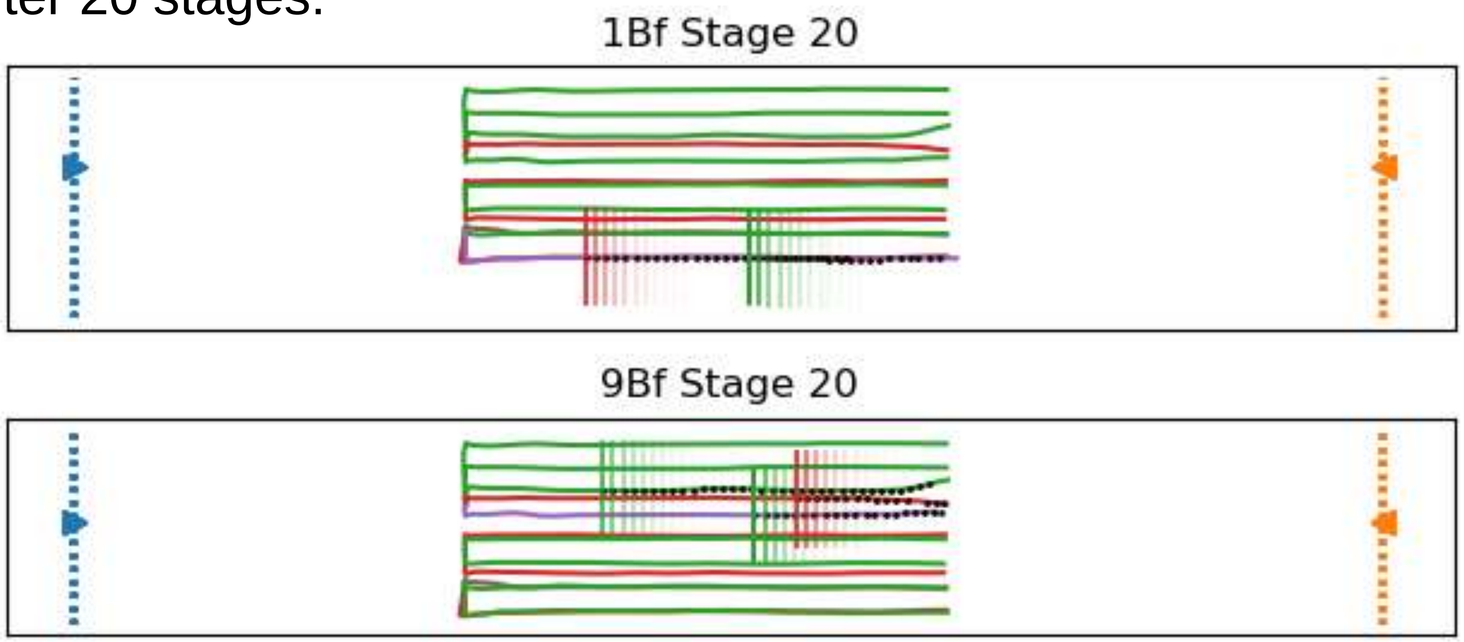
- Other wells have a significant influence on the time shift distribution

- Modeling all zipper group wells is needed to explain these observations

Multi-Well Modeling Approach

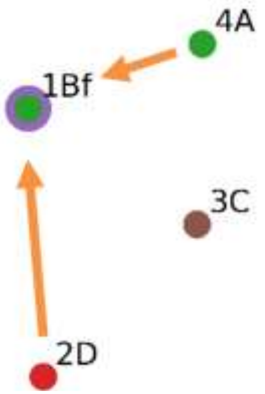
- Previous modeling can be generalized from 2D to pseudo-3D
- Assume each stage creates a planar distribution of vertical fractures
- All stages have the same parameters
- Approximate sources as lines to use 2D finite difference modeling

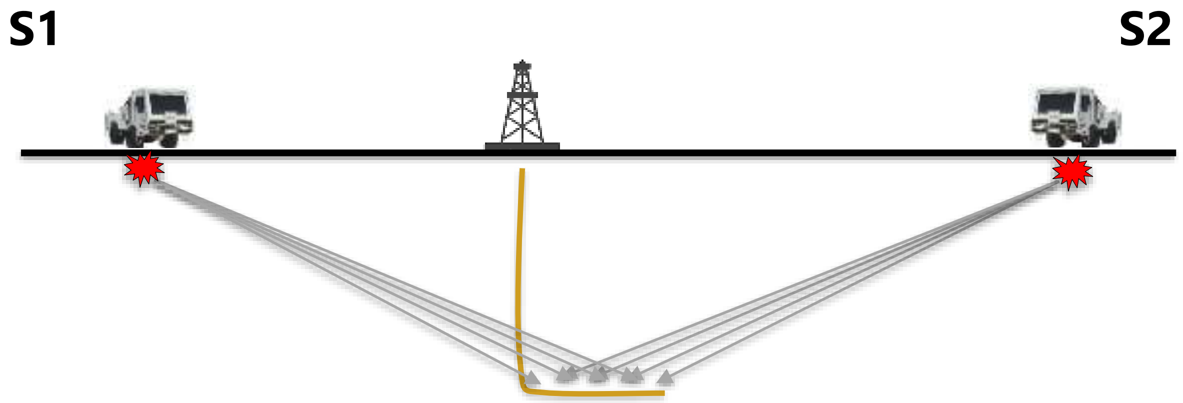
Map view of fracture compliance distribution after 20 stages:



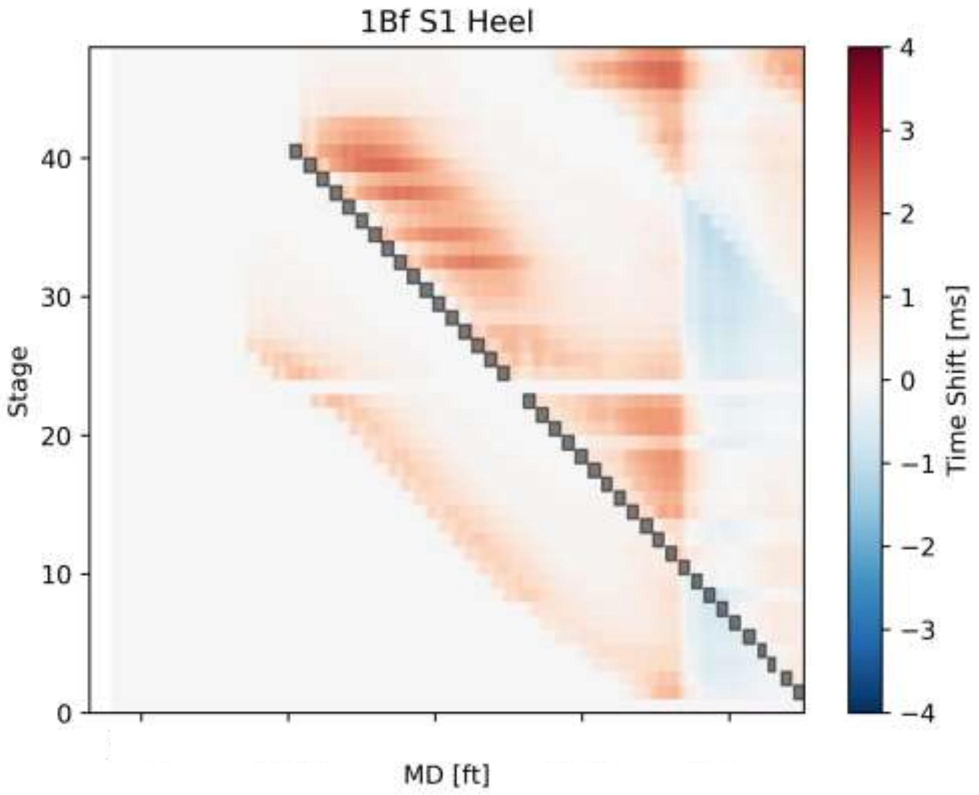
Parameter	Value
h, half-height	1100 ft
L, length	1600 ft
w, half-width	30 ft
ϕ, strike	90° from well
τ, decay time	1 day
Z_N, normal fracture compliance	4.8×10^{-11} m/Pa
Z_N/Z_T, compliance ratio	0.1

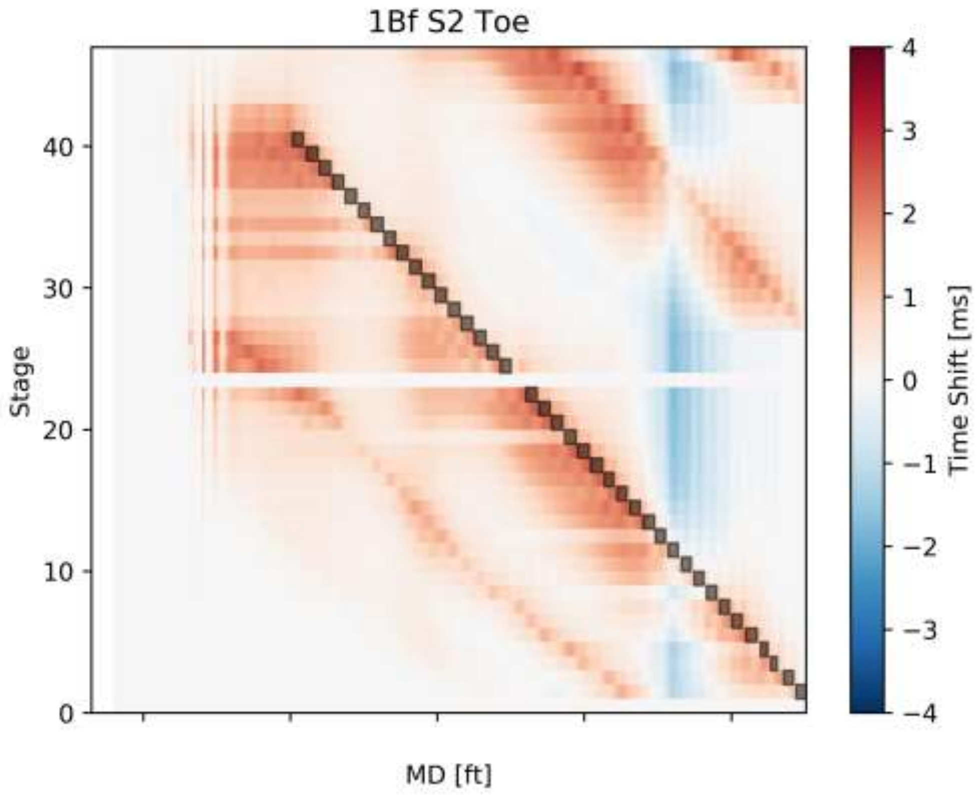
1Bf: Modeled P-Wave Time Shifts



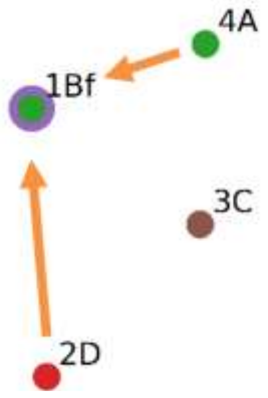


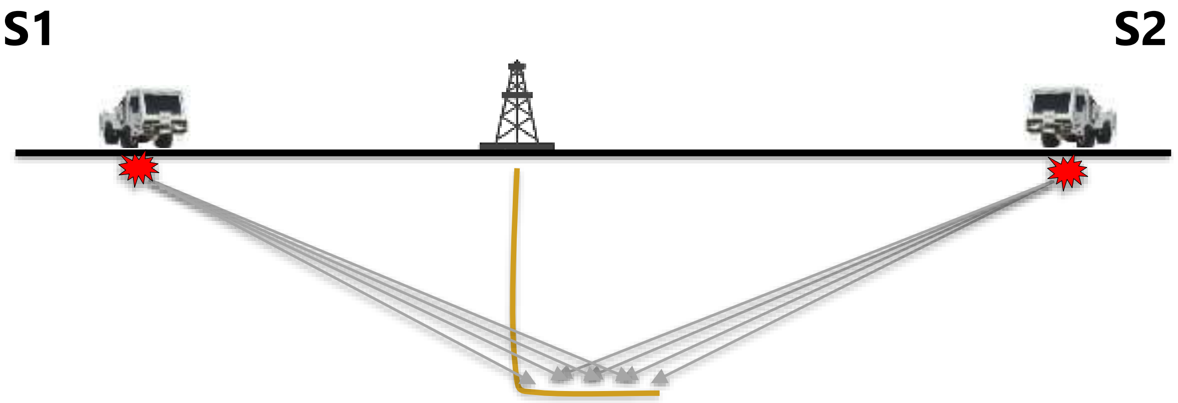
Speedup ← → Slowdown



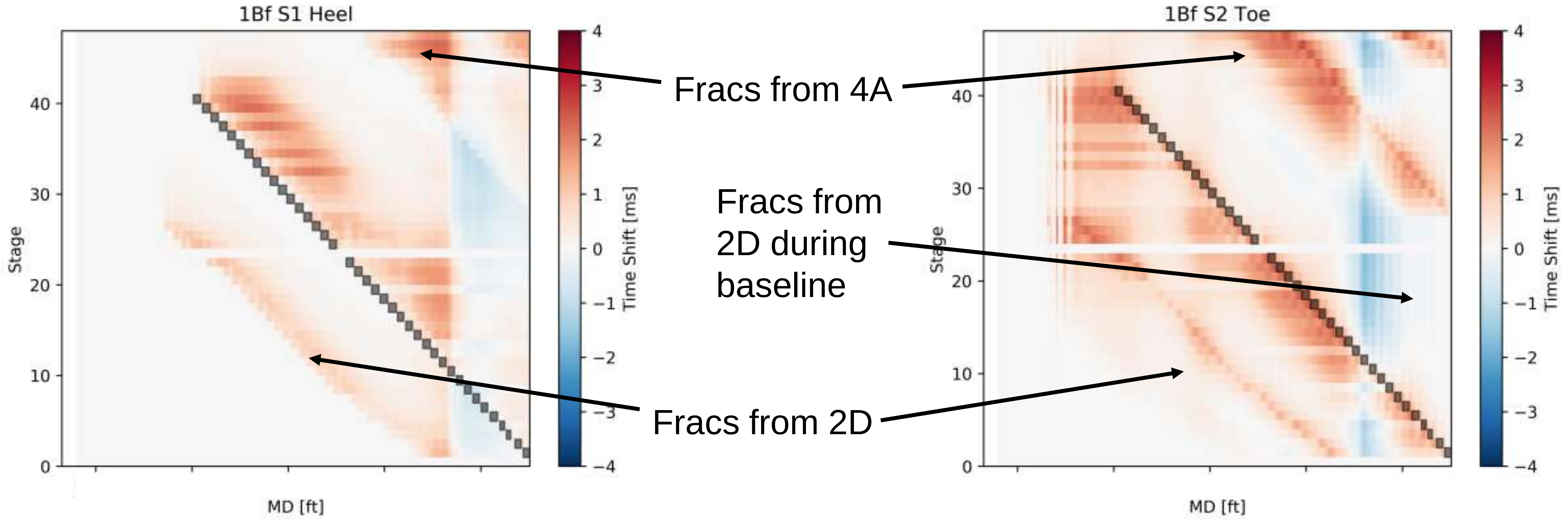


1Bf: Modeled P-Wave Time Shifts

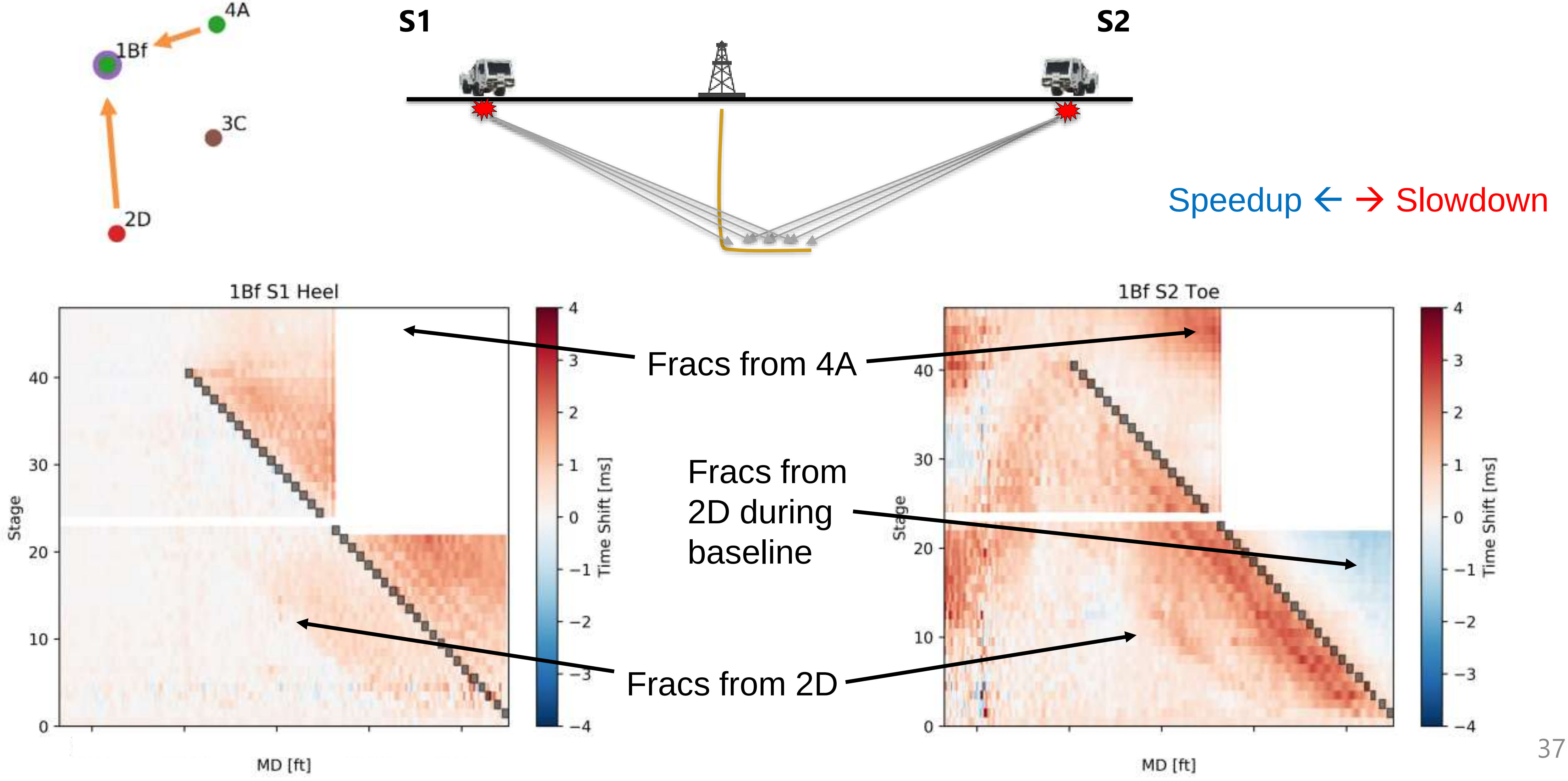




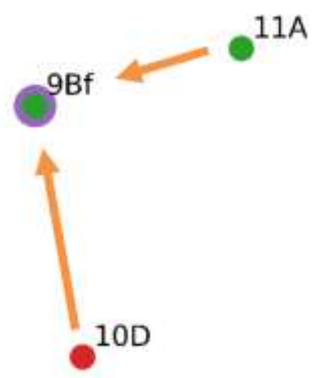
Speedup ← → Slowdown

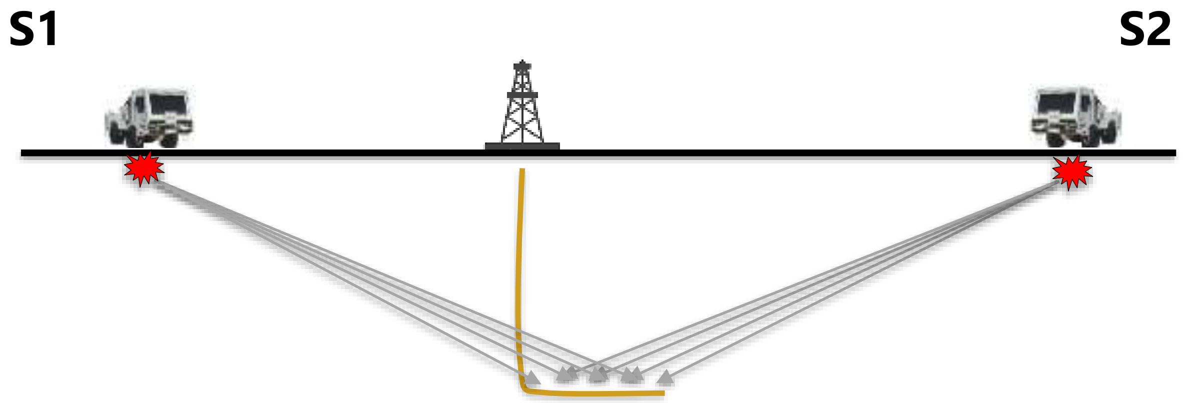


1Bf: Observed P-Wave Time Shifts

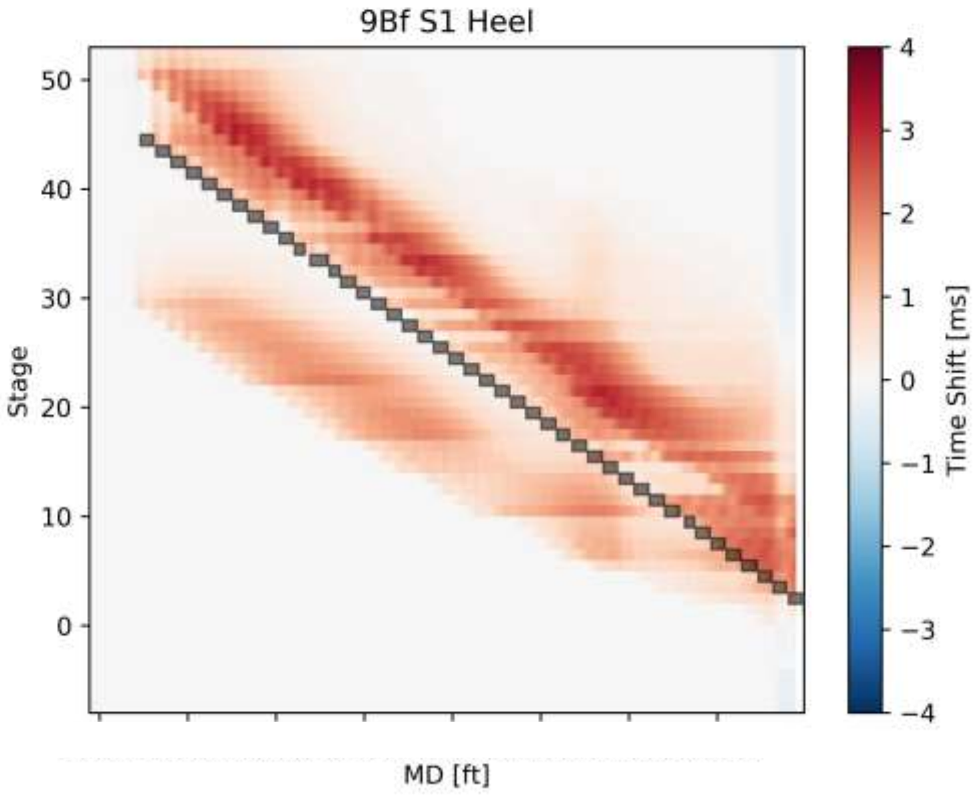


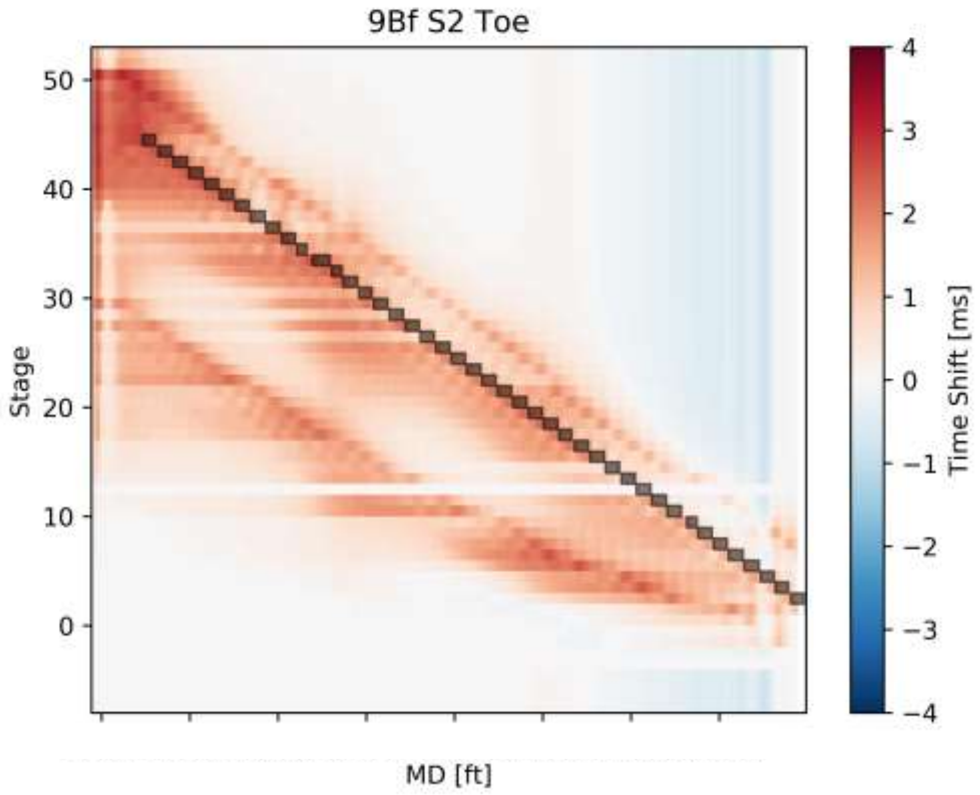
9Bf: Modeled P-Wave Time Shifts





Speedup ← → Slowdown





9Bf: Modeled P-Wave Time Shifts

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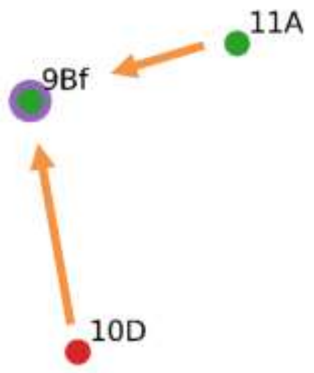
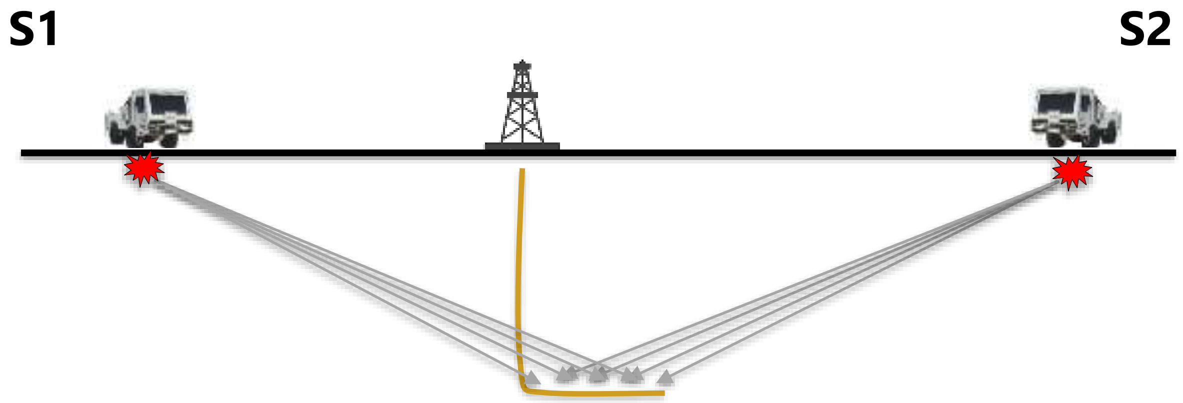
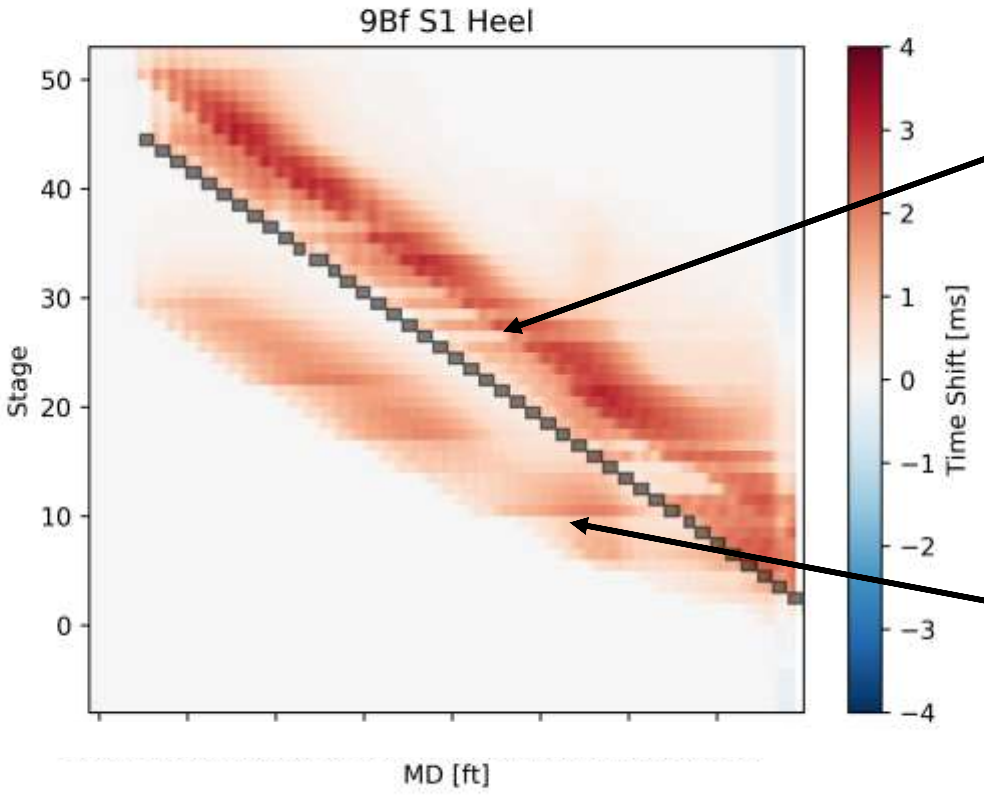


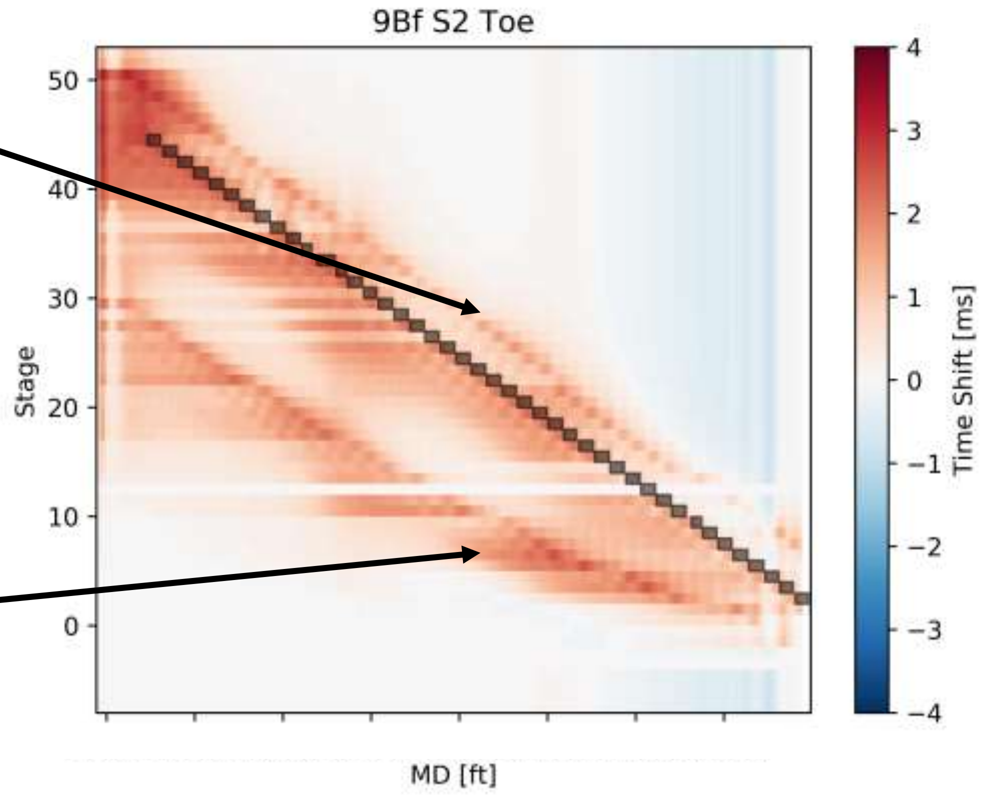


Speedup ← → Slowdown

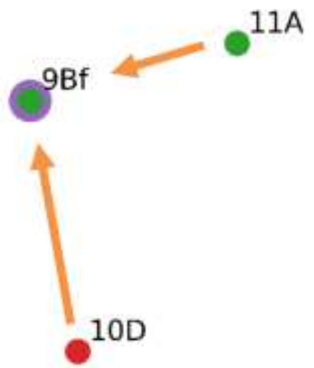


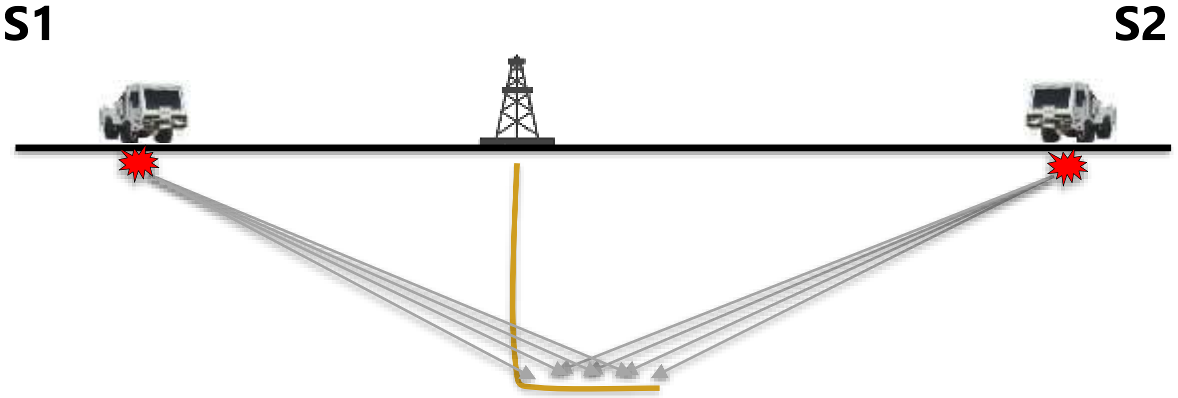
Fracs from 10D

Fracs from 11A cause large shadow

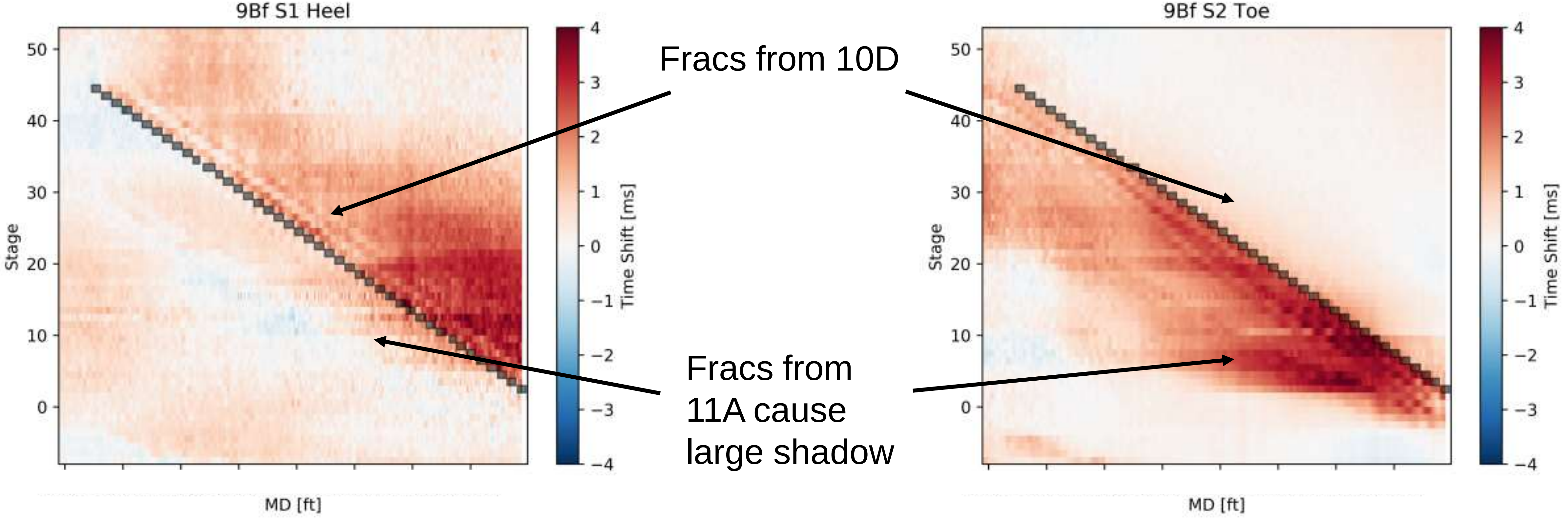


9Bf: Observed P-Wave Time Shifts





Speedup ← → Slowdown



Data Processing

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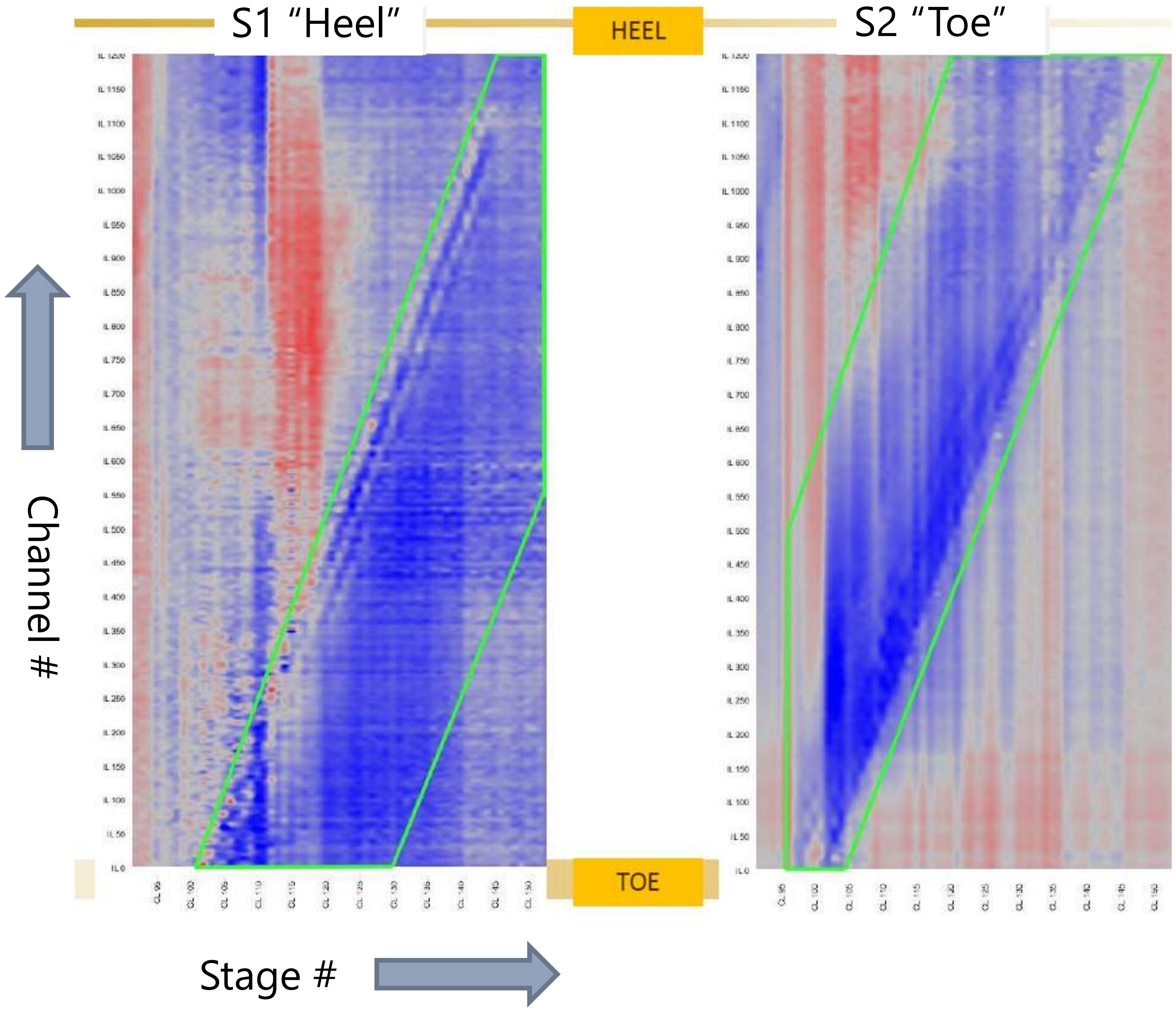
- Stacked, processed shot records were provided by Apache
- Significant statics caused by weather changes and vibe shifts are observed
- A control region (outside green polygon) is needed to estimate statics and subtract
- This region likely has significant signal from other wells

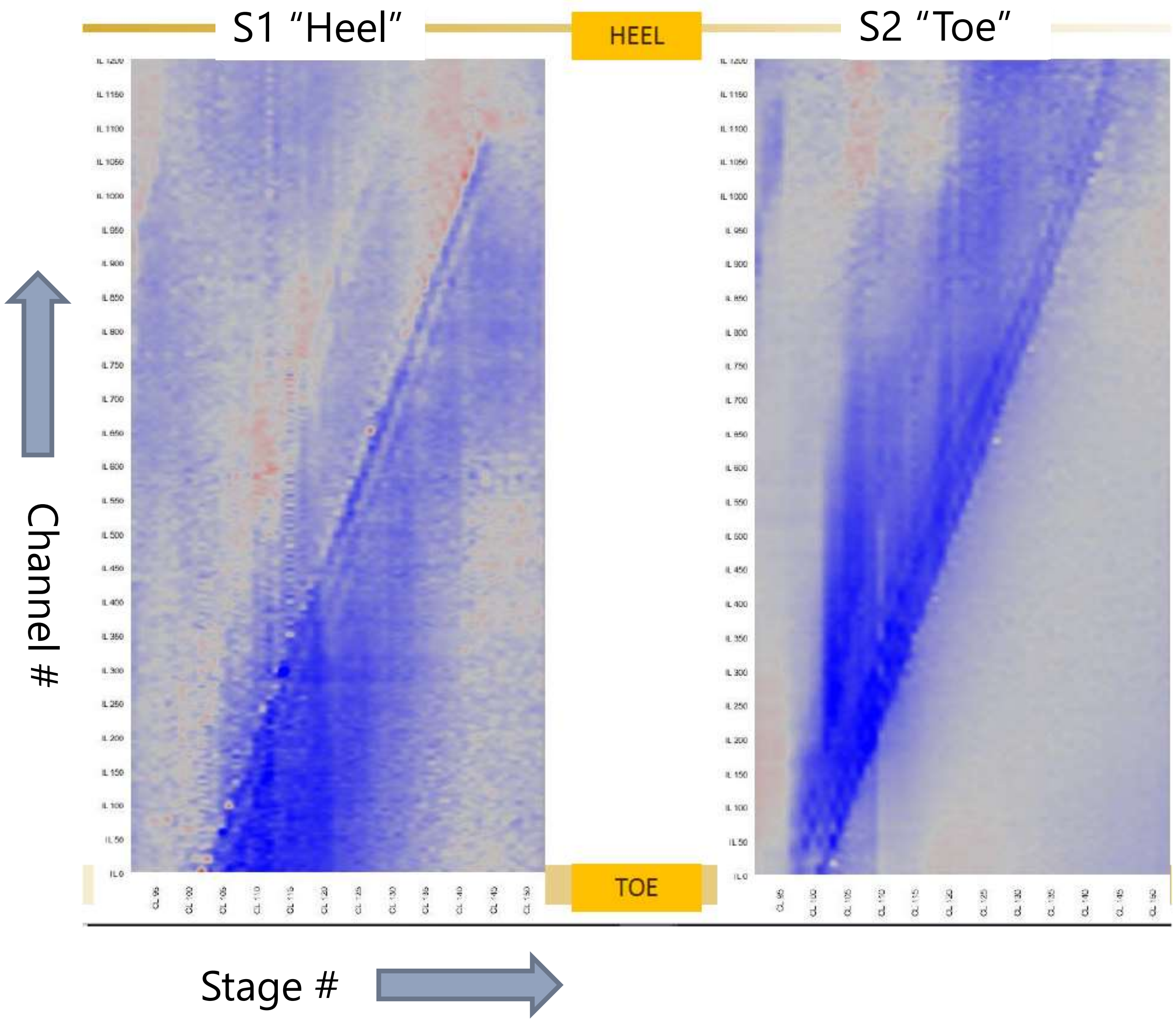
9Bf Time Shifts: Before Static Correction



Data Processing

- Stacked, processed shot records were provided by Apache
- Significant statics caused by weather changes and vibe shifts are observed
- A control region (outside green polygon) is needed to estimate statics and subtract
- This region likely has significant signal from other wells

16HS Time Shifts: After Static Correction

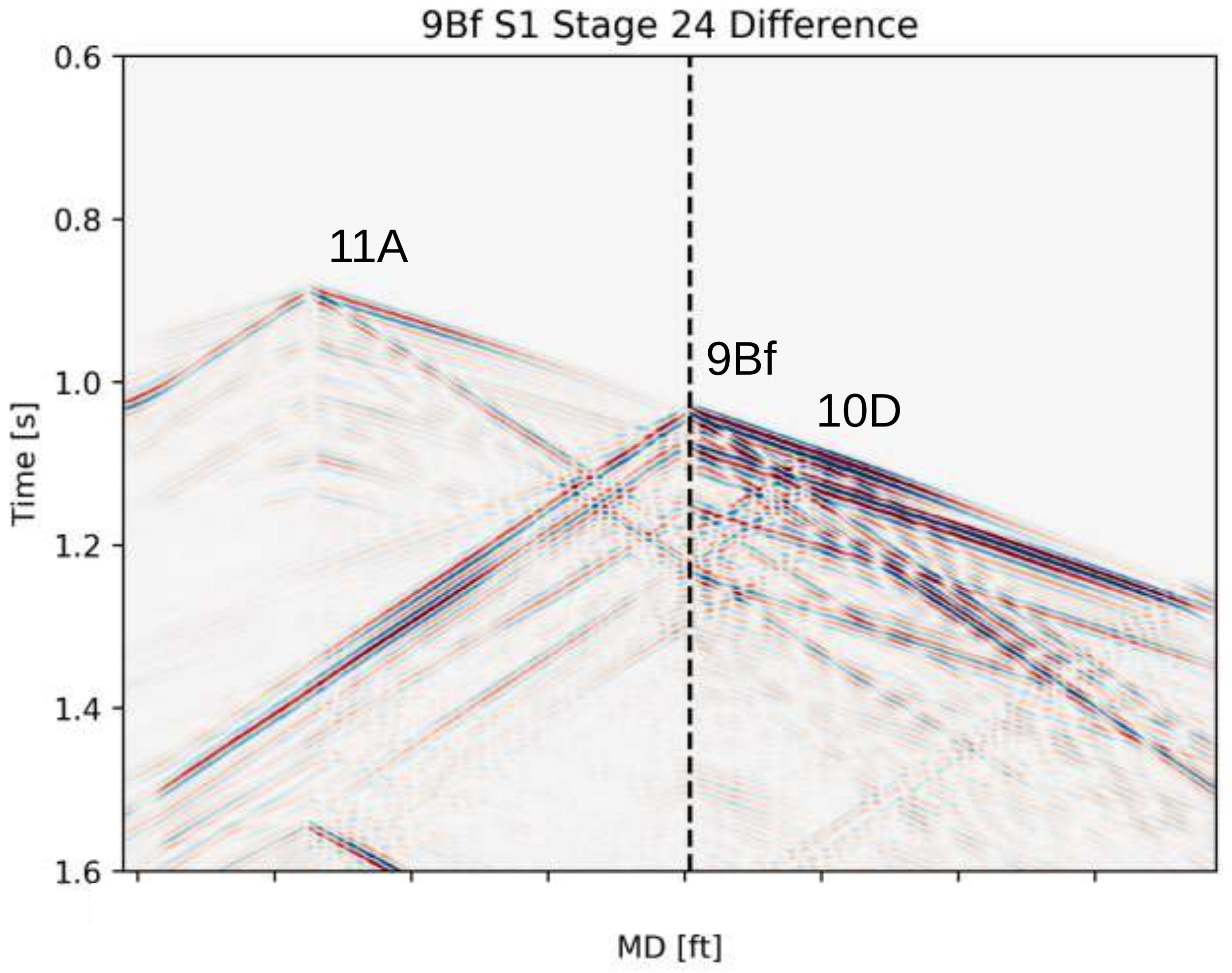


Modeling Summary

- Modeling indicates that secondary bands visible in time shifts are spatially and temporally consistent with fracs from other wells
- More work needed to fit model parameters to data
- Estimation of time shift statics will be revisited to remove potential contamination from other wells
- Interference from other wells also explains the large shadow from the toe source seen for both wells
- New methods are needed to estimate SRV height

Modeled Scattered Waves

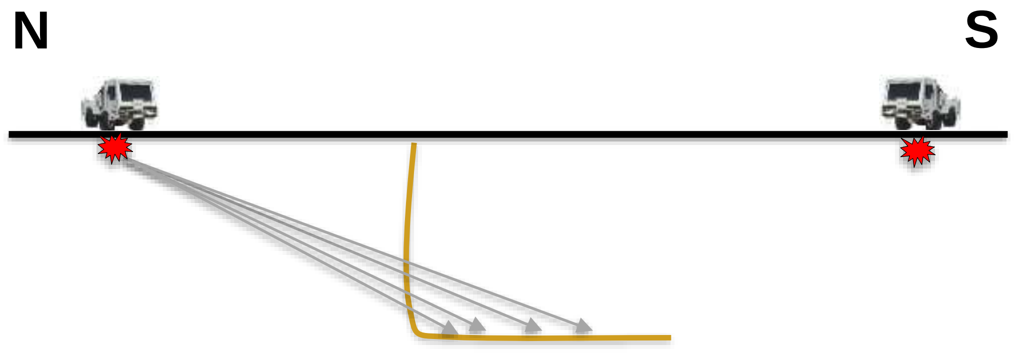
- Scattered waves are seen from multiple wells in synthetic shot records
- A cleaner separation between between wells may enable a height estimate
- What do we see in data?

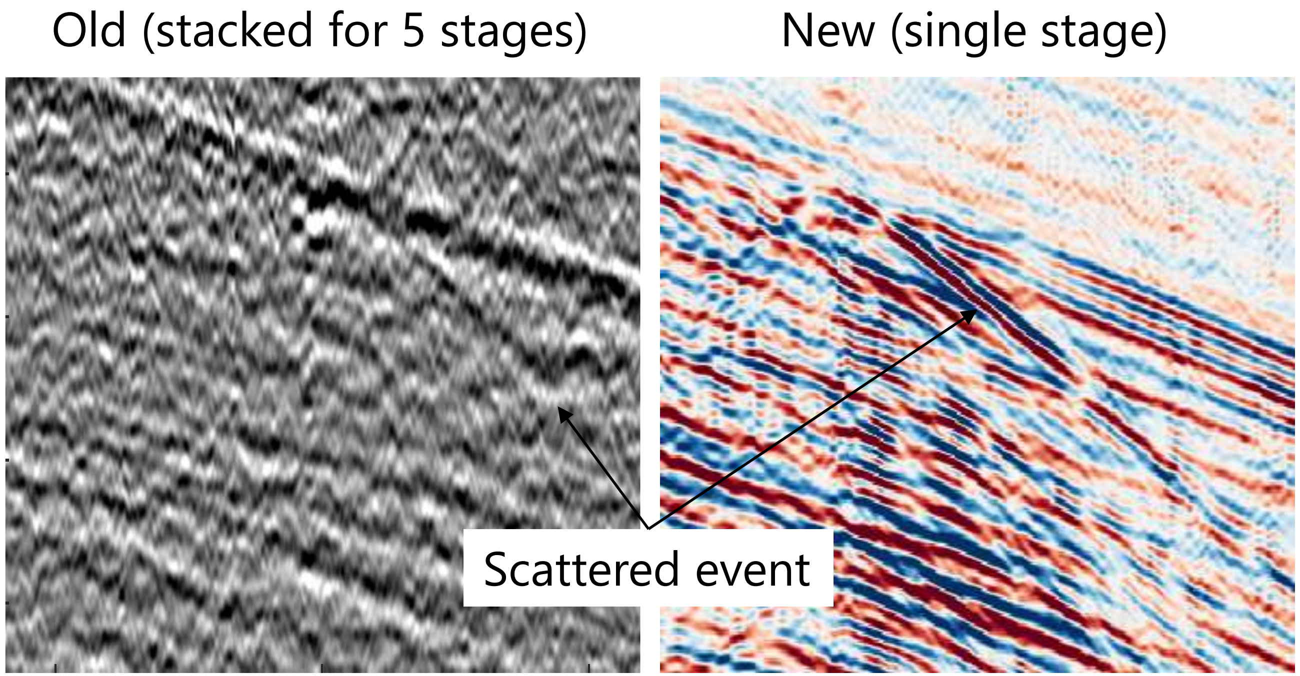


Observations and Modeling of Scattered Waves from Hydraulic Fractures in a DAS VSP

Aleksei Titov

Motivation





- What are the scattered events?
- How often are they observable?
- How long do they last?
- Can we use them to characterize hydraulic fractures and efficiency of fracturing?

- How to properly model them?
- What parameters influence kinematic and dynamic response?

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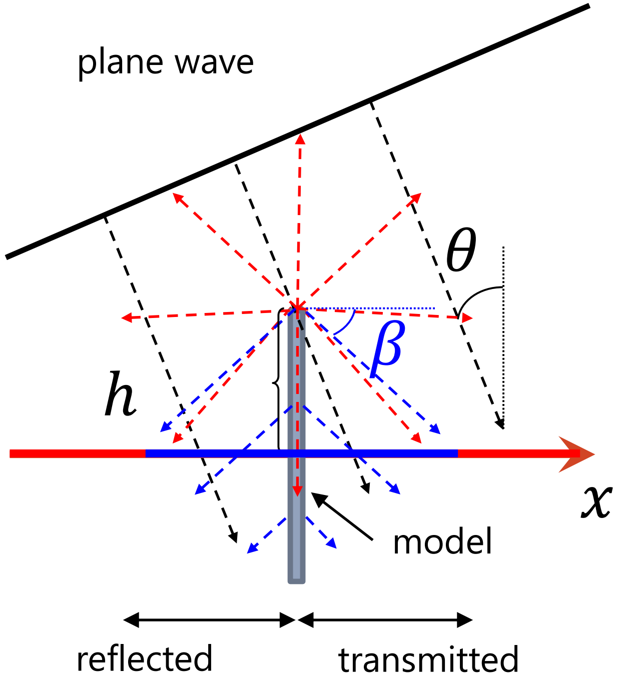
PREVIOUS WORK RECAP

Recap: Travel-Time Equations



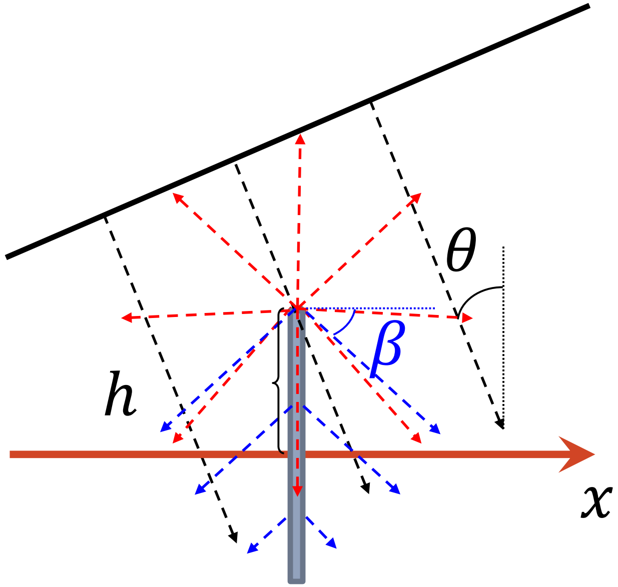
h is a half-height

Wavefield	Travel-time equation
Incident P-wave	$t_P^i(x) = \frac{\sin\theta}{V_P^m} x$
Diffracted PS-wave	$t_{PS}^d = -\frac{\mathrm{h}\cos\theta}{V_P^m} + \frac{\sqrt{x^2 + \mathrm{h}^2}}{V_S^m}$
Converted PS-wave	$t_{PS}^c = \left(-\frac{\cos\theta\tan\beta}{V_P^m} + \frac{1}{V_S^m\cos\beta}\right)\lvert x\rvert$

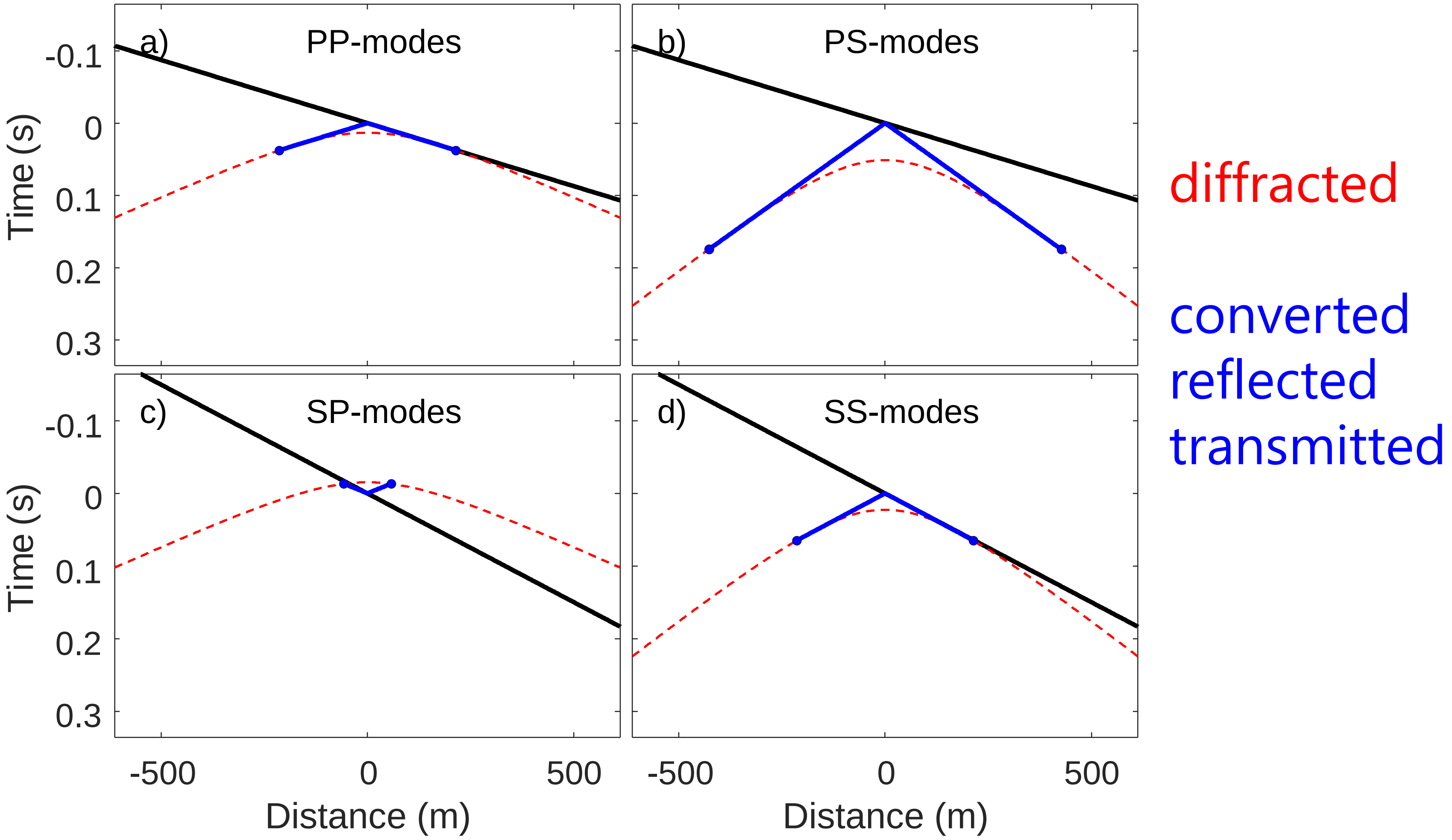
Angle β defined from the Snell's law:

$$\sin\left(\frac{\pi}{2} - \theta\right) / \sin\beta_{PS} = V_P^m / V_S^m$$

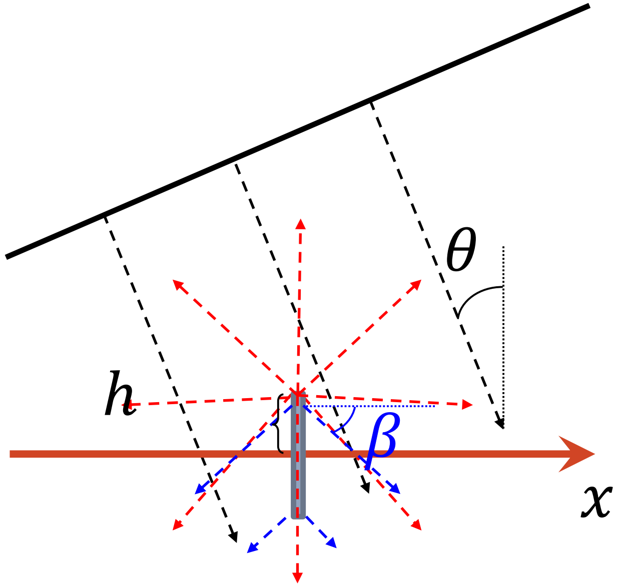
Recap: Travel-Time Curves



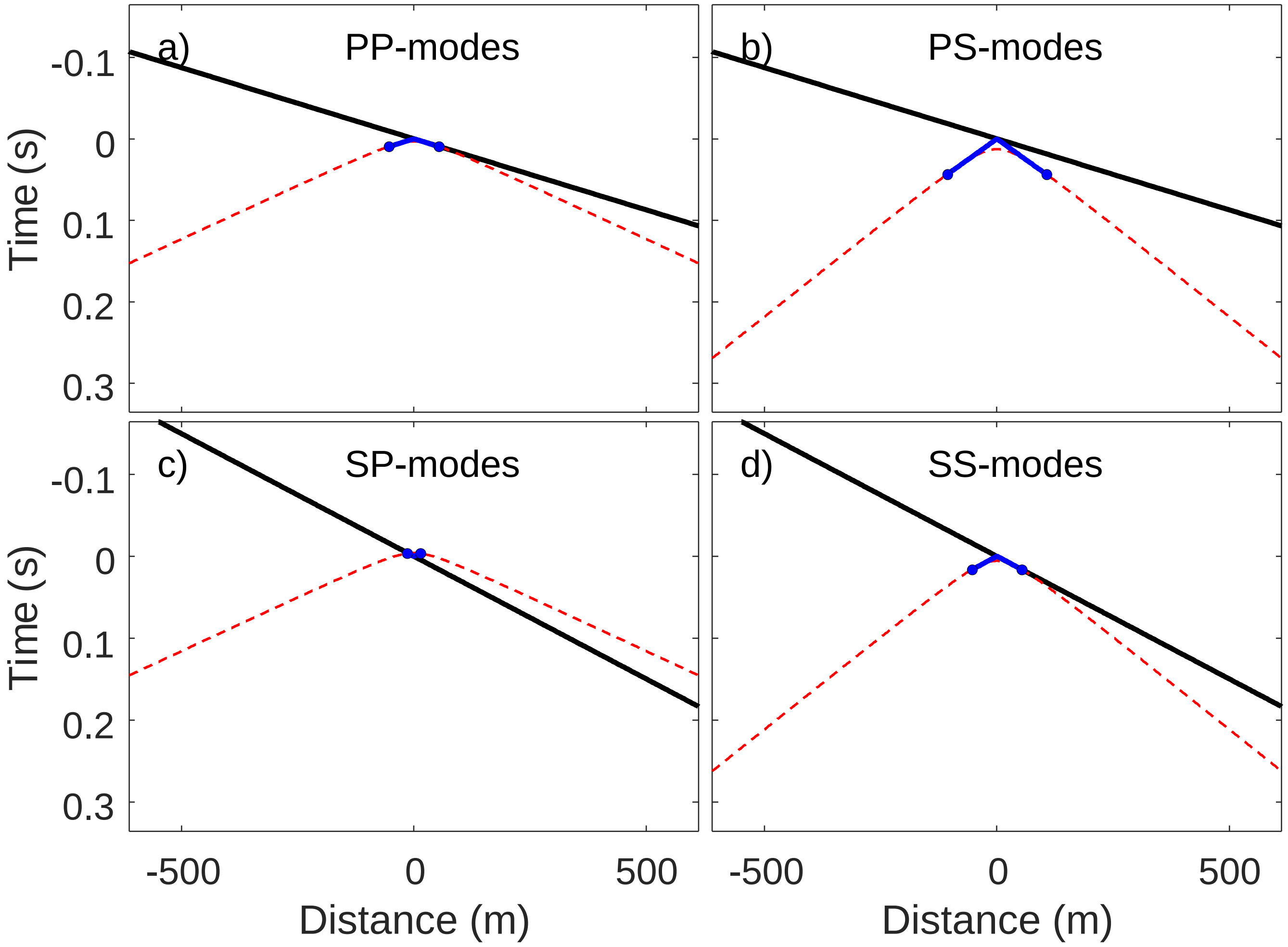
$h = 200\ m$



Recap: Travel-Time Curves



$h = 50\ m$

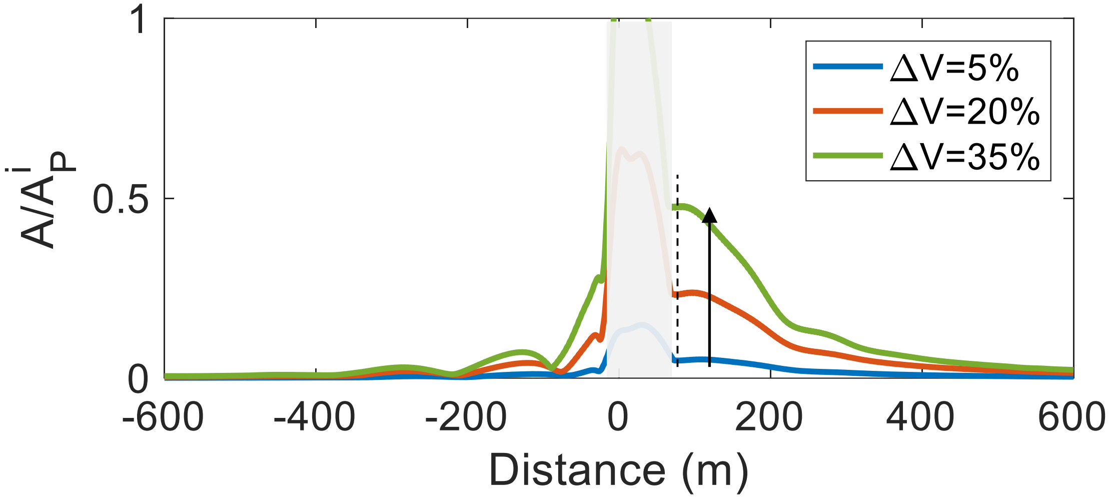


diffracted

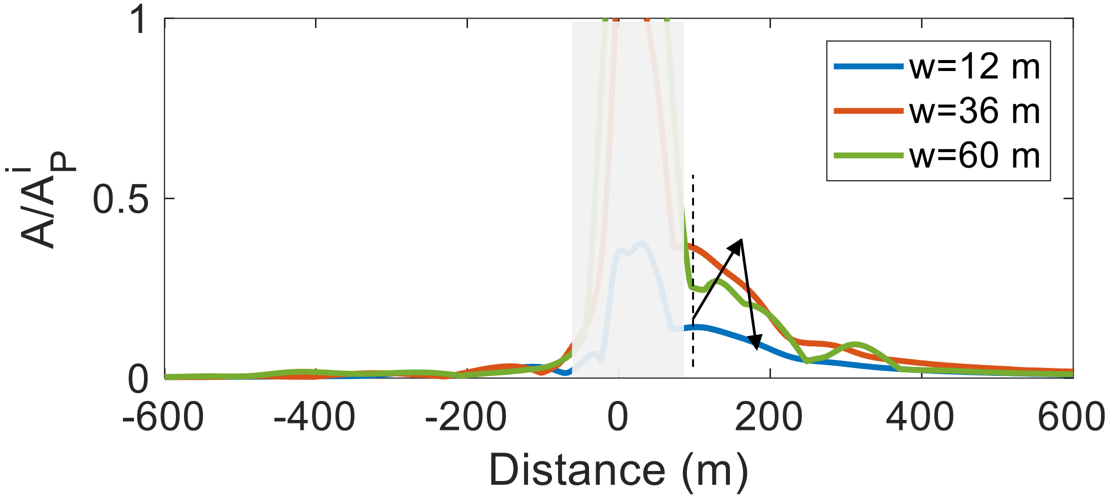
converted
reflected
transmitted

Recap: PS-Scattered Waves Amplitude Sensitivity

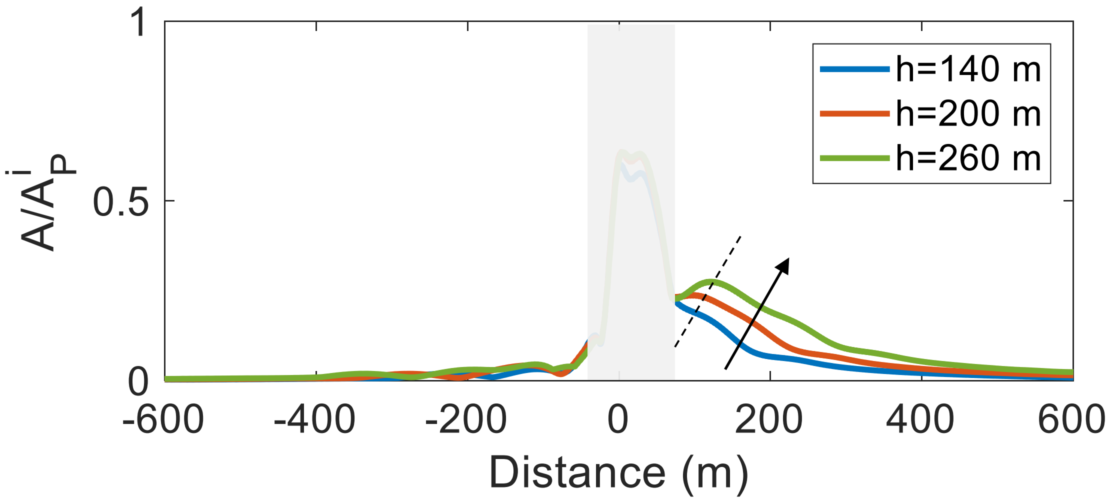
- $A(\Delta V)$ – monotonic, in direct ratio



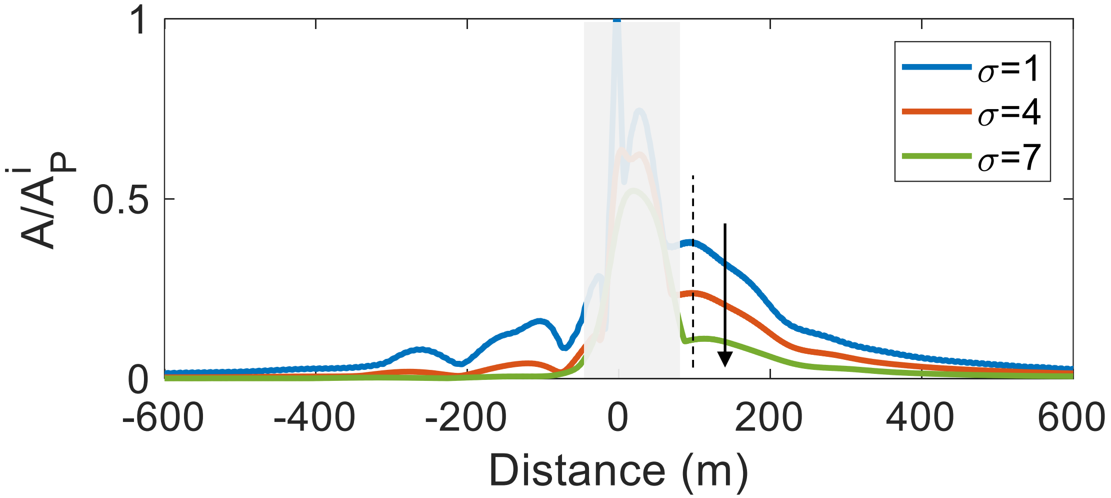
- $A(w)$ – non-monotonic



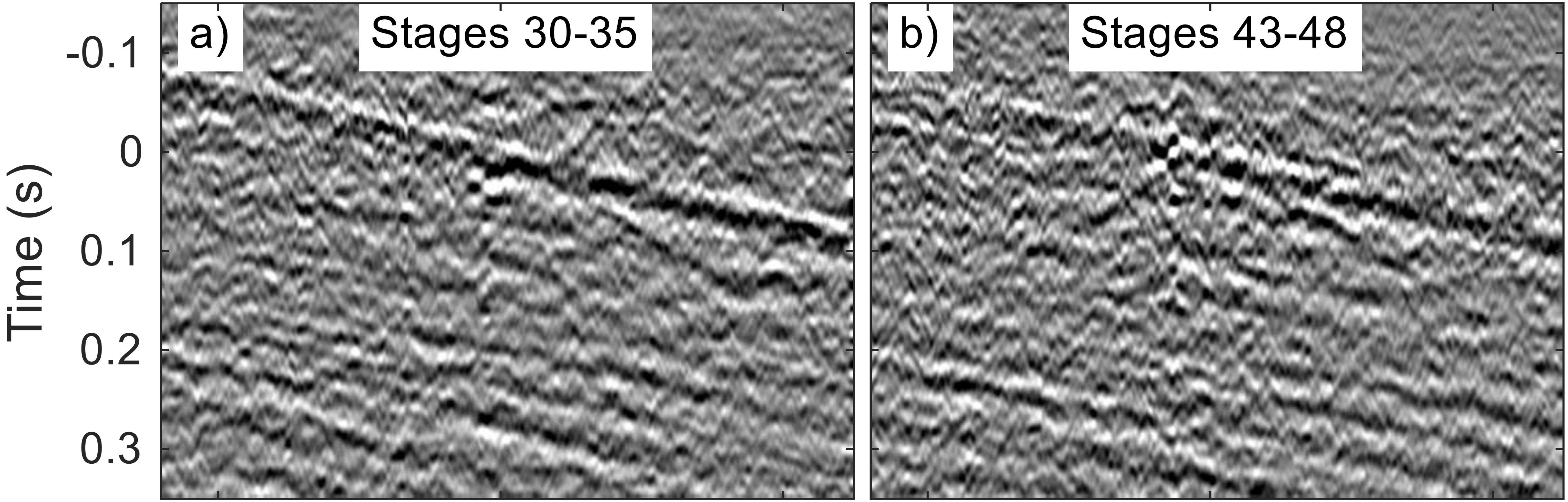
- $A(h)$ – monotonic, in direct ratio



- $A(\sigma)$ – monotonic, in inverse ratio



Recap: 4D Data



Recap: Scattered Events Distribution

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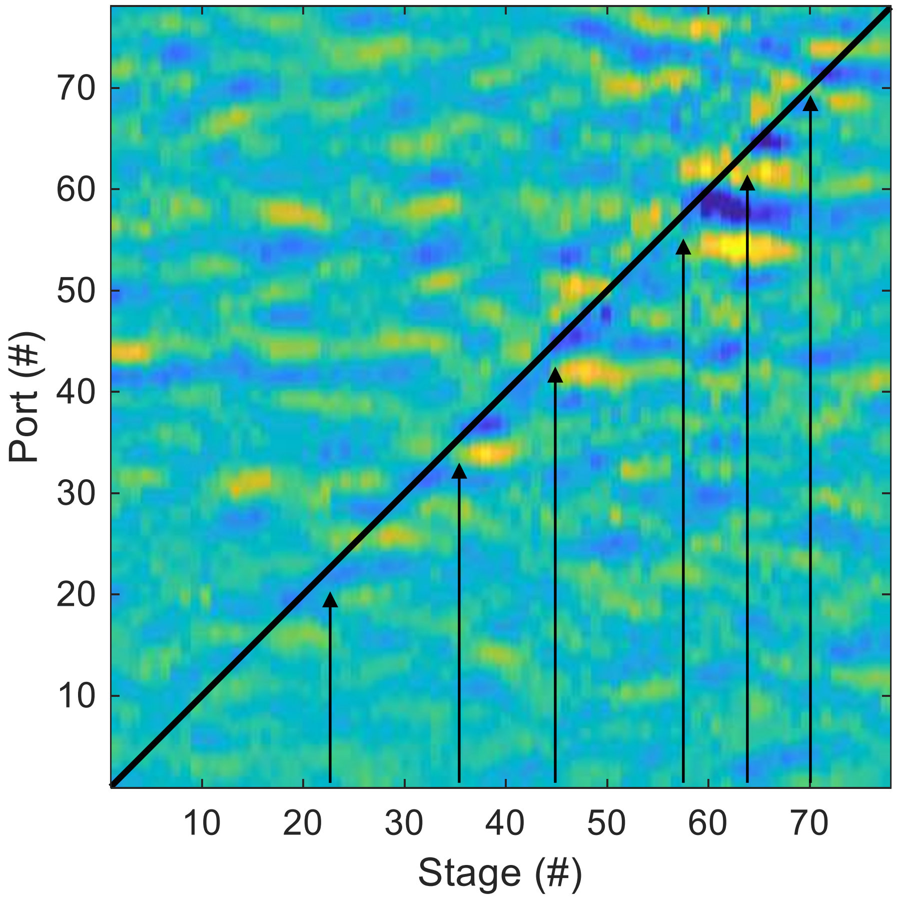
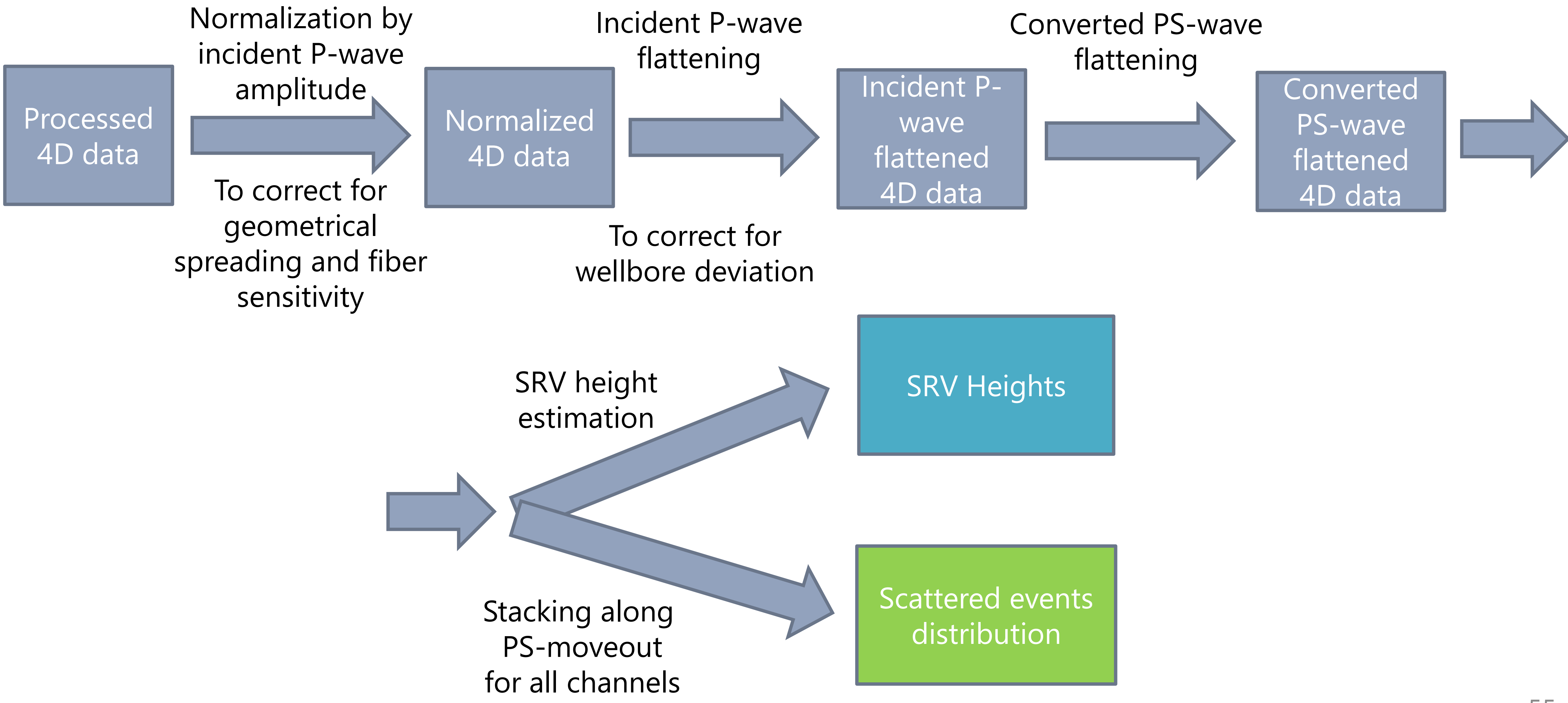


- 6 scattered events are observed
- Each event lasts from 5 to 24 hours
- Larger amplitude – larger height or velocity contrast (fracturing efficiency)

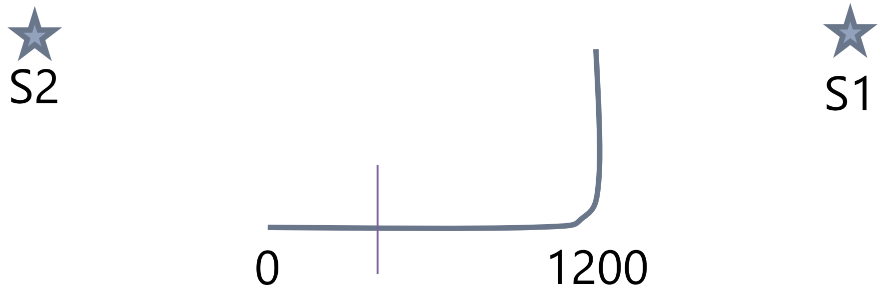
SCATTERED WAVE OBSERVATIONS FOR MIDLAND BASIN PROJECT

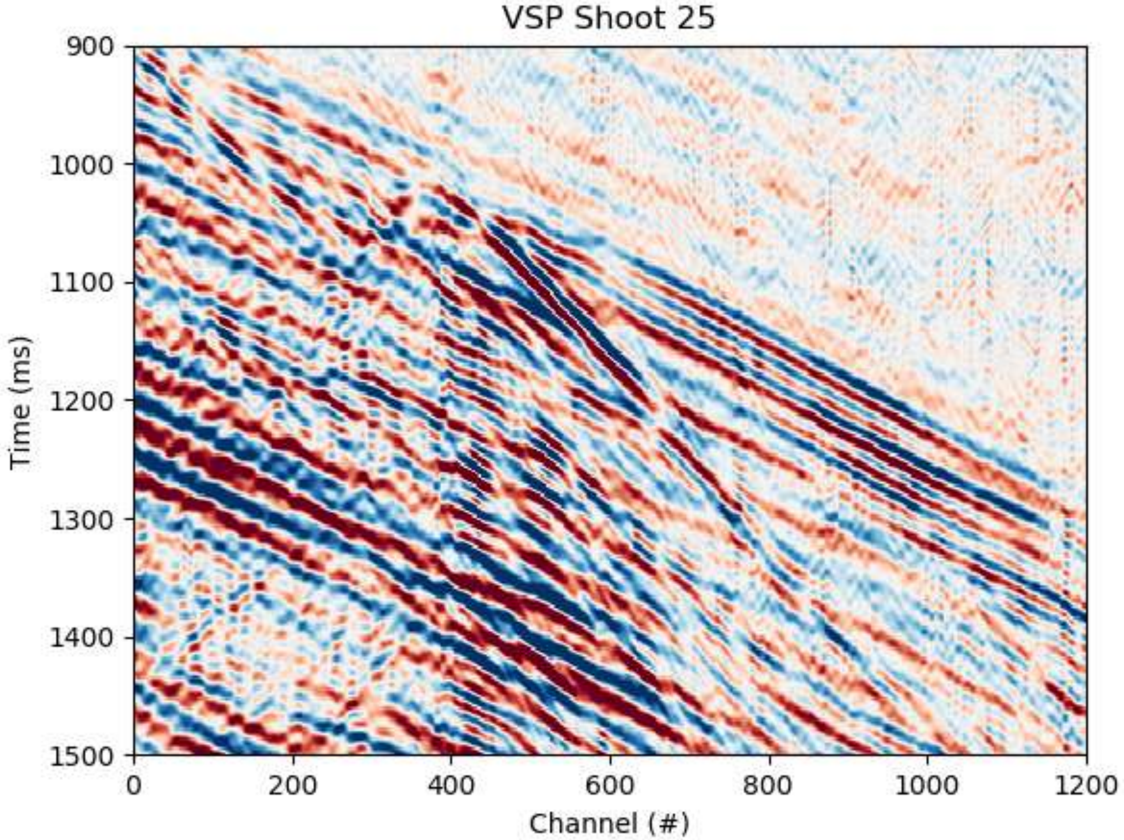
Scattered Events Analysis Preliminary Workflow

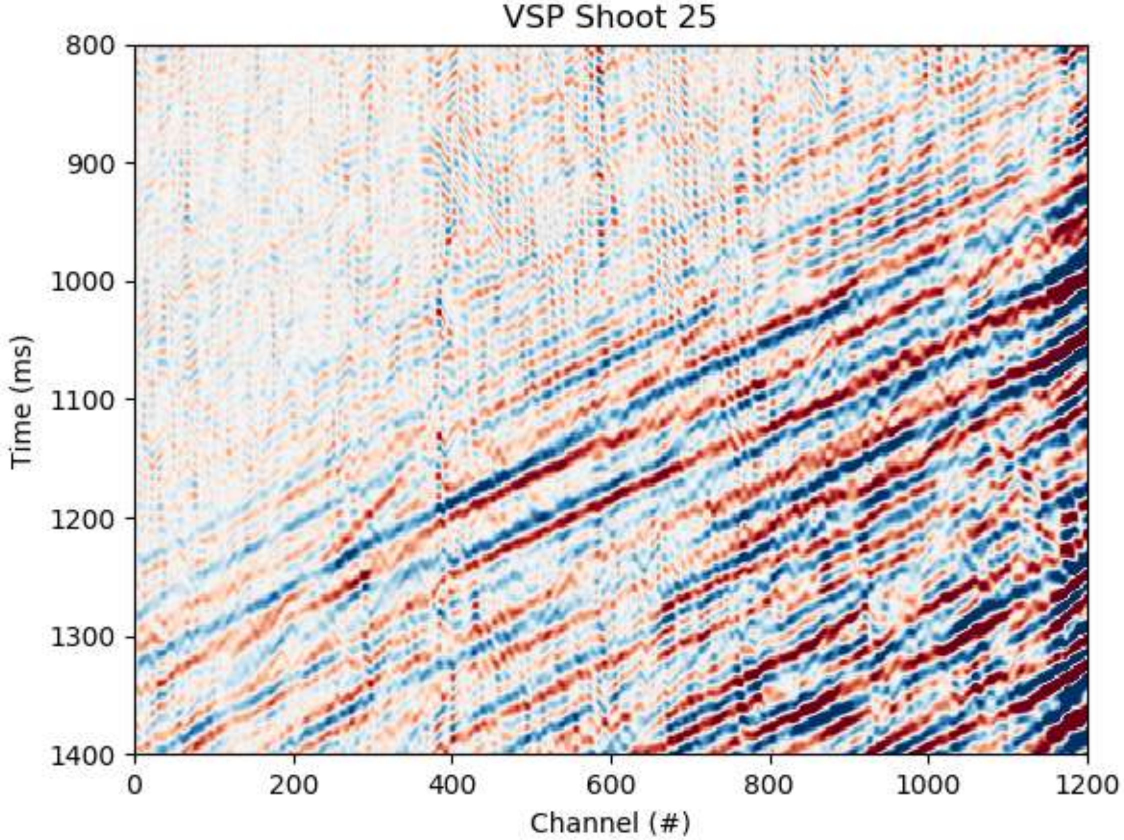
RCP
In pursuit of new ideas



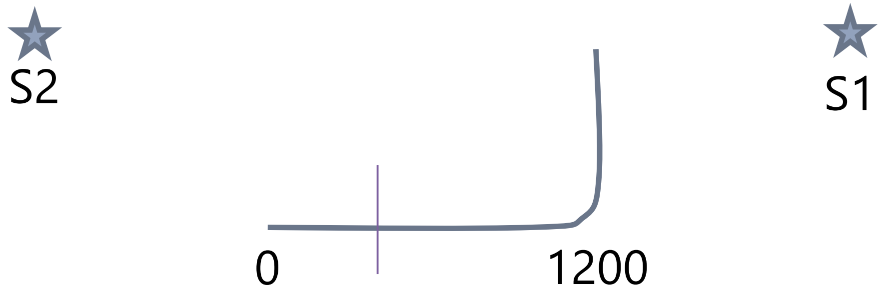
9Bf Processed 4D Data (Stage 16)

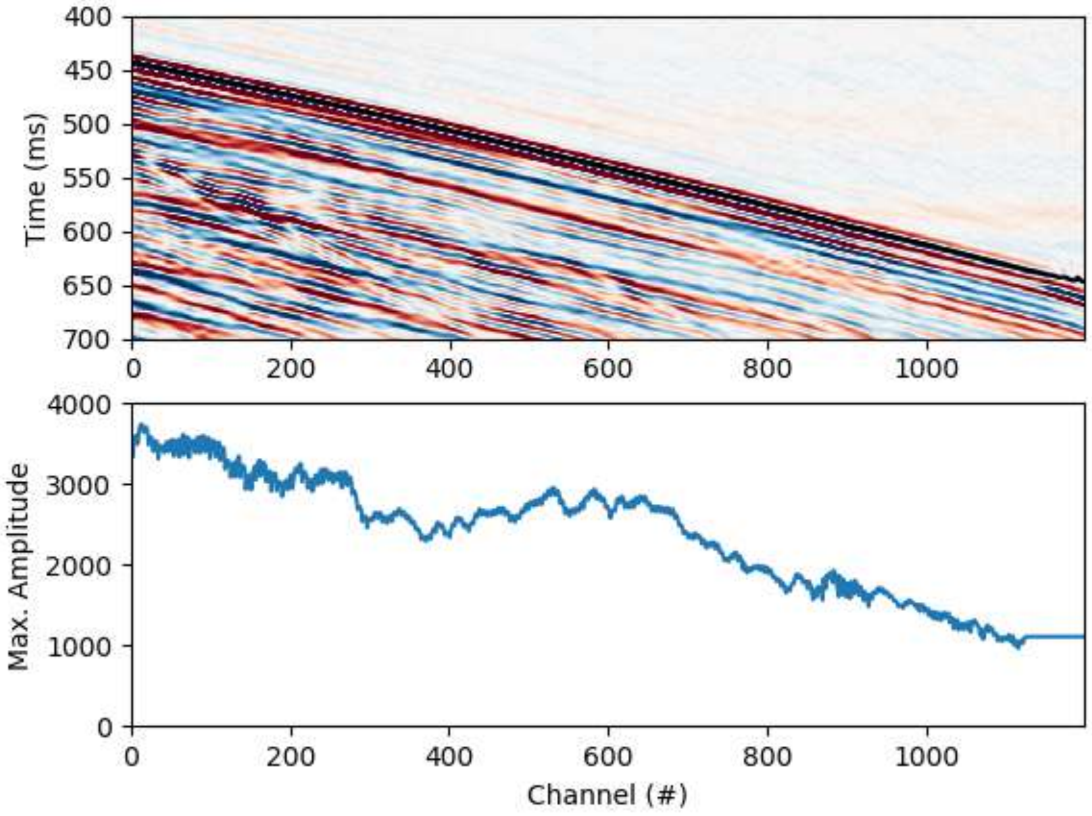


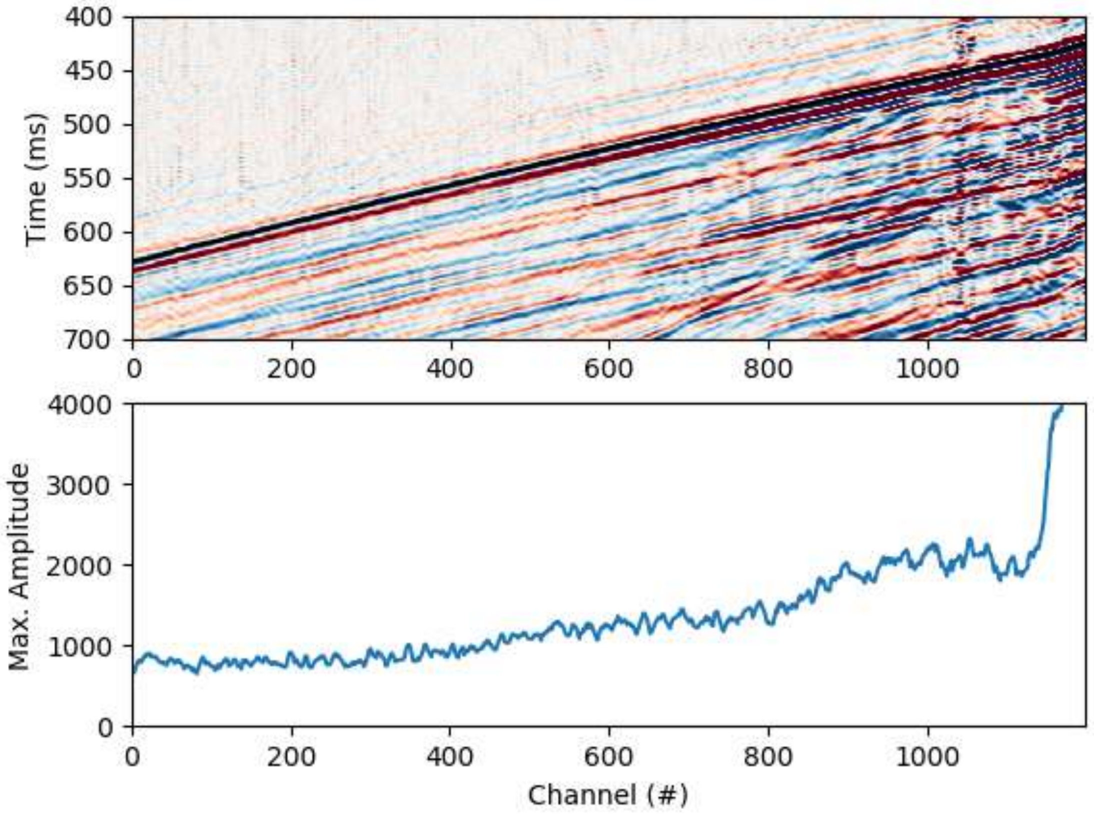




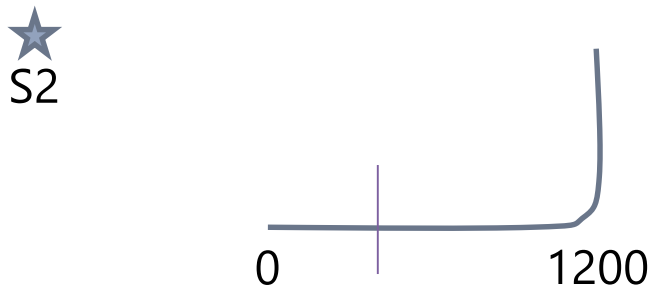
9Bf Incident P-wave Amplitude (Baseline)

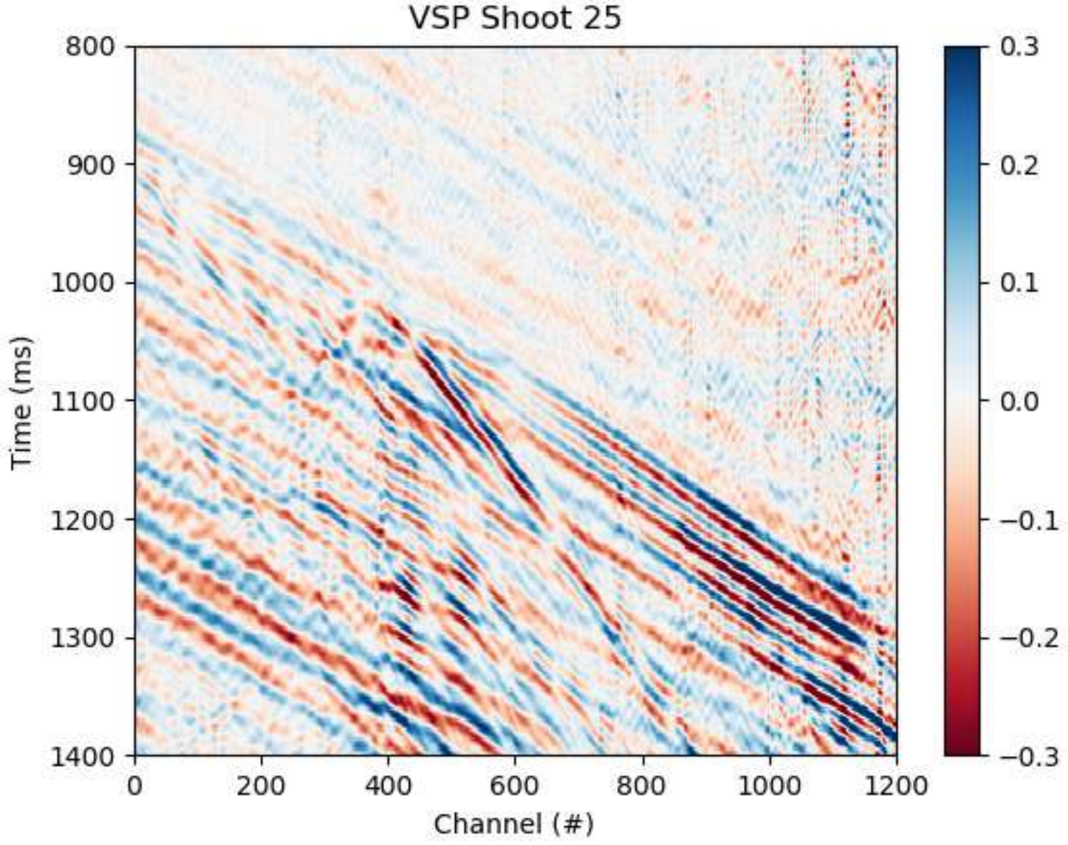


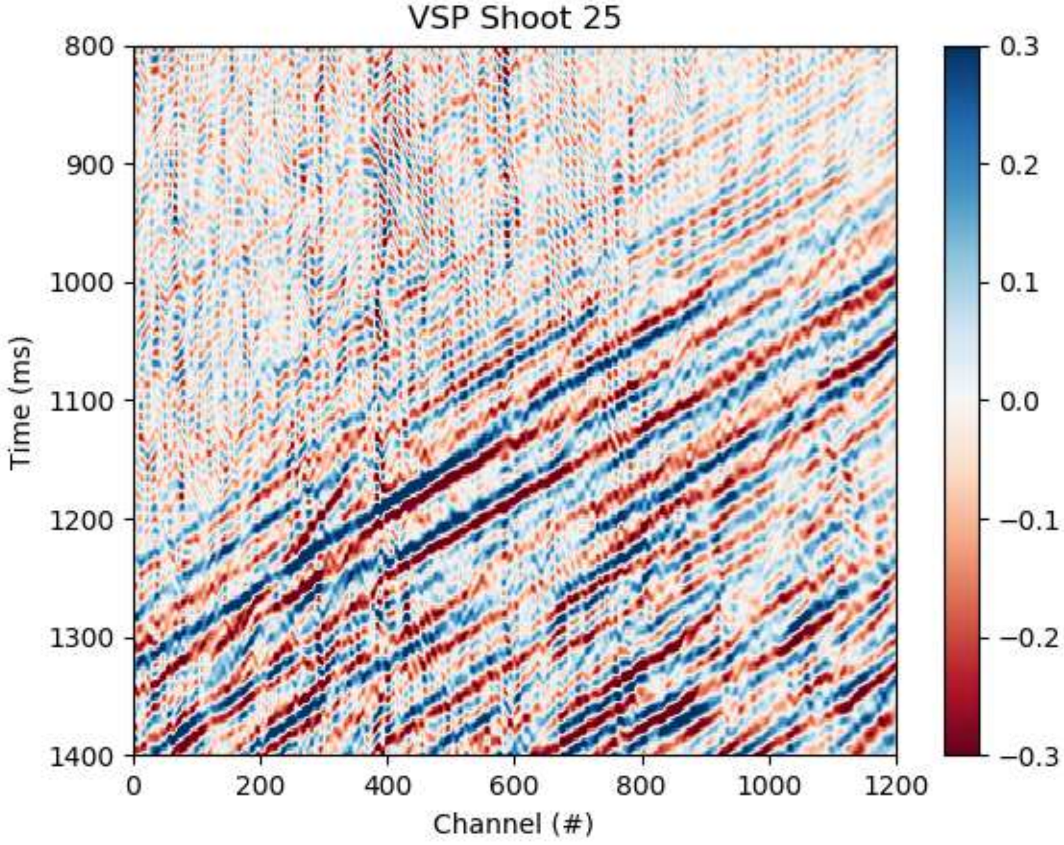




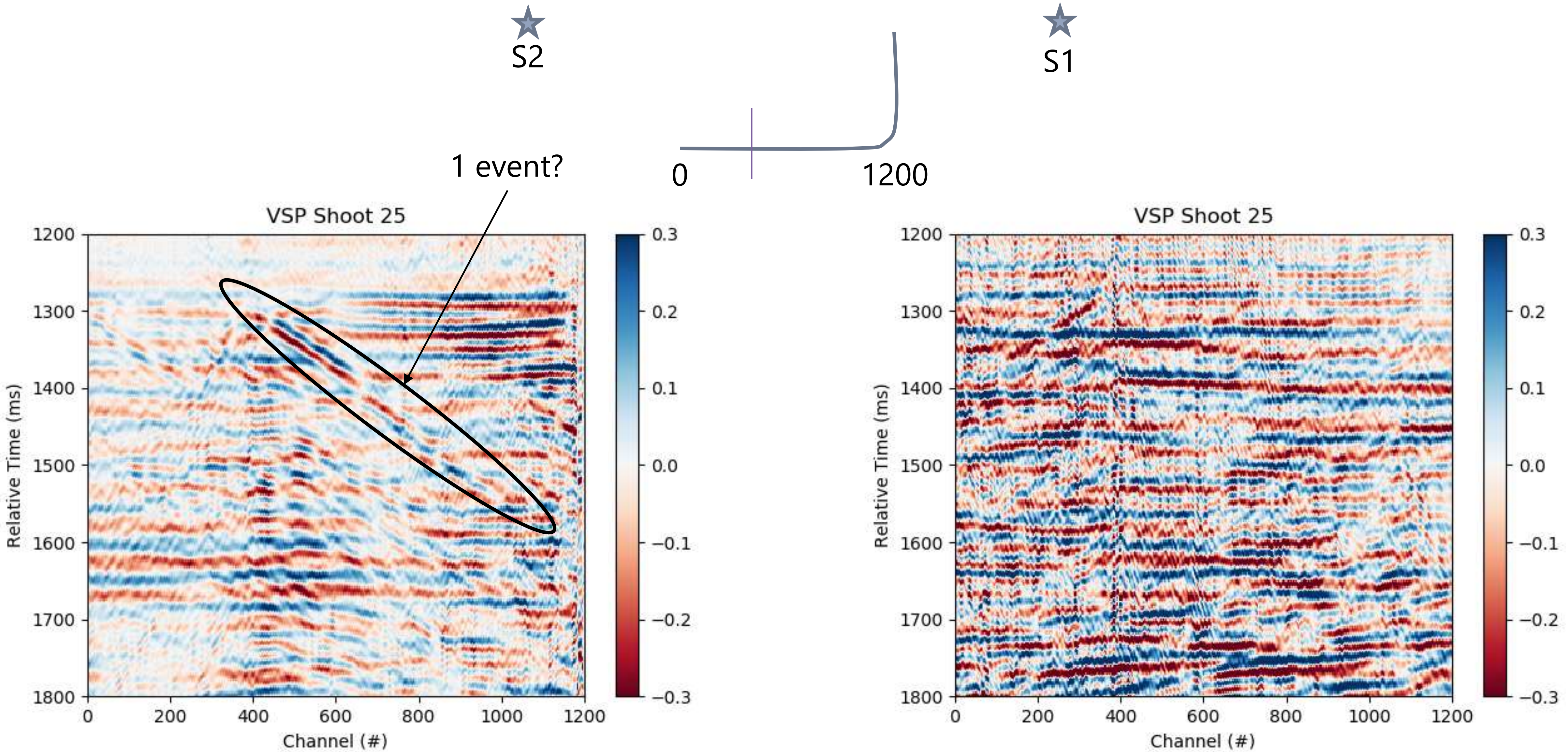
9Bf Normalized 4D Data







9Bf Incident P-wave Flattened 4D data



9Bf Converted PS-wave Flattened 4D data

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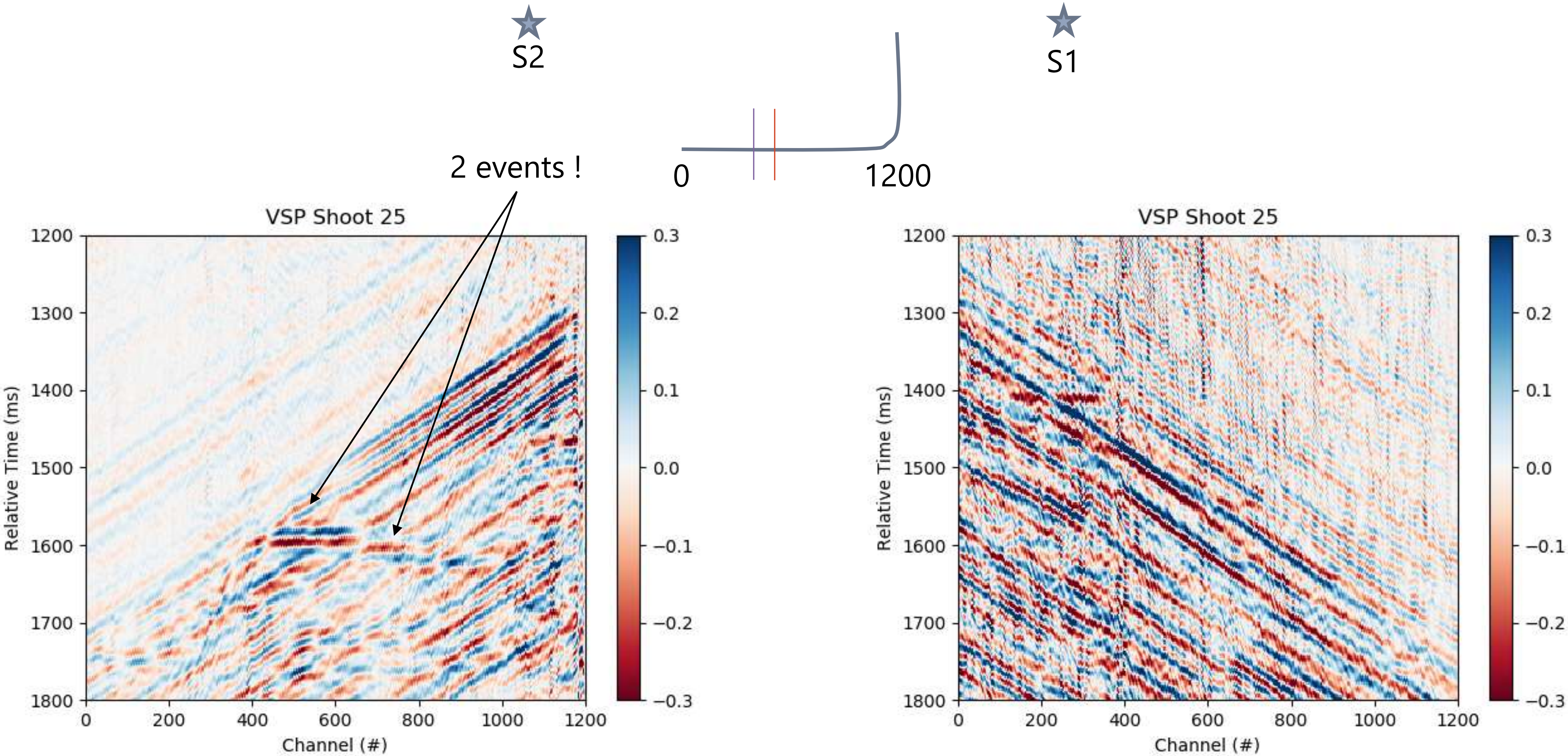
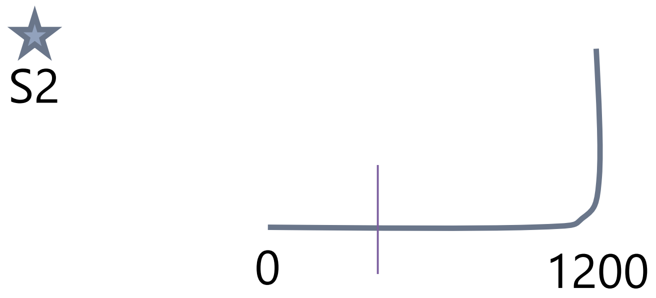
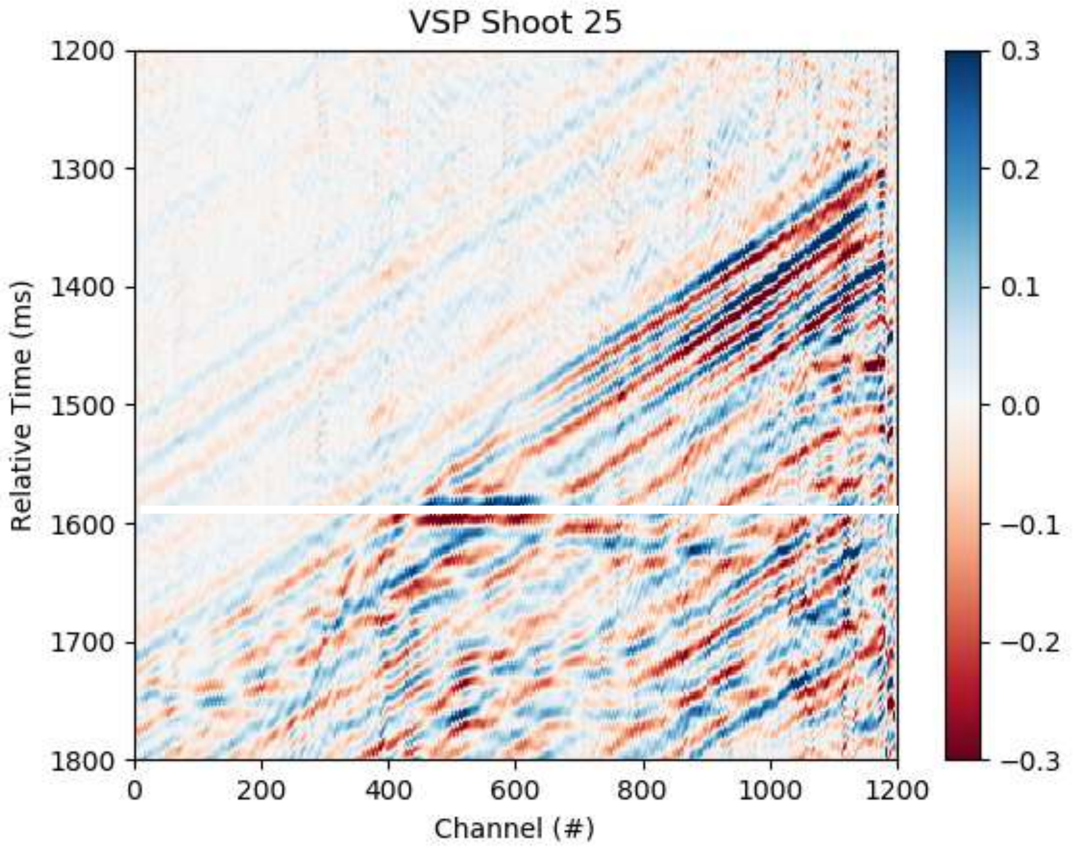
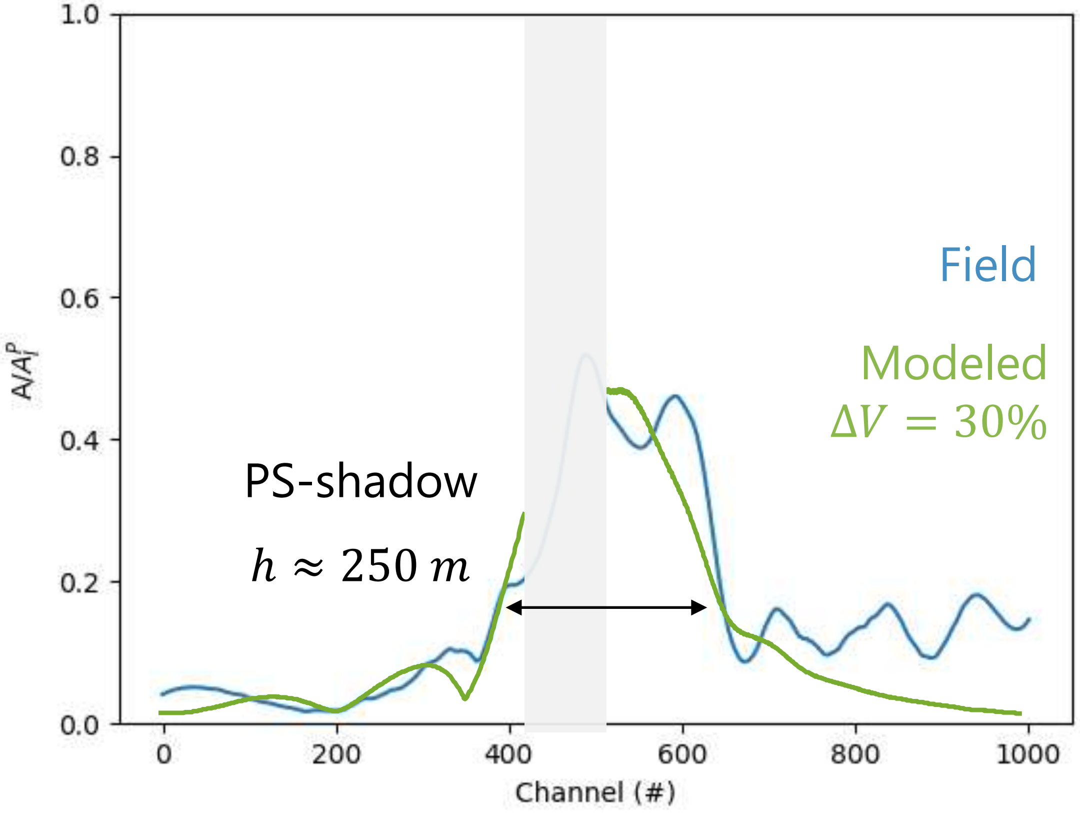


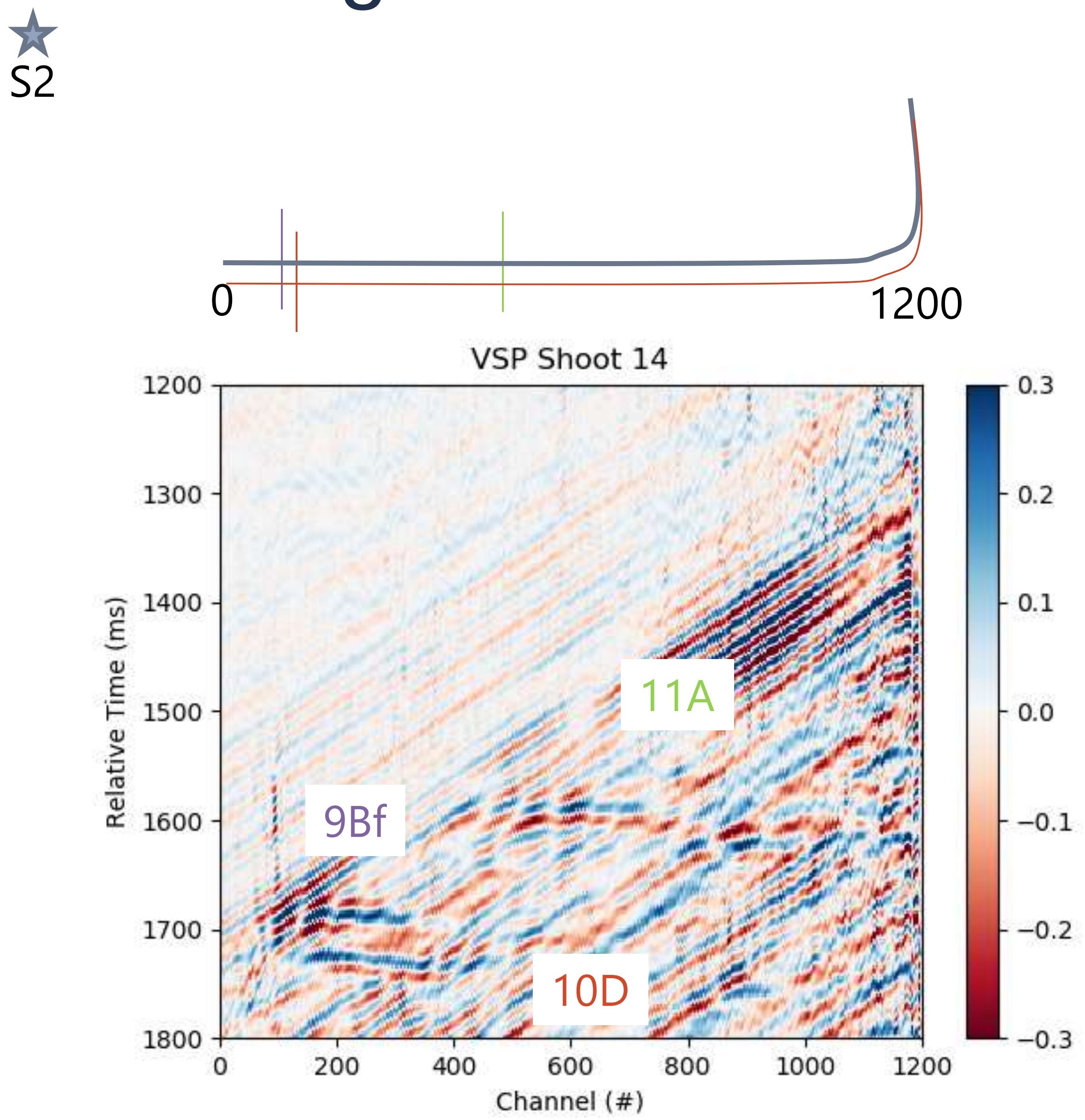
9Bf Scattered Waves Amplitude

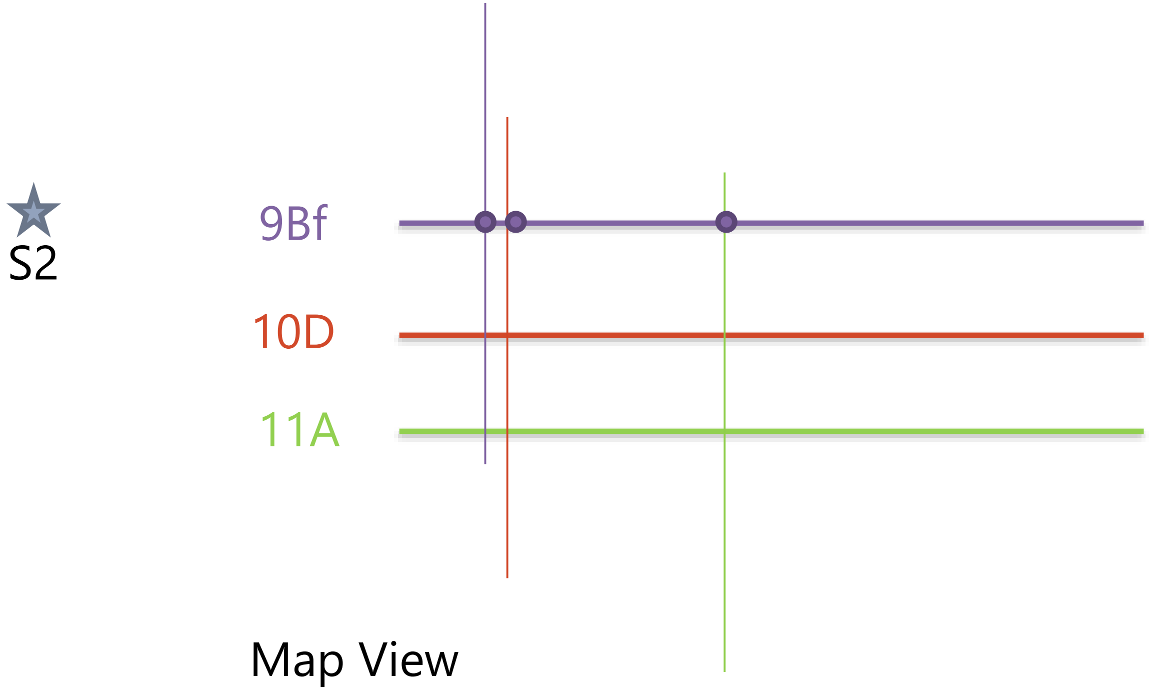




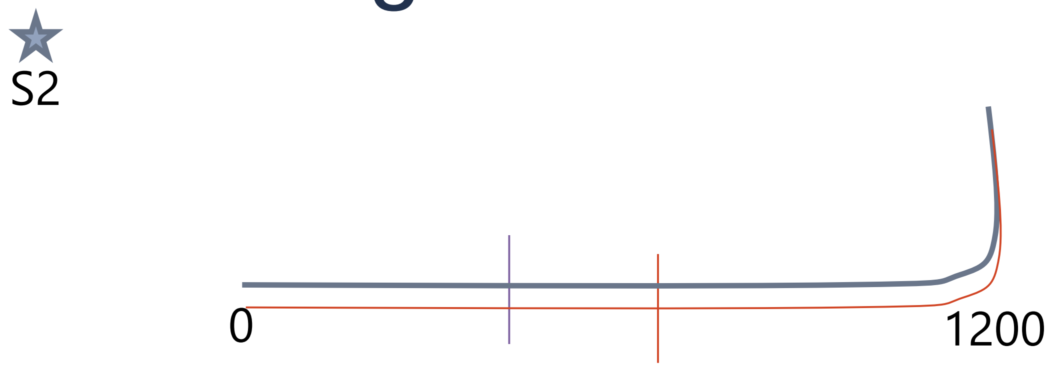


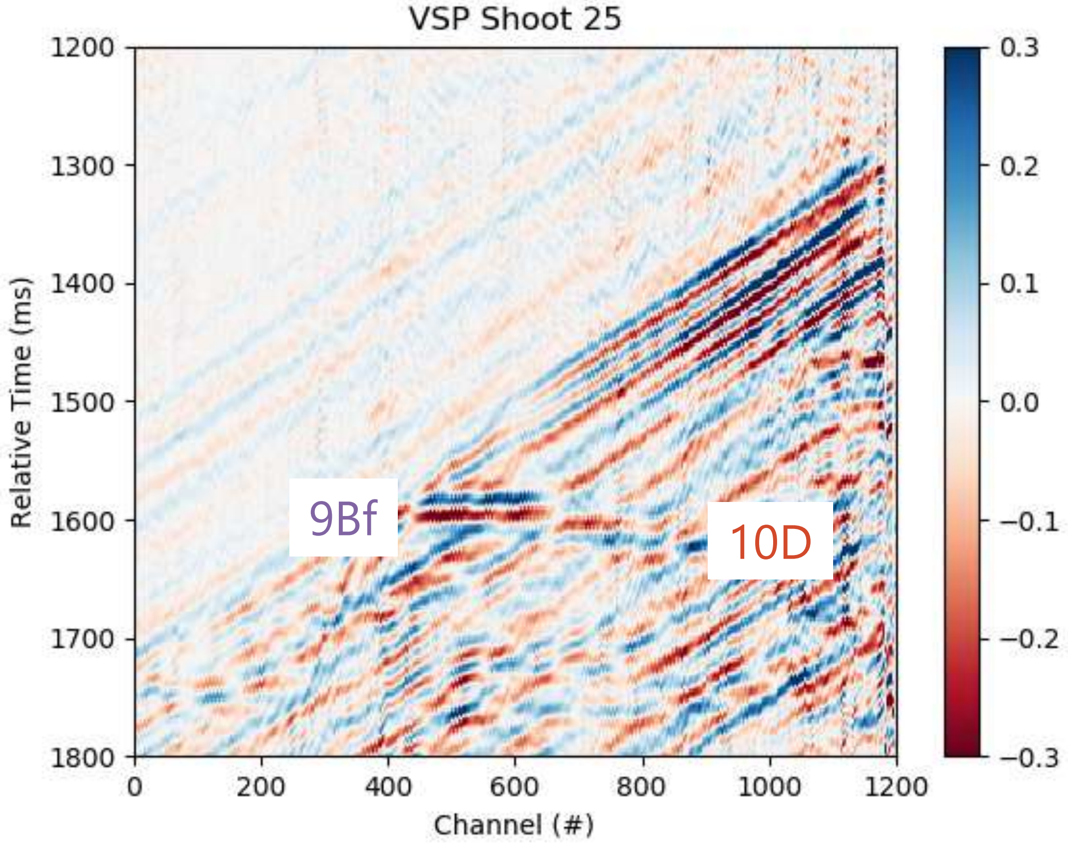
Scattering on SRV from Fiber and Adjacent Wells

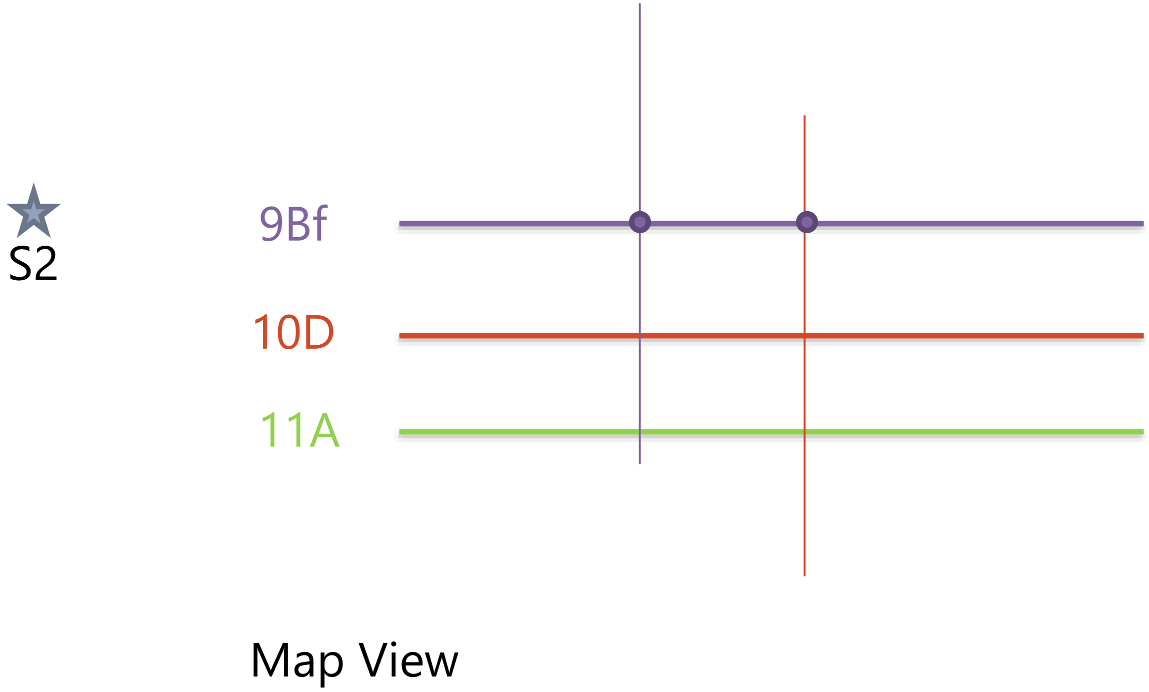




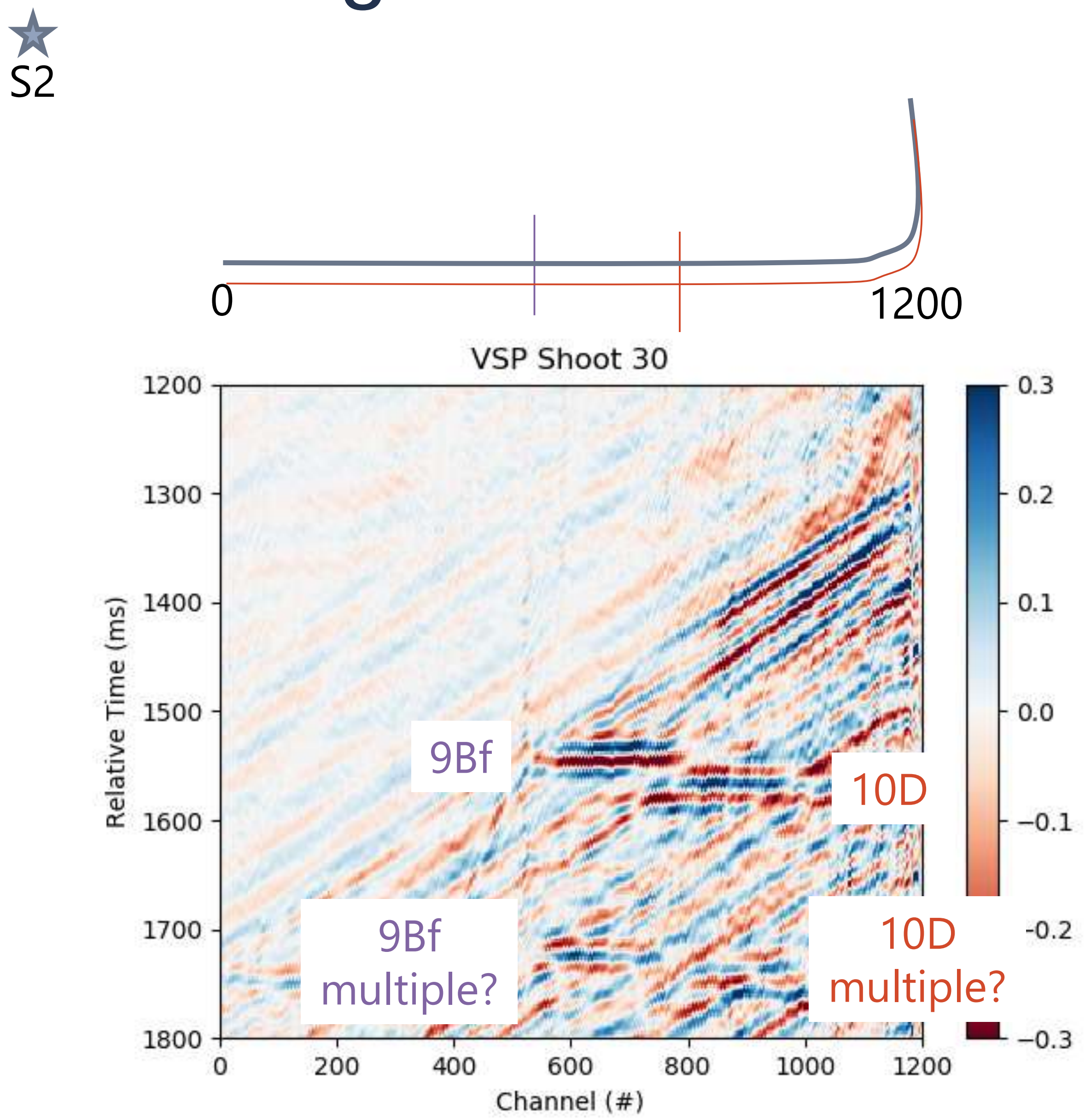
Scattering on SRV from Fiber and Adjacent Wells

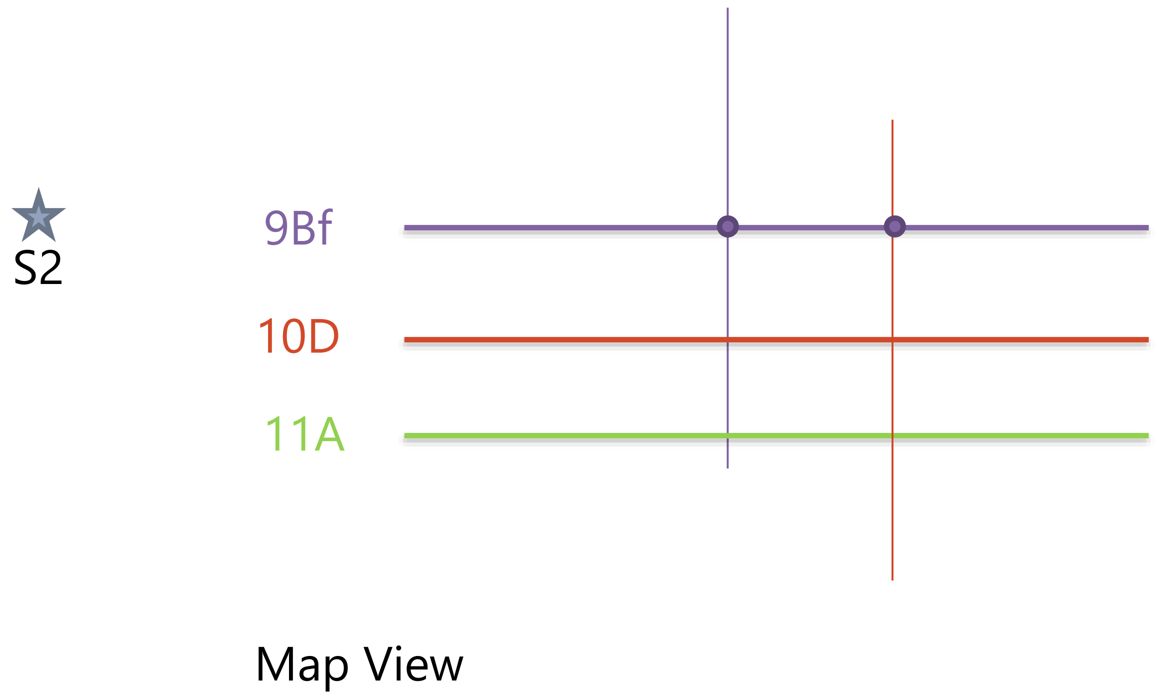




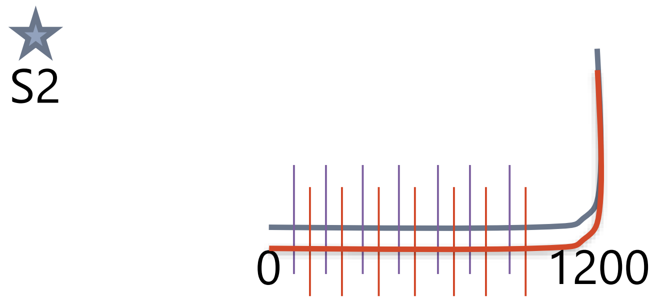


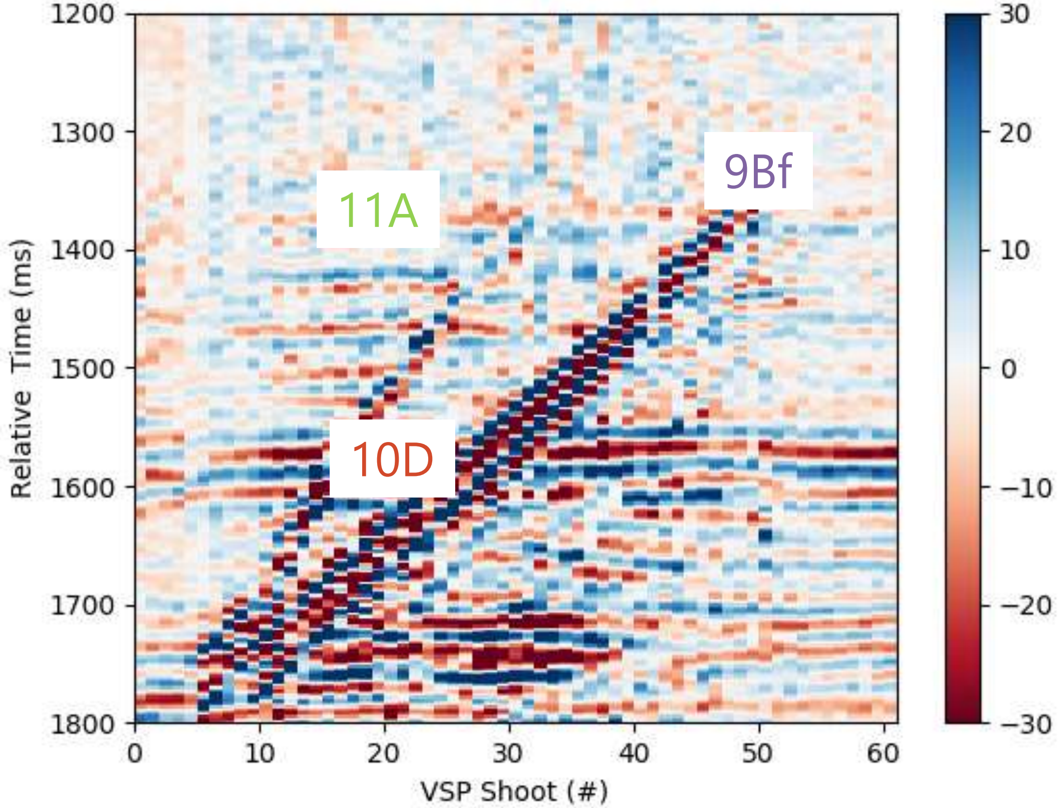
Scattering on SRV from Fiber and Adjacent Wells

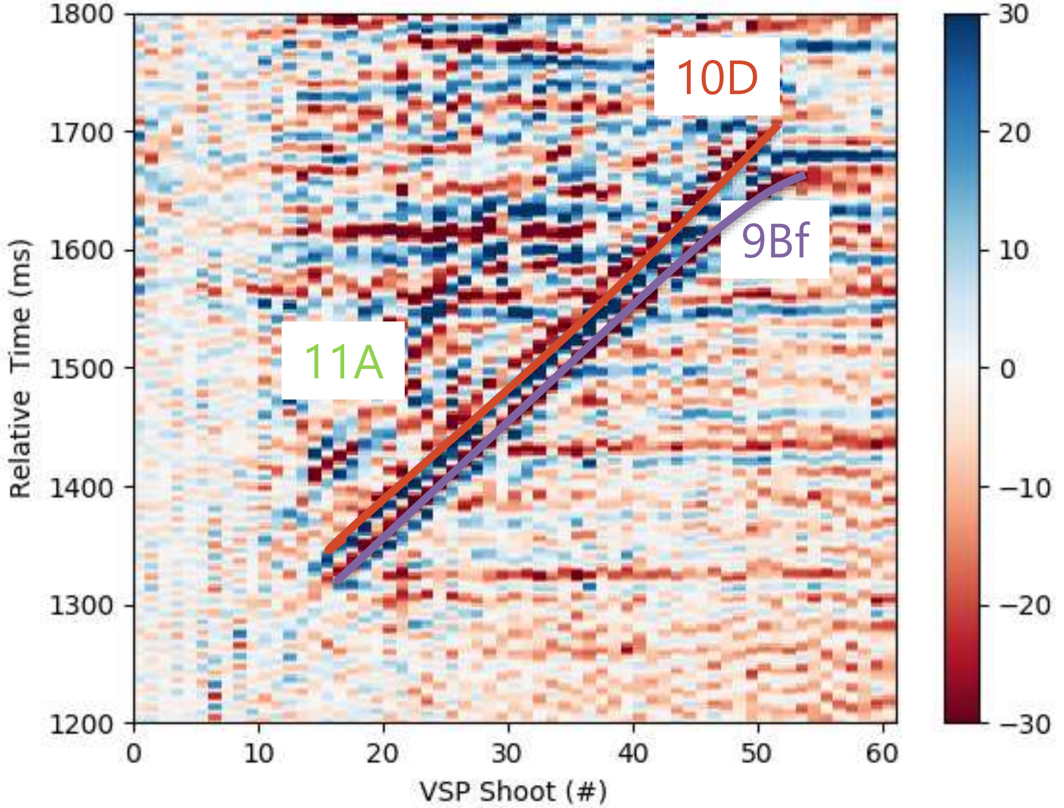




9Bf Scattered Events Distribution





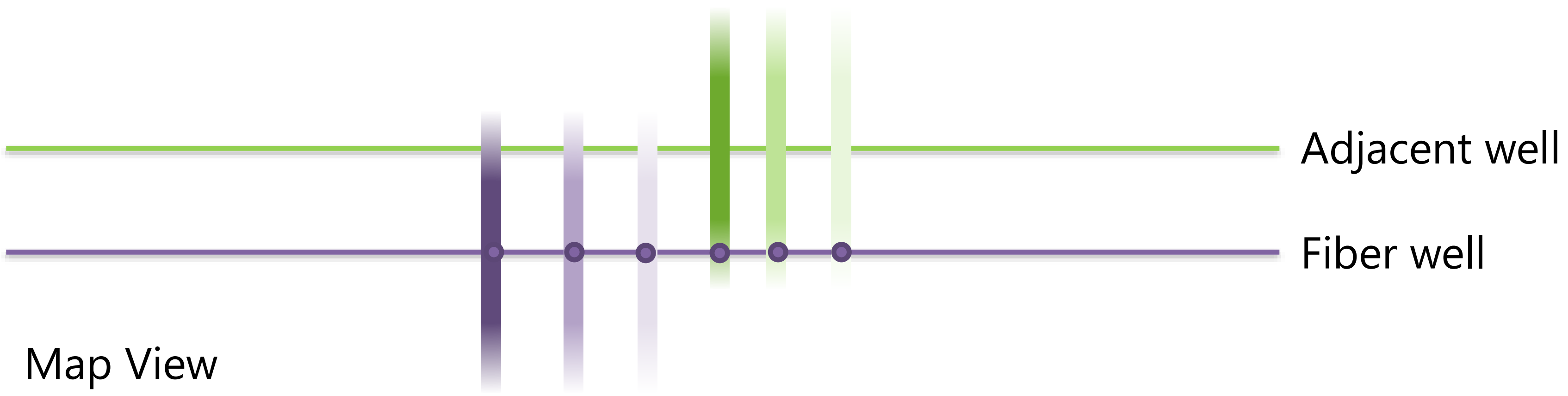


9Bf Scattered Waves Observations

- Scattered waves observed for each stage of fracturing in 9Bf
- Events last less than the time between adjacent VSP shoots (< 5 hours)
- Quality of data allows analyzing amplitude distributions for the PS scattered events
- Scattering from SRV induced by other wells (10D, 11A) is observed and will be examined in detail

Future Work

- Model amplitude distributions for the PS scattered events
- Quantitatively analyze scattered wavefield for 1Bf and 9Bf
  - Calculate height for each SRV in fiber and adjacent wells
  - Calculate amplitude attributes for each scattered event
- Relate the derived parameters with treatment parameters



CONCLUSIONS AND FUTURE WORK

Project Summary

RCP
In pursuit of new ideas

Objectives

- Analyze P and S-wave time shifts, amplitude changes, and scattering effects caused by each stage of hydraulic fracturing
- Use time-lapse response to characterize the geometry and dynamics of hydraulic fractures
- Characterize the interference of other zipper group wells in the time-lapse signal
- Associate time-lapse changes with variations in completion design parameters
- Use findings to design future acquisition geometries

Conclusions

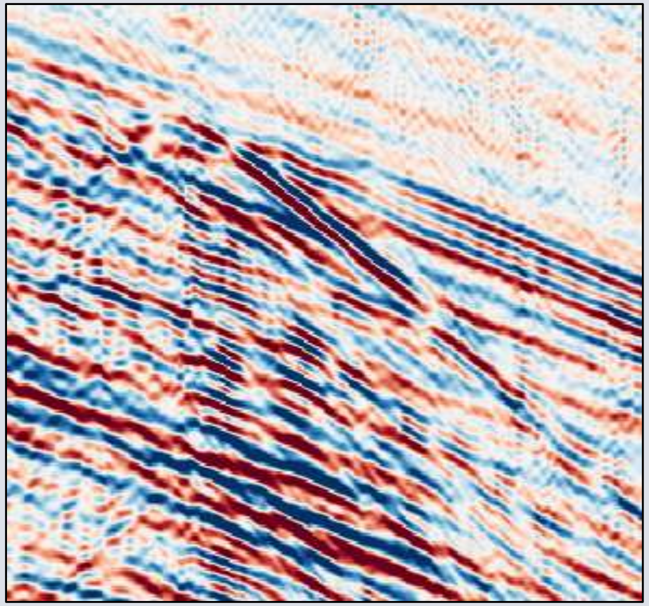
Future Work

Project Summary

RCP
In pursuit of new ideas

Objectives

- Analyze P and S-wave time shifts, amplitude changes, and scattering effects caused by each stage of hydraulic fracturing



Conclusions

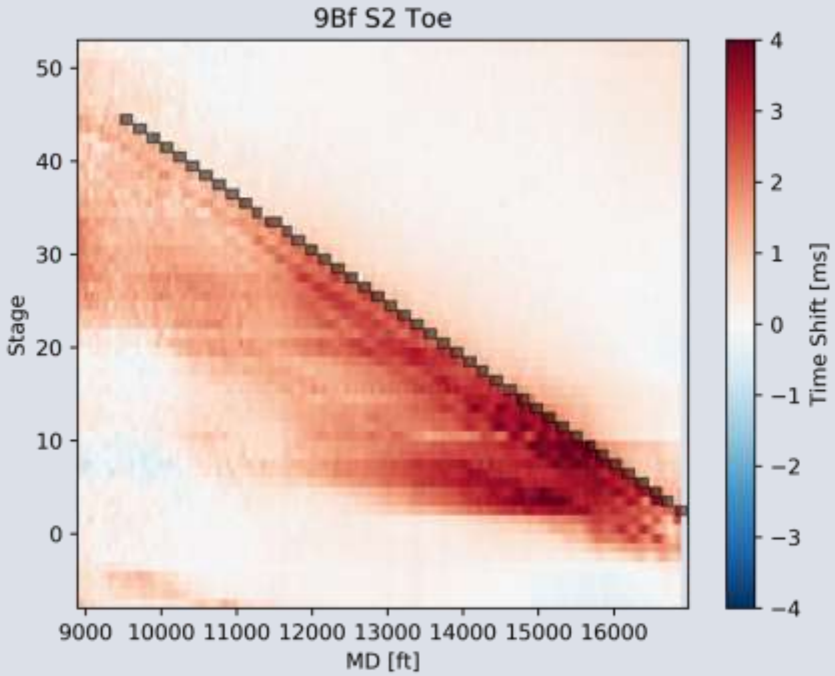
- ~ 1 ms P-wave time shifts and PS converted waves observed consistently after each stage
- Both decay quickly after each stage
- Time shifts and scattered waves are also observed from other wells in the zipper group

Future Work

- Search for S-wave time shifts, amplitude changes, and SS/SP scattered waves

Project Summary

Objectives	Conclusions
• Use time-lapse response to characterize the geometry and dynamics of hydraulic fractures	• Interference from other wells currently prevents estimates of SRV height based on shadowing and the leak-off decay time • Length and azimuth of fracs from neighboring wells can be estimated



Future Work

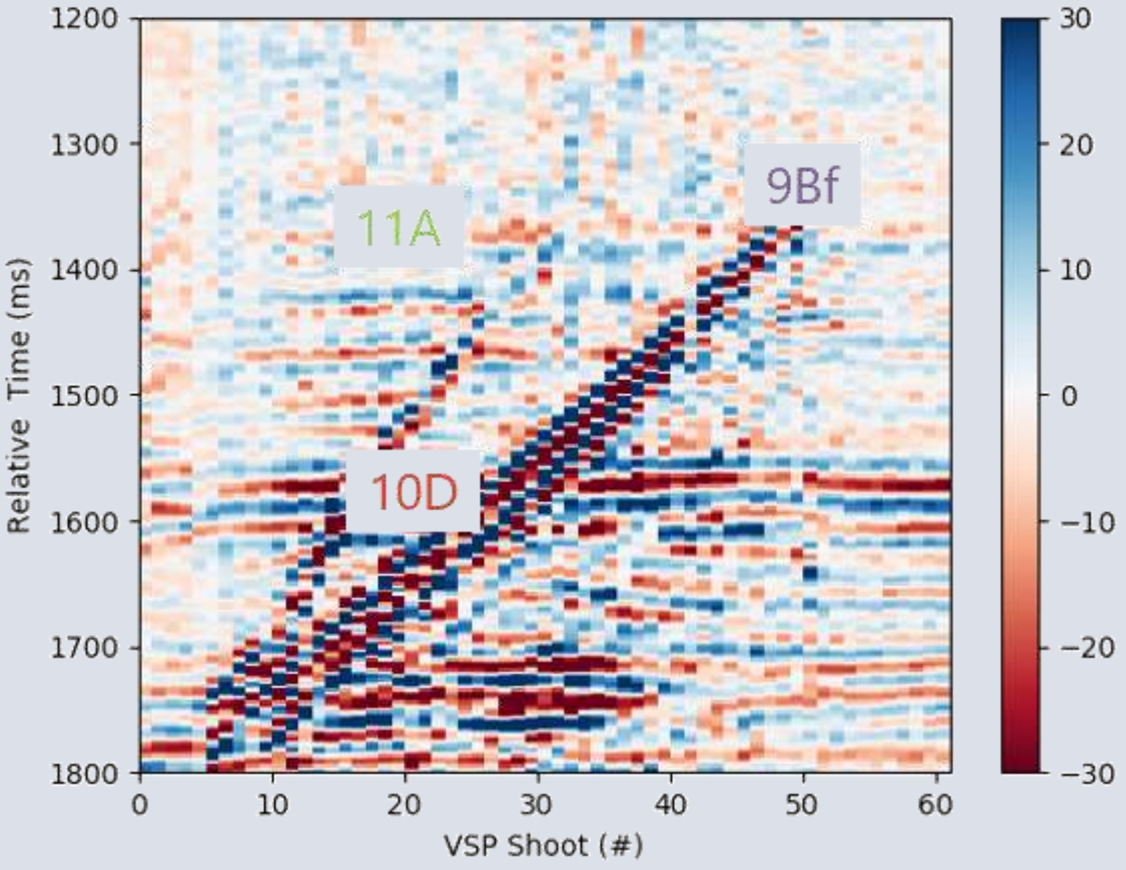
- Develop inversion approaches taking into account into account overlap of each stage’s response
- Utilize methods based on scattered waves that are less sensitive to stage and well interference

Project Summary

RCP
In pursuit of new ideas

Objectives

- Characterize the interference of other zipper group wells in the time-lapse signal



Conclusions

- Clear signs of fracs from all zippered wells are observed
- Scattered waves show a cleaner signal separation between wells

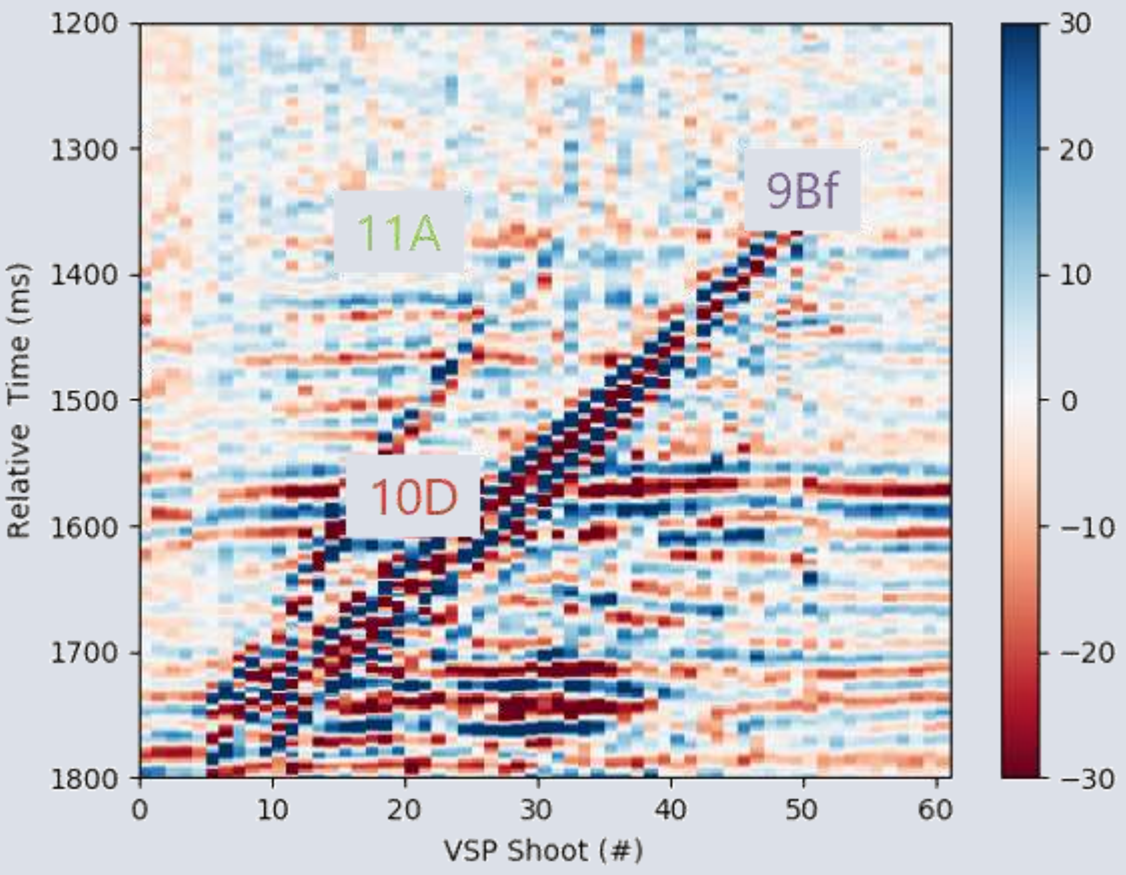
Future Work

- Determine length, azimuth, and height of fracs from neighboring wells

Project Summary

Objectives

- Associate time-lapse changes with variations in completion design parameters



Conclusions

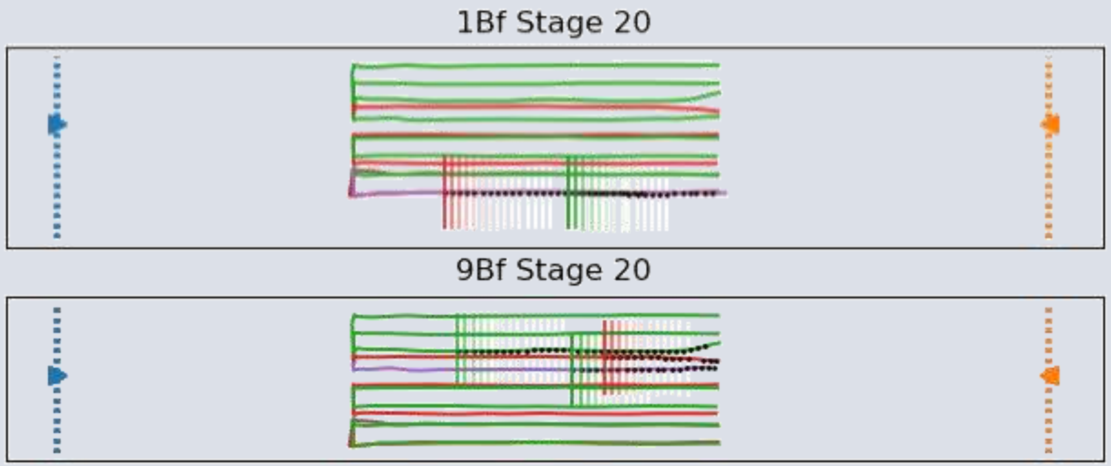
- Clear stage-to-stage variations above noise level are observed in time shifts and scattered waves that may be tied to varying geology and stage designs

Future Work

- Inversion approaches will be developed to account for changing incidence angles, fiber angular response, and scattering angles to associate time lapse changes with properties of underlying fractured rock

Project Summary

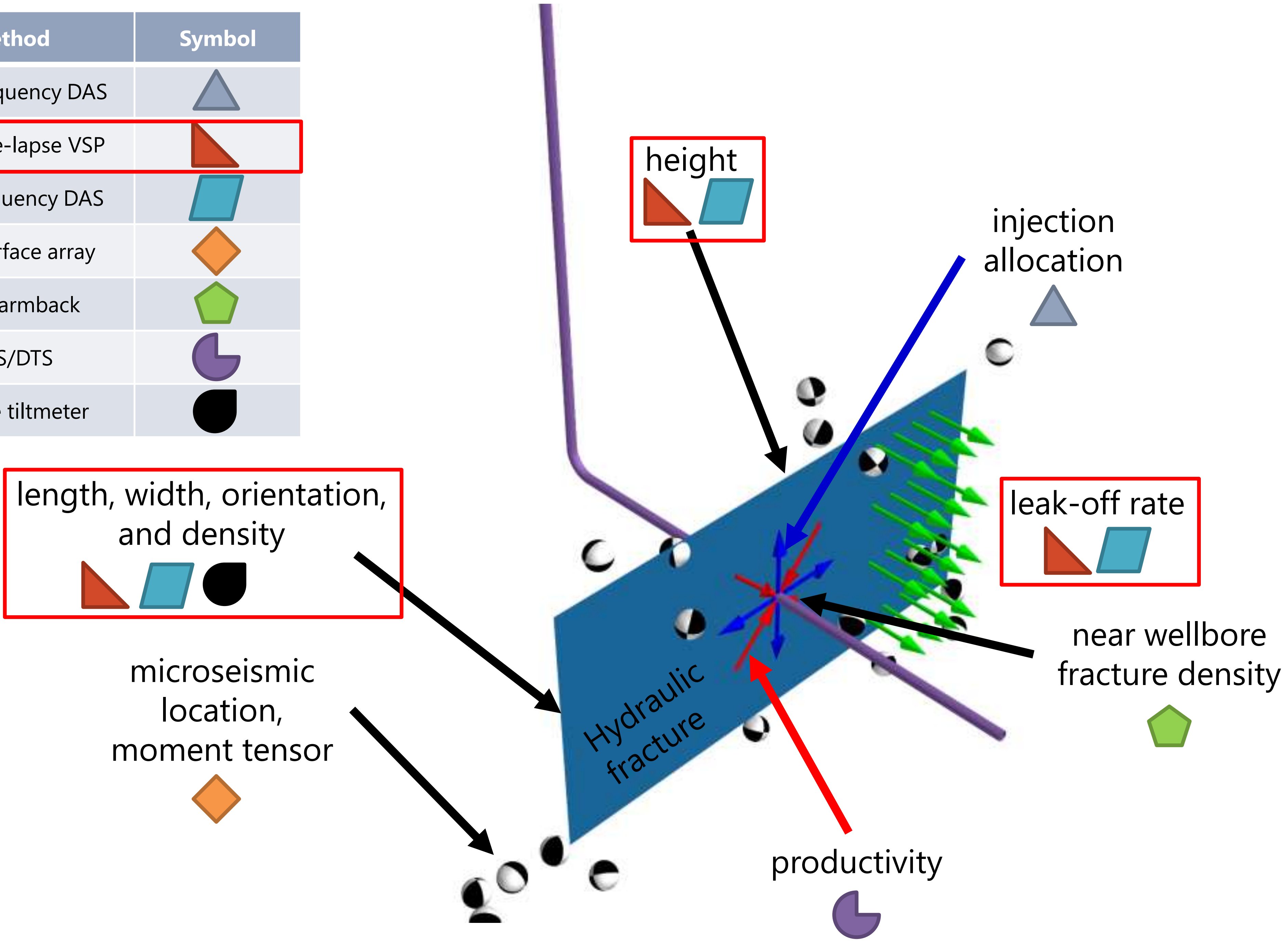
Objectives	Conclusions
• Use findings to design future acquisition geometries	• Modeling software has been generalized to pseudo-3D • Multiple wells can be modeled to study survey sensitivity to well interference



Future Work

- True 3D modeling
- Study alternate survey geometries in 3D that could better constrain fracture geometry and well interference

Method	Symbol
High-frequency DAS	△ (triangle)
DAS time-lapse VSP	◣ (right triangle)
Low-frequency DAS	▱ (parallelogram)
DAS/surface array	◇ (diamond)
DTS warmback	⬠ (pentagon)
DAS/DTS	◔ (pie)
Surface tiltmeter	● (teardrop)



Thank you to Apache and all RCP Phase XVII Sponsors