Time-lapse VSP results from the CaMI.FRS

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VSP surveys were performed 2017-2020

- Vibe source (10Hz-150Hz), 3C geophones, Silixa (2017) and Fotech (2018) DAS interrogators
- Fall 2020 survey data not processed

Geophones

2019-2018 (7t CO_2)

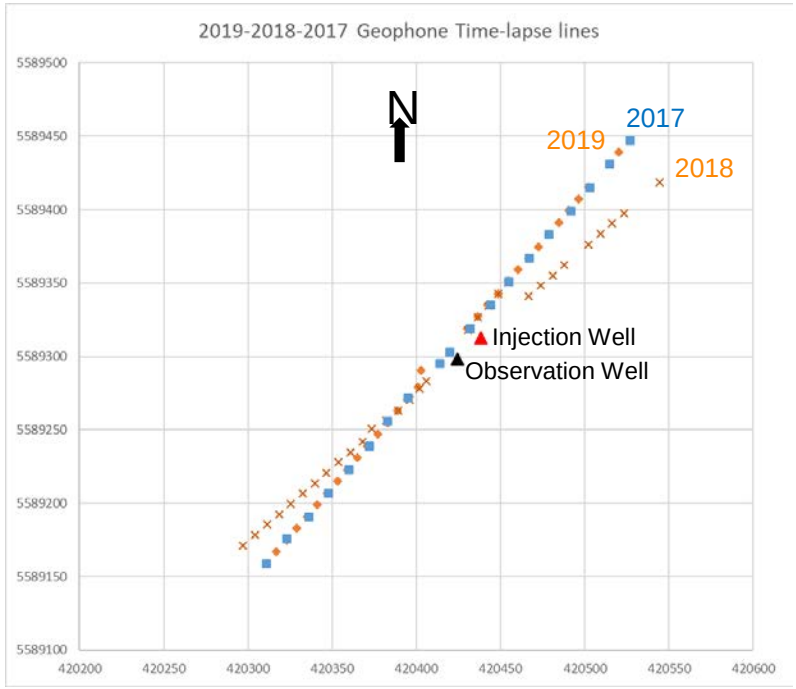
2019-2017 (15t CO_2)

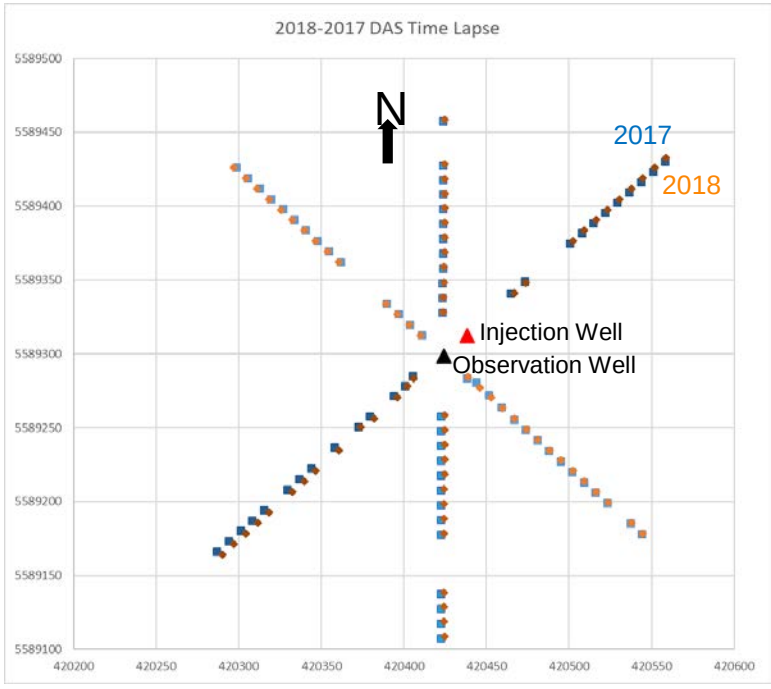
DAS

2018-2017 (8t CO_2)

Injection well is 20m to the NE of the geophysics well

These lines span up to 160m to 190m offset





NRMS and Predictability gauge repeatability

Normalized root-mean-square:

$$NRMS = \frac{200 \times RMS(a_t - b_t)}{RMS(a_t) + RMS(b_t)}$$

- Low value means traces a & b are similar
- Calculated over a time window
- Sensitive to amplitude, phase differences, and random noise

Predictability:

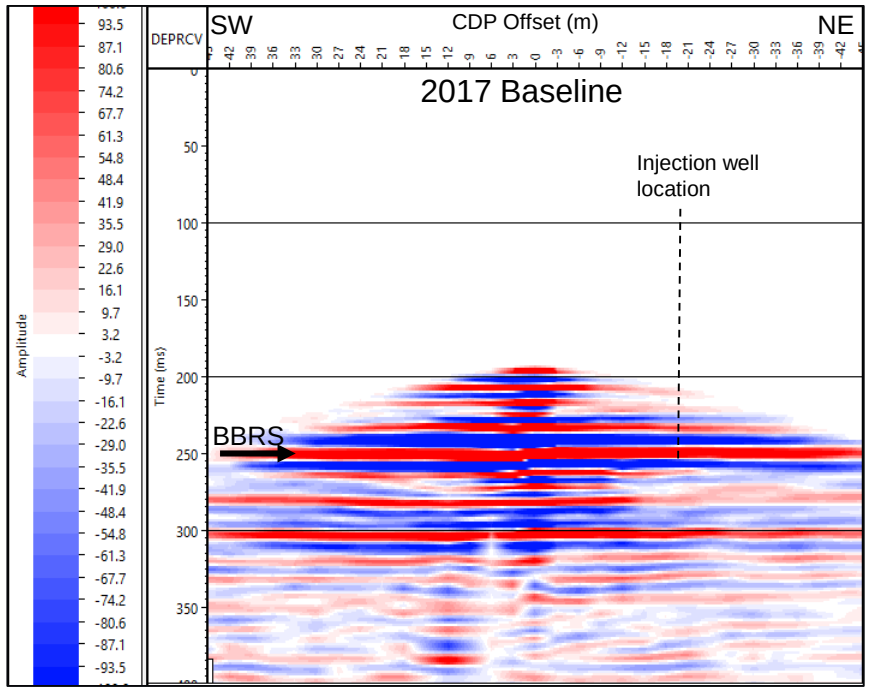
$$PRED = \frac{\sum(\varphi_{ab}(t) \times \varphi_{ab}(t))}{\sum(\varphi_{aa}(t) \times \varphi_{bb}(t))}$$

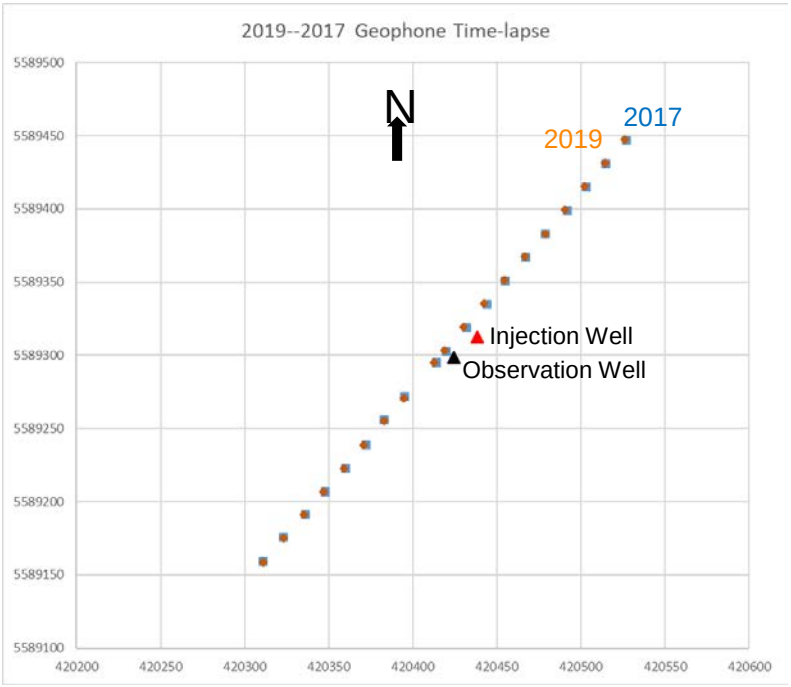
(Kragh and Christie, 2010)

- High value means traces a & b are similar
- Based on correlations and autocorrelations φ of traces a & b for time window t
- Sensitive to correlation lag, reflectivity differences, random noise

Geophone NE-SW VSP CDP

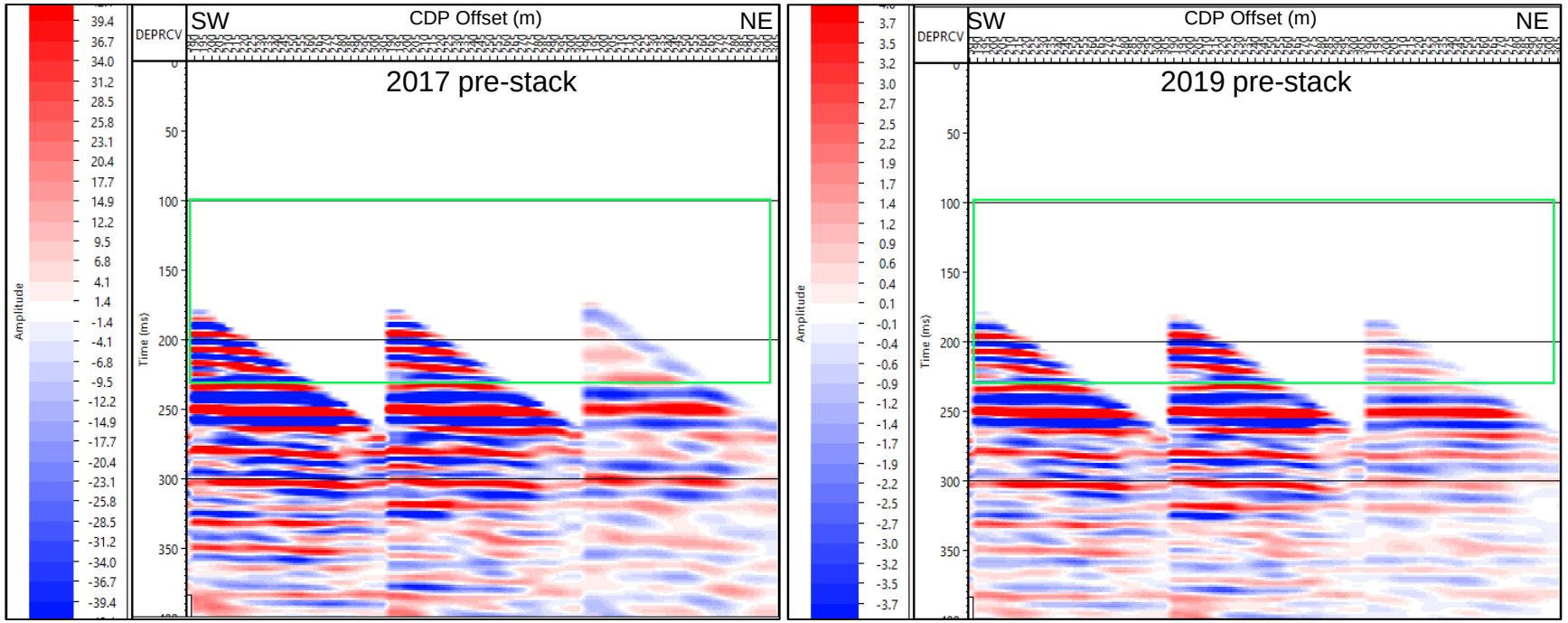
- Strong positive reflection at the top of the reservoir, Basal Belly River Sandstone (BBRS)
- Challenging to scale the BBRS reflection for time-lapse
- Limited data above BBRS at injection well offset (20m) with low amplitude, low fold data





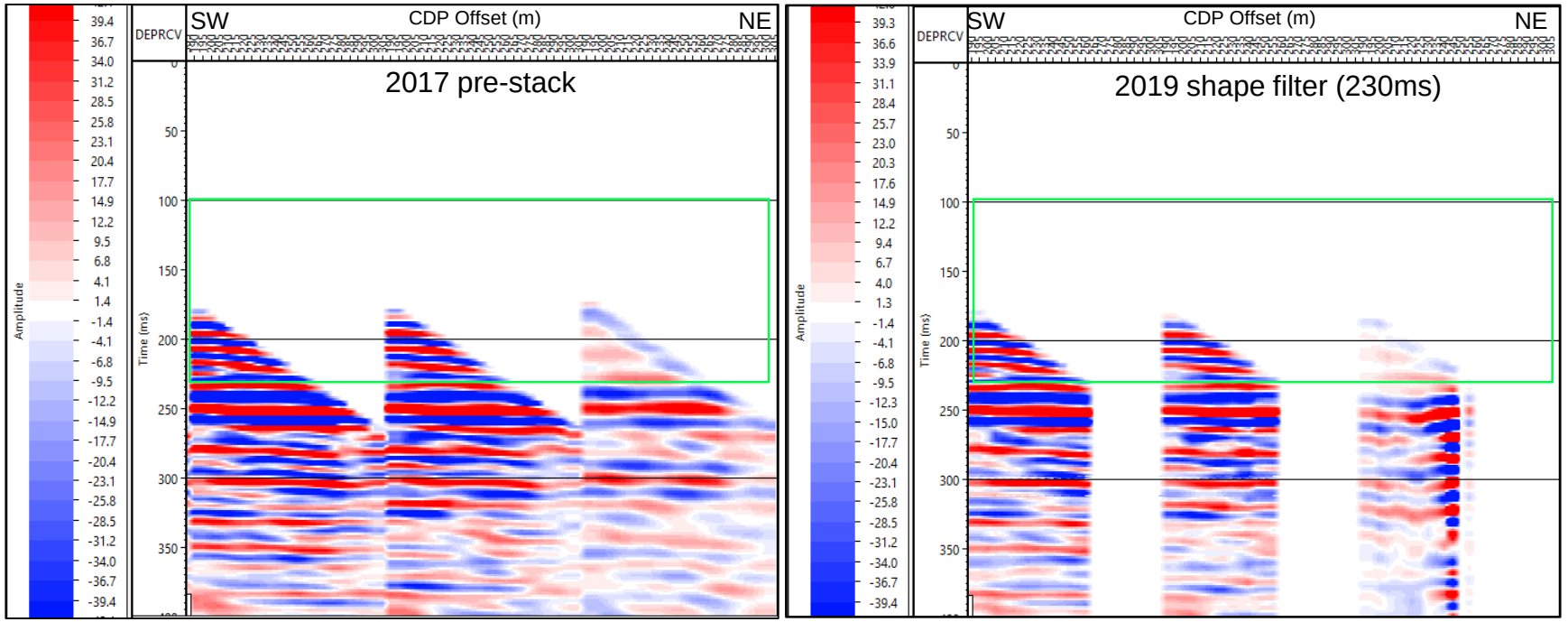
Unable to exclude reservoir from shape filter design

- BBRS at 250ms
- 0-230ms and 0-240ms windows had deleterious effect on data



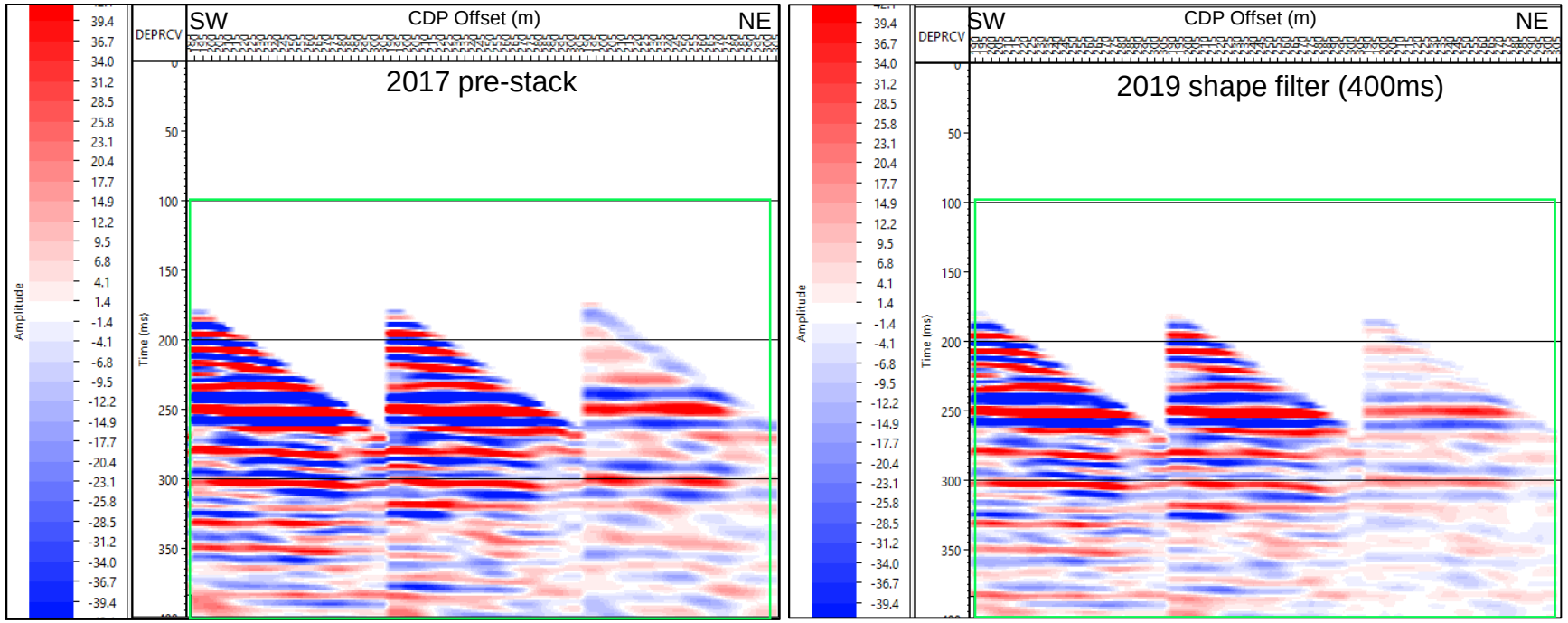
Unable to exclude reservoir from shape filter design

- BBRS at 250ms
- 0-230ms and 0-240ms windows had deleterious effect on data
- BBRS reflection amplitudes scaled poorly, useful data is cut-out



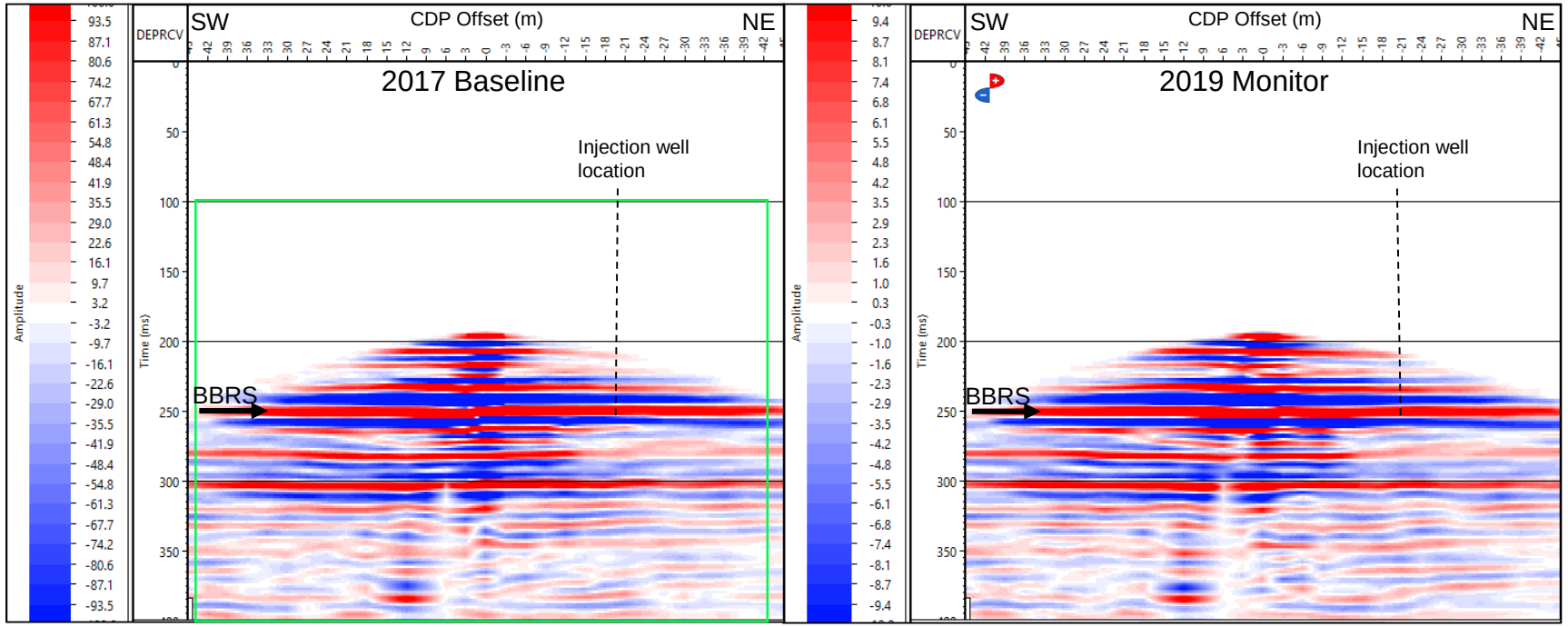
Shaping filter includes BBRS reflection

- 0ms-400ms shaping filter includes reservoir and as much coherent signal below as possible
- Intended to scale amplitude and phase without altering local CO2 anomaly too much



Shaping filter applied to 2019 monitor data

- Filter applied to pre-stack, TWT gathers

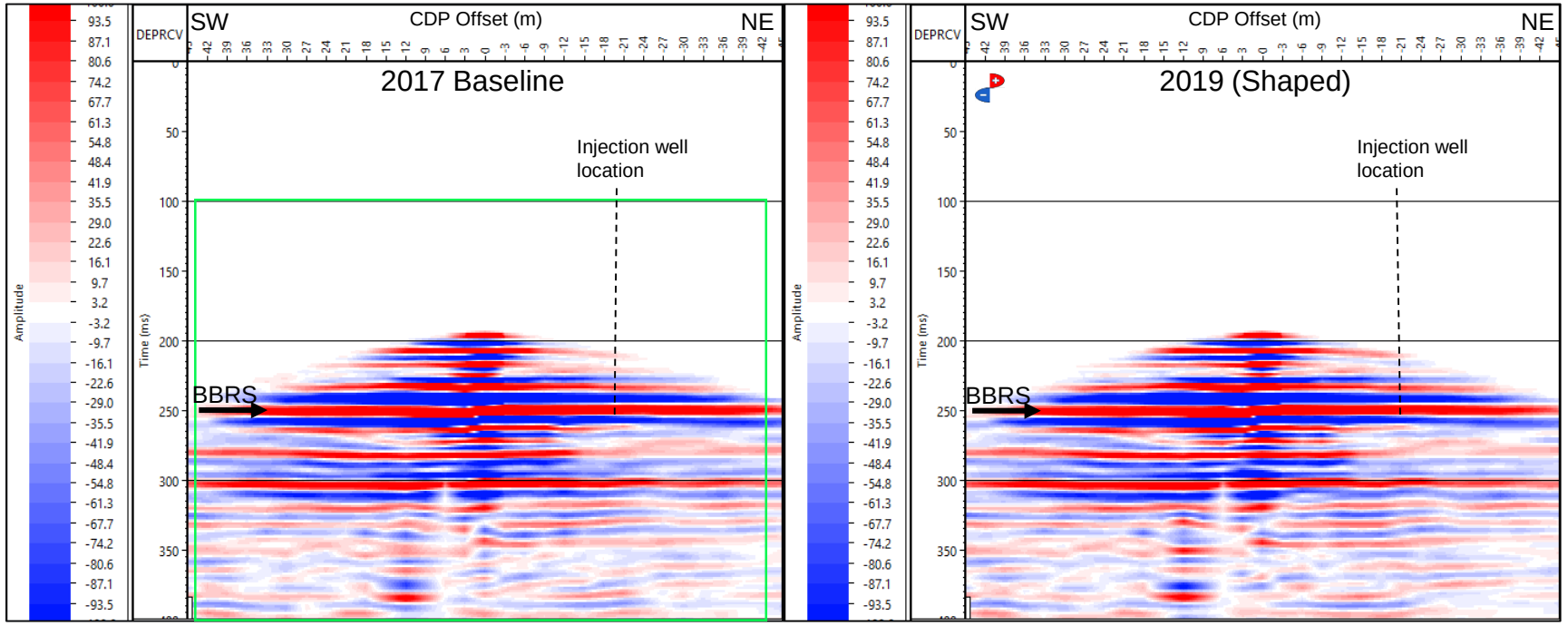


Shaping filter applied to 2019 monitor data

- Filter applied to pre-stack, TWT gathers
- 400ms design window, 40ms filter operator length
- Shaped 2019 matches 2017 quite well

0-400ms	
NRMS	PRED
15.6%	98.9%

230ms-270ms	
NRMS	PRED
12.3%	99.4%



Full-stack time lapse

- Affected by residuals from high amplitude near offset shots
- This is a consistent problem across all VSP lines

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230ms-270ms	
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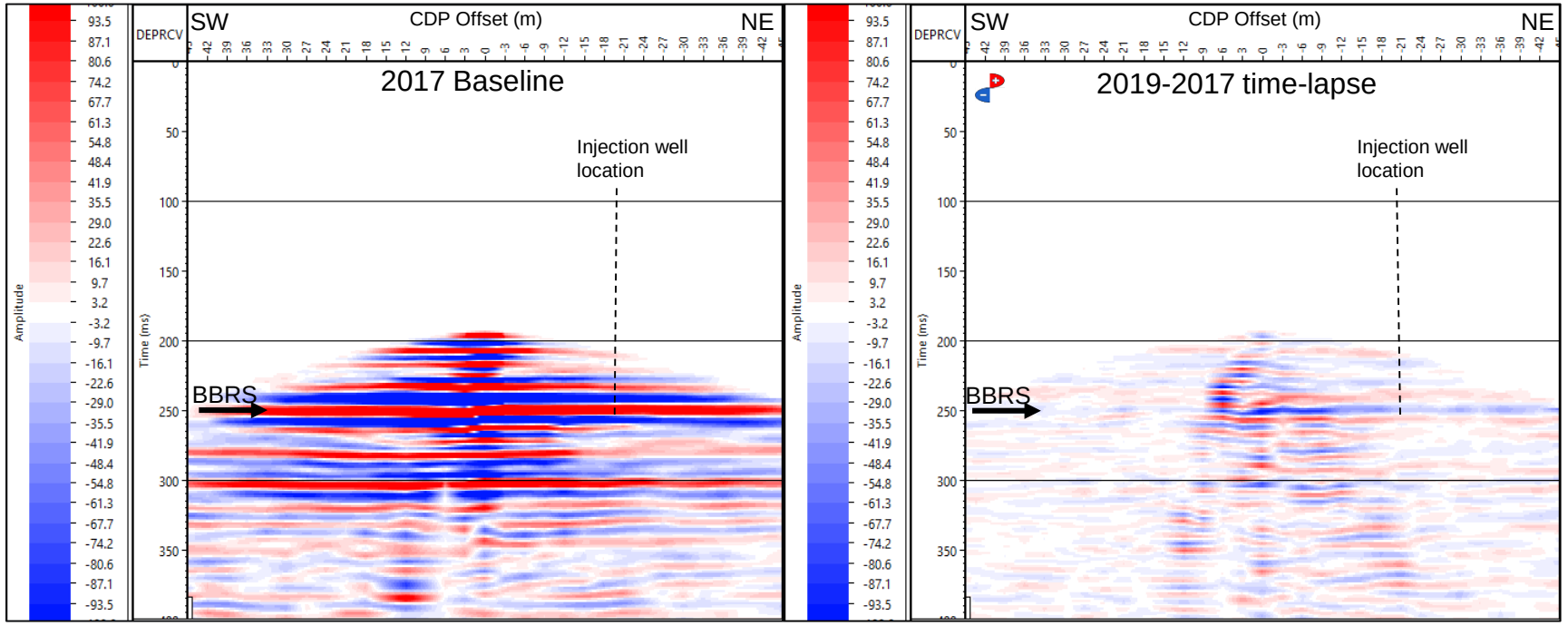
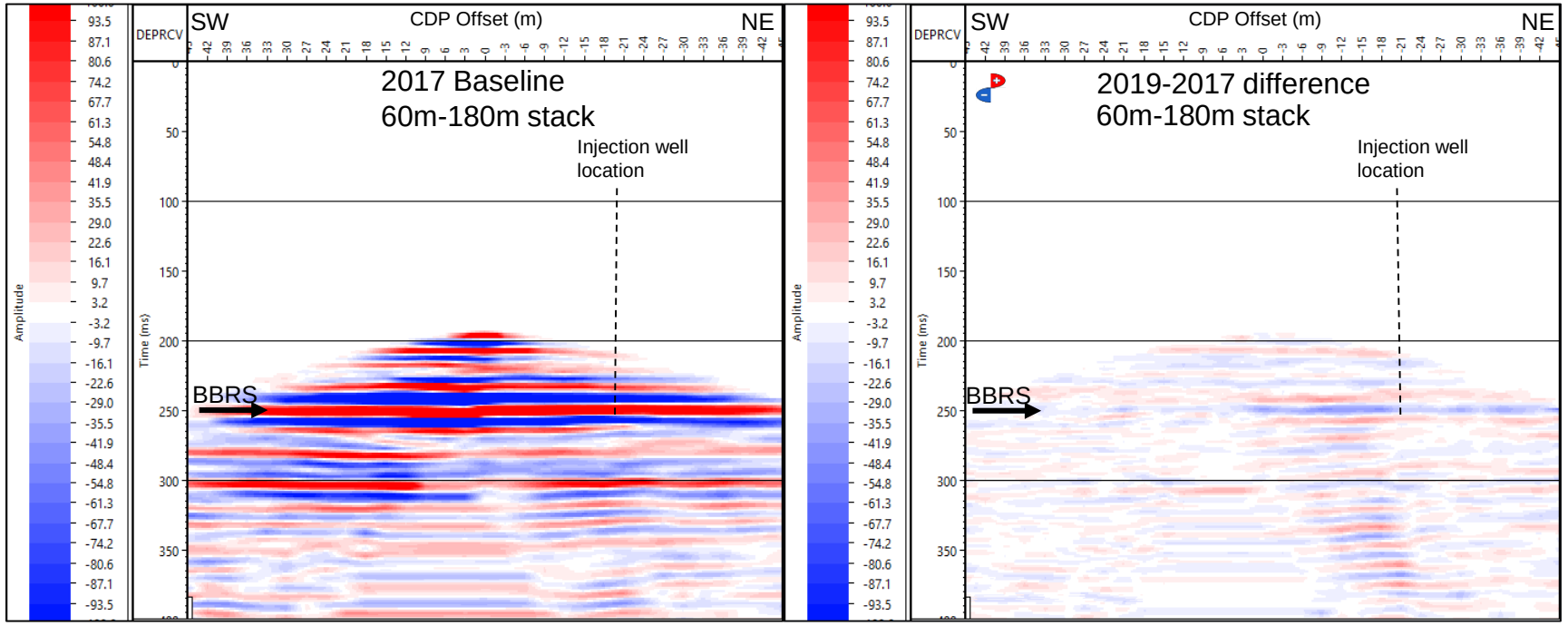


Removing near offset shots reduces residual amplitude

- <50m offset shots cause most of the unwanted residuals
- 60m offset shot still causing problems

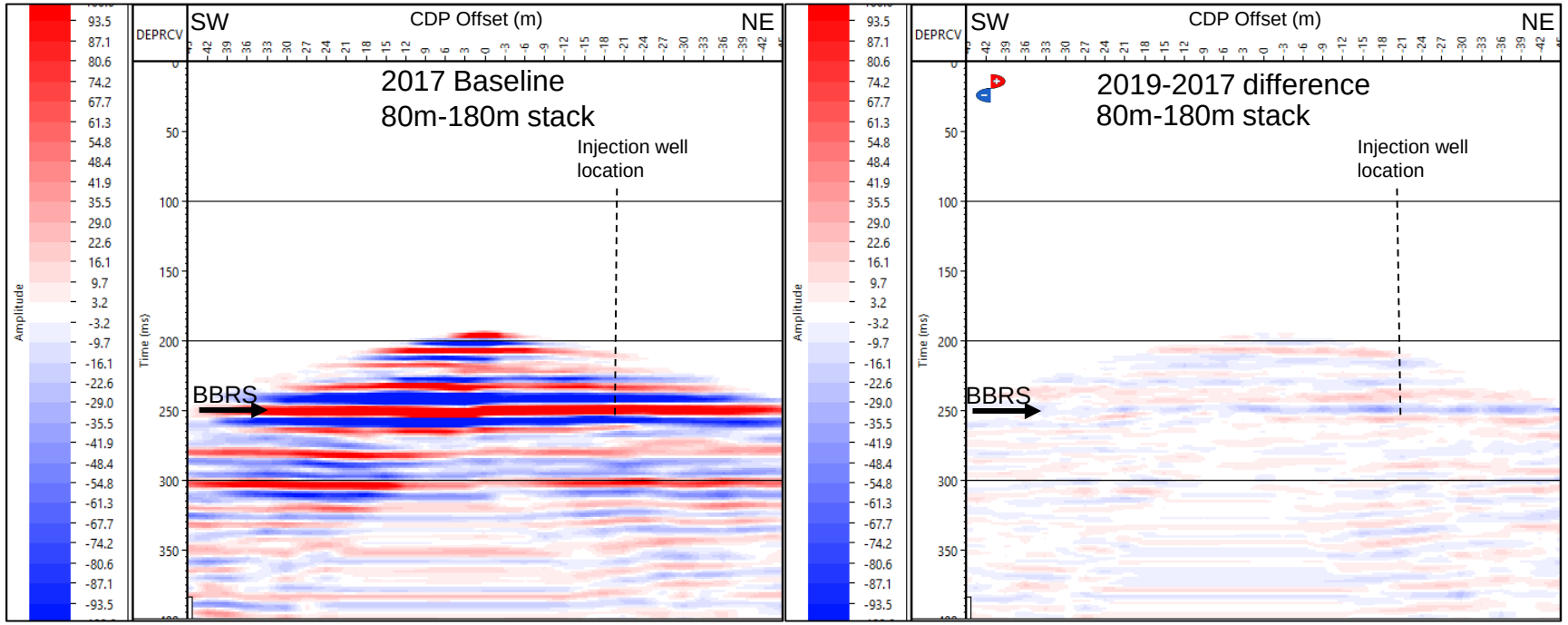


Removing near offset shots reduces residual amplitude

- 80m-180m mid-far offset stack has the lower fold, frequency content, but good NRMS
- BBRS amplitude successfully reduced to nearly zero on the SW side
- Minor negative amplitude anomaly may be present within general BBRS residual to the NE

0-400ms	
NRMS	PRED
11.8%	99.2%

230ms-270ms	
NRMS	PRED
8.3%	99.8%



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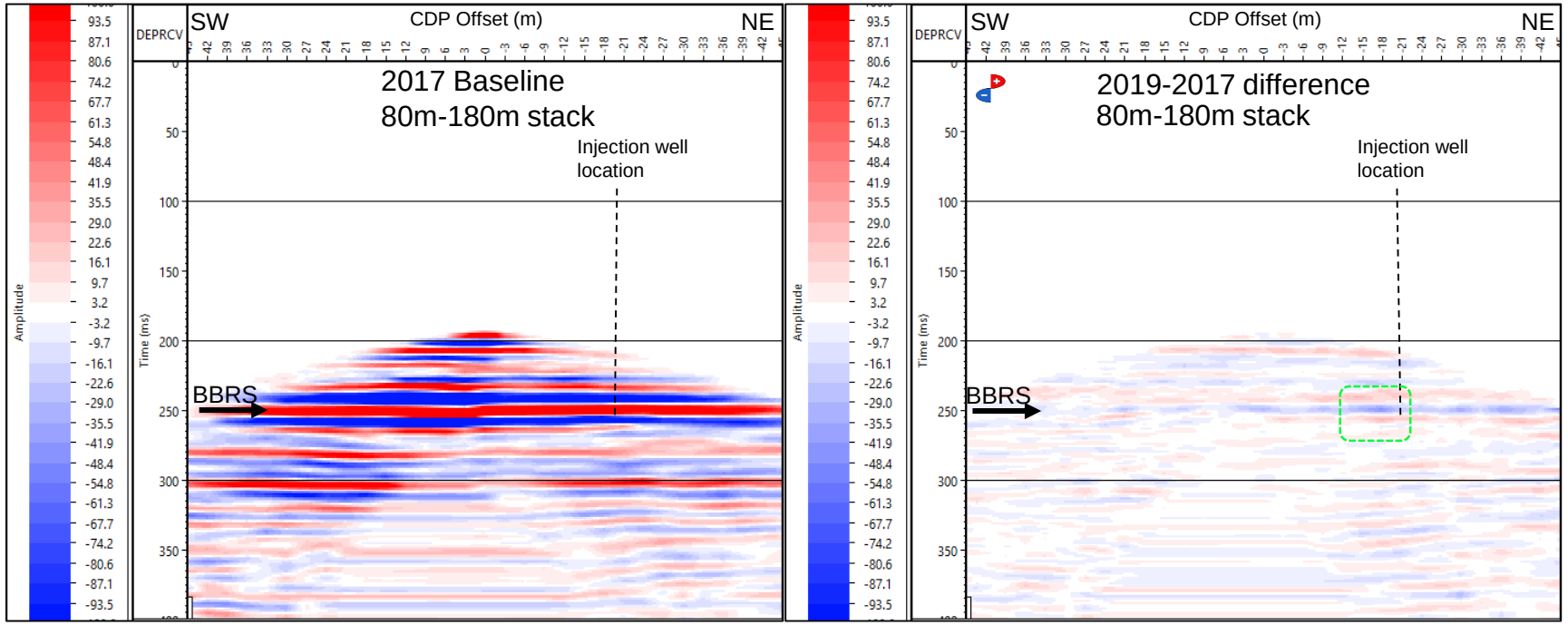

Lateral resolution contributes to uncertainty

- The most negative residual near the well is only on one 3m bin
- Successful removal of high amplitude BBRS reflection in most of the section
- Difficult to distinguish anomaly from poorly scaled shot

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230ms-270ms	
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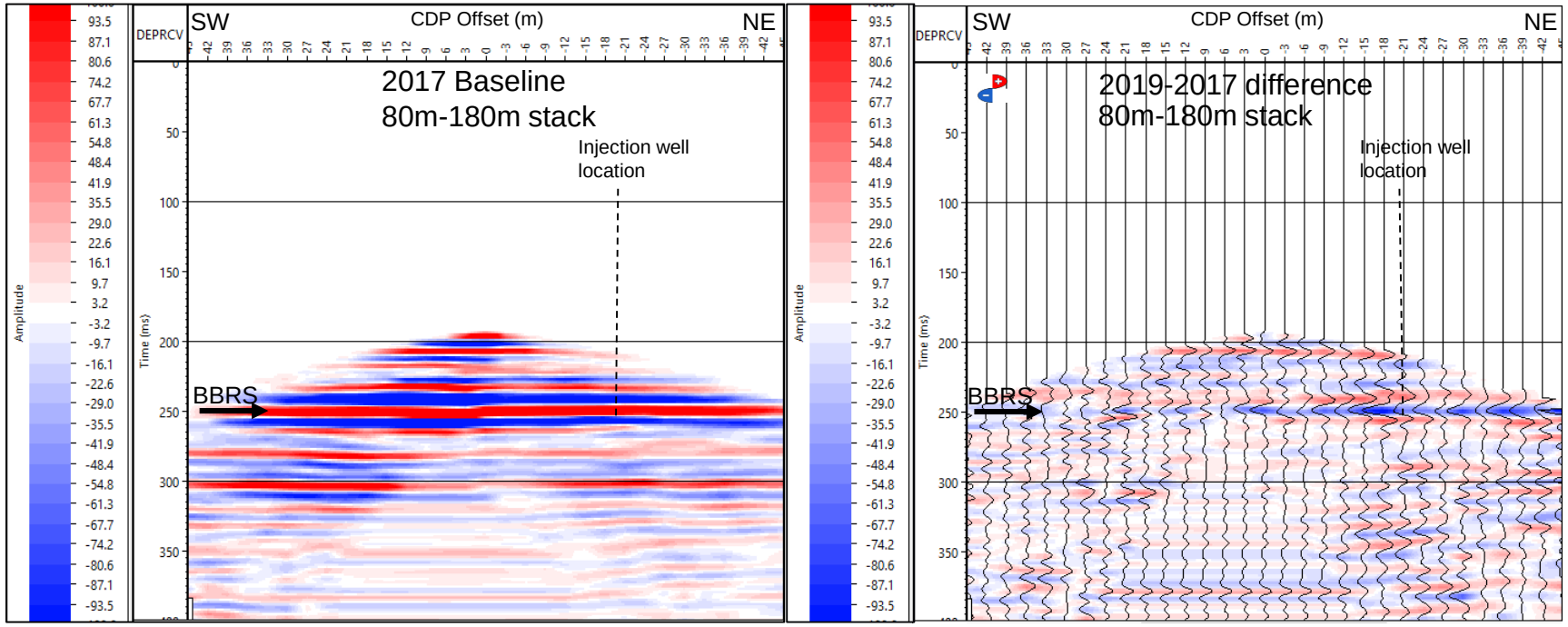
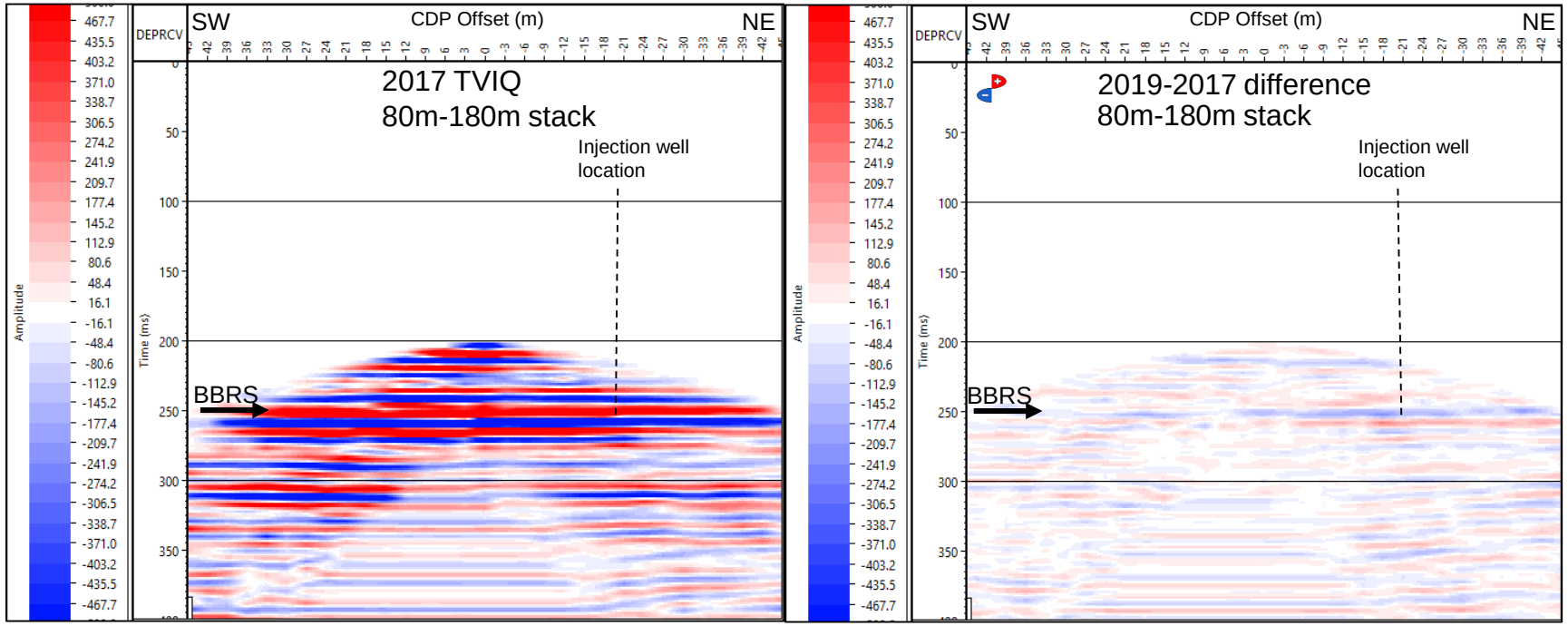


Time-variant inverse Q filter

- 1D 5 layer attenuation model designed from 2018 MEMS Accelerometer VSP
- Inverse Q filter raises amplitudes of high frequencies based on two-way travel-time
- Intended to improve vertical resolution of reservoir, generally worsens NRMS and PRED
- 2% increase in NRMS from TVIQ filter

0-400ms	
NRMS	PRED
14.4%	98.7%

230ms-270ms	
NRMS	PRED
10.2%	99.6%

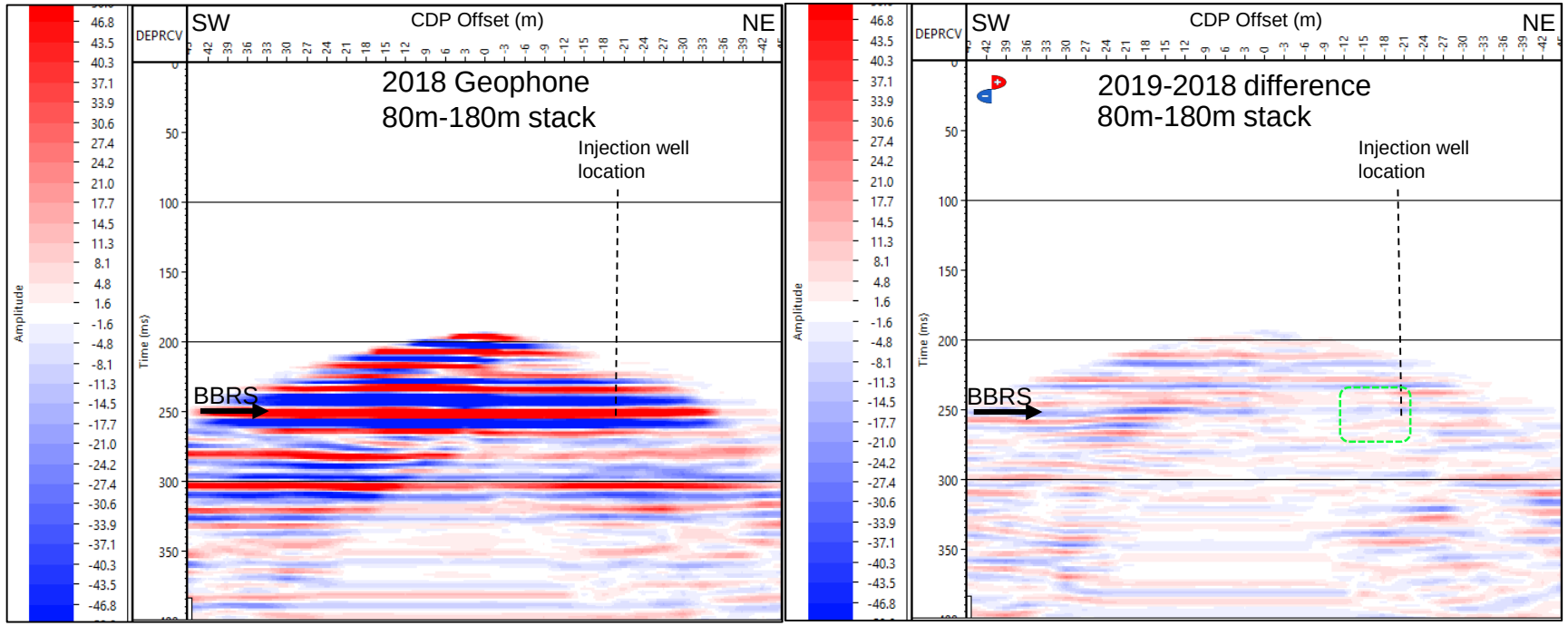


2019-2018 results have worse NRMS and PRED

- No CO_2 amplitude anomaly evident above background
- 2%-4% higher NRMS than 2019-2017 result
- SW residuals likely skewing NRMS compared to 2019-2017

0-400ms	
NRMS	PRED
17.8%	98.5%

230ms-270ms	
NRMS	PRED
12.5%	99.4%



TVIQ result for 2019-2018

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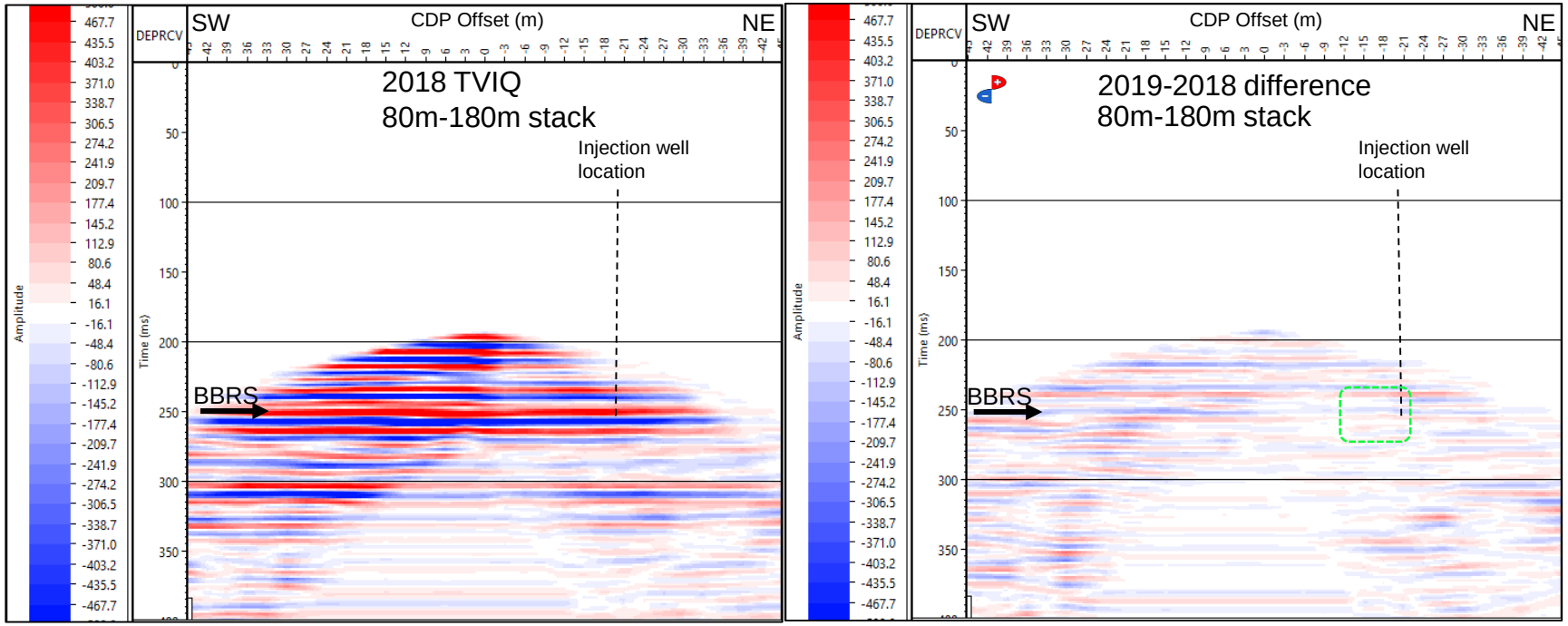
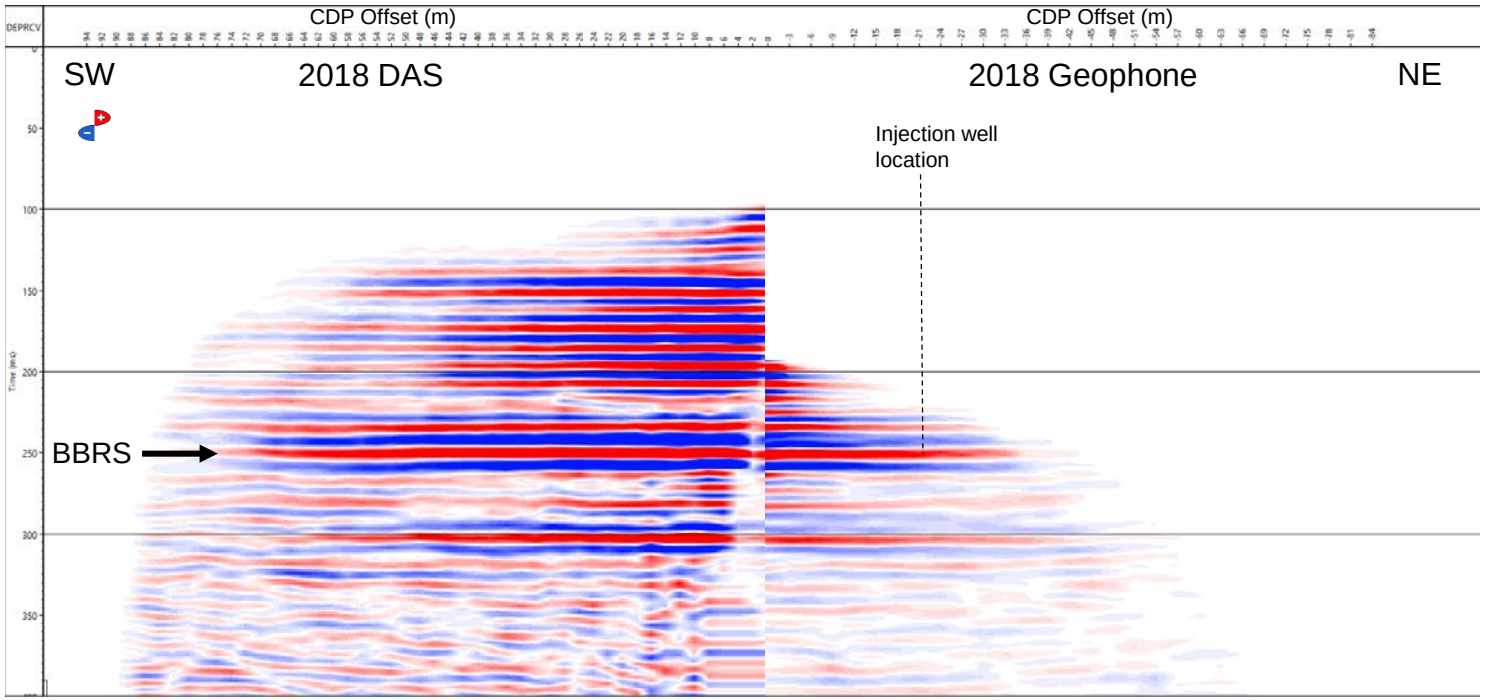


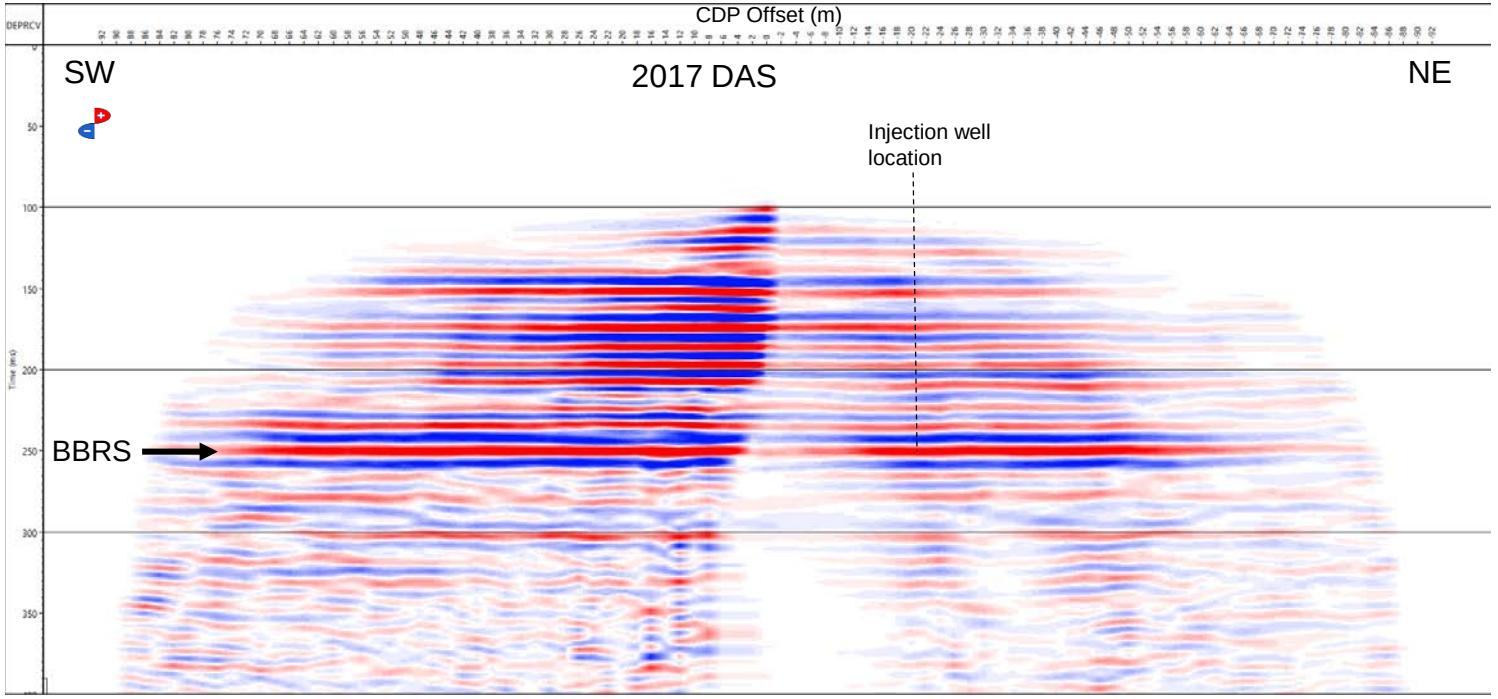
DAS data has significantly more coverage

- Geophone data lacks shallow and far-offset reflections
- DAS has ~100ms of reflection data above the BBRS injection zone
- Excluding BBRS from pre-stack shaping filter was not successful, used 400ms window again



DAS data has more variables at play for repeatability

- Different interrogators, Silixa (2017) and Fotech (2018)
- Different trace spacing (0.25m vs 0.67m) required stacking traces to yield 2m trace spacing
- 2017 baseline is lower amplitude for near offset CDPs, unclear why (both pre- and post-stack)
- These DAS data are integrated from strain rate to strain, but not scaled for particle velocity[1] and broadside insensitivity



[1] Daley et. al, 2015

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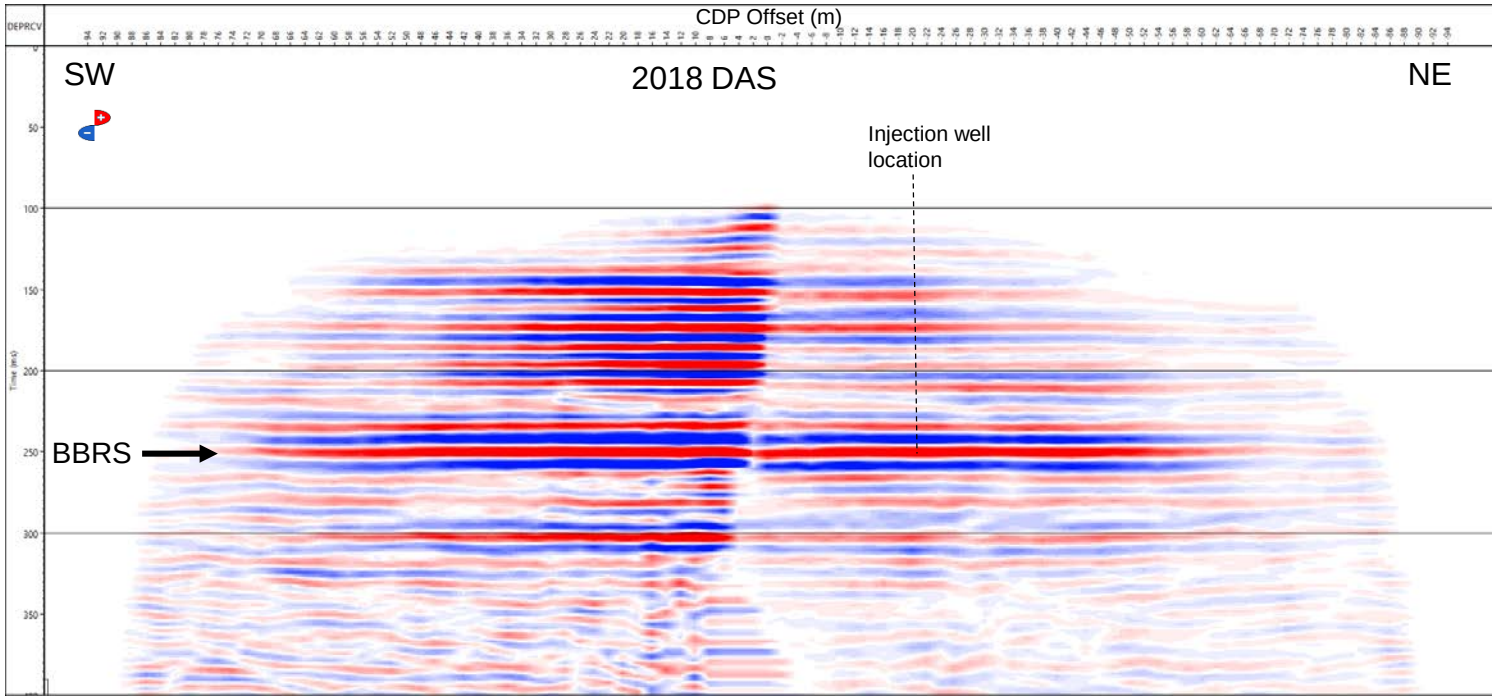
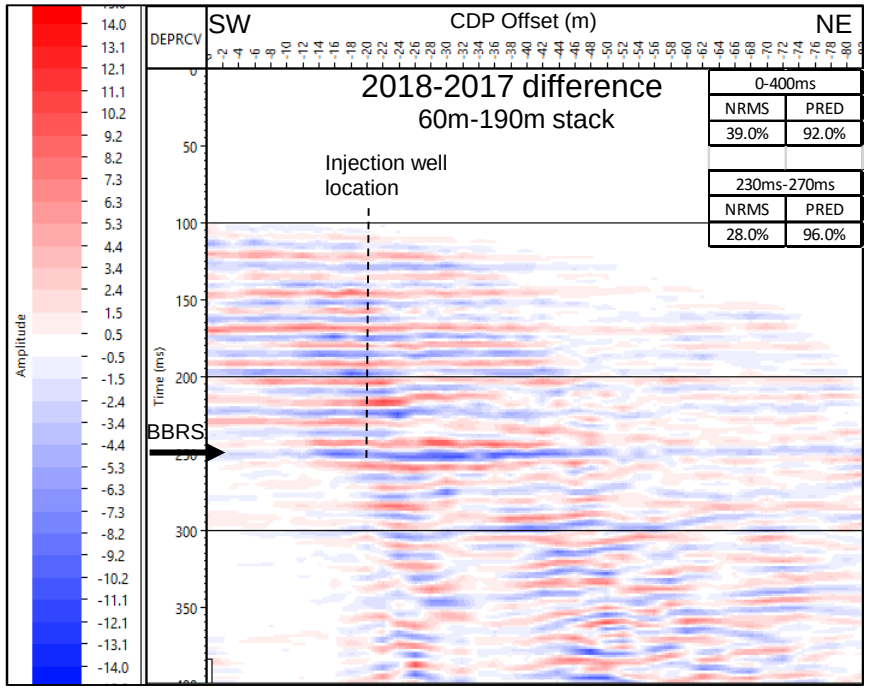
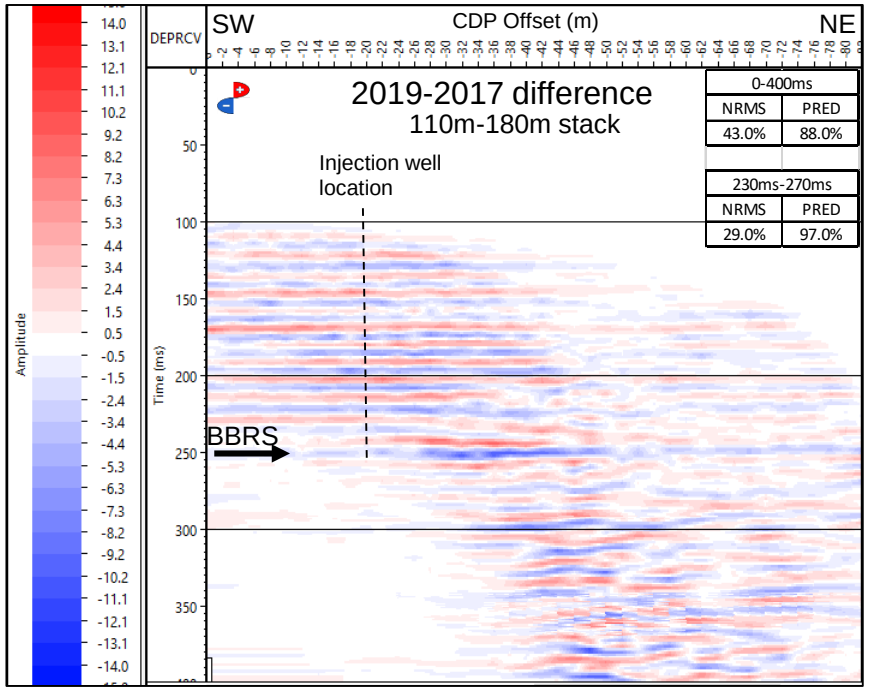


[1] Daley et. al, 2015

Mid- and far-offset shots more reliable

- Significant residual amplitude from BBRS reflection
- No obvious negative residual from CO_2
- NRMS and PRED are ~15% higher than geophone results, require significant improvement to be useful





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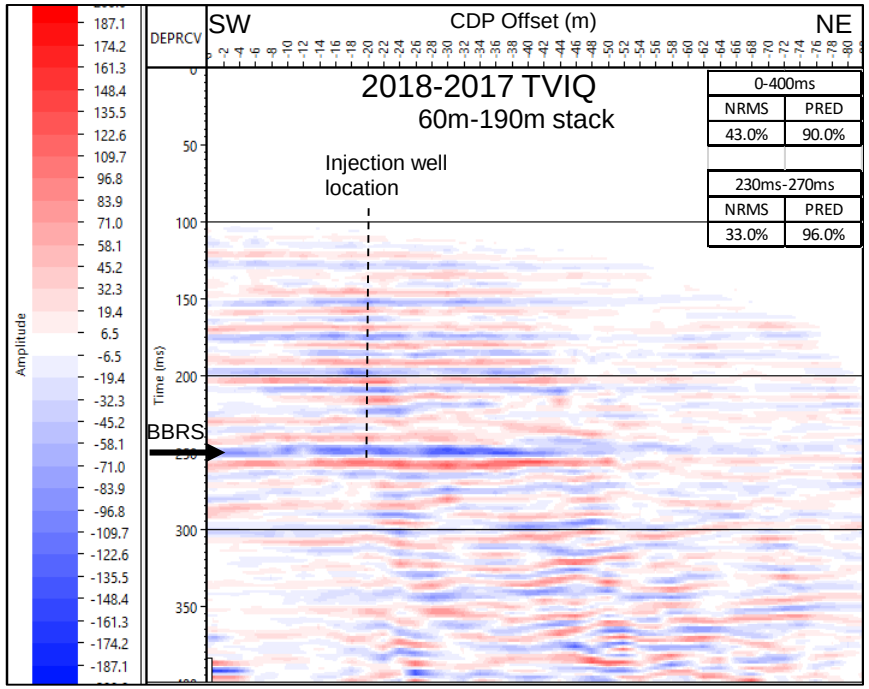
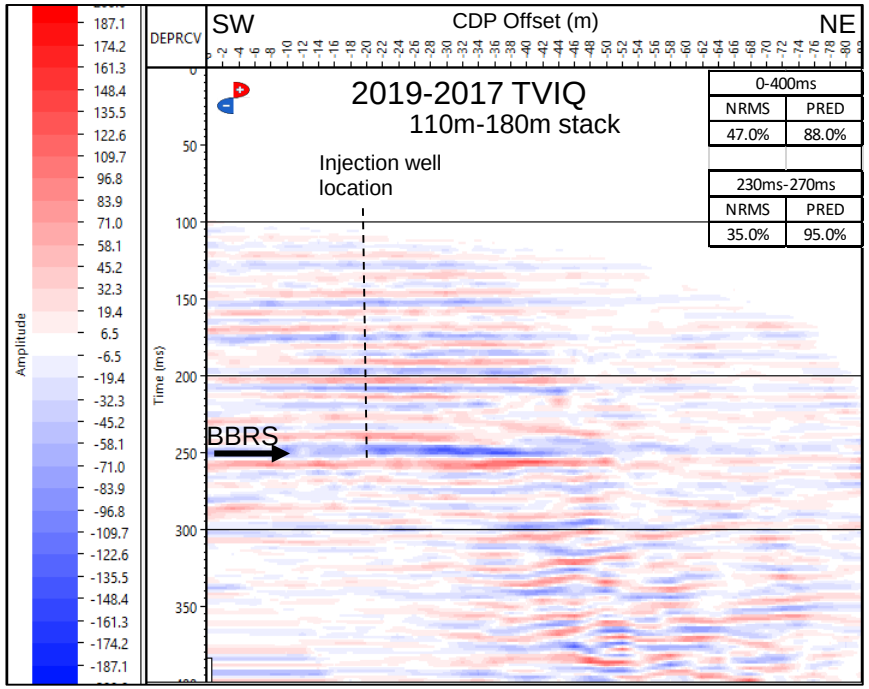
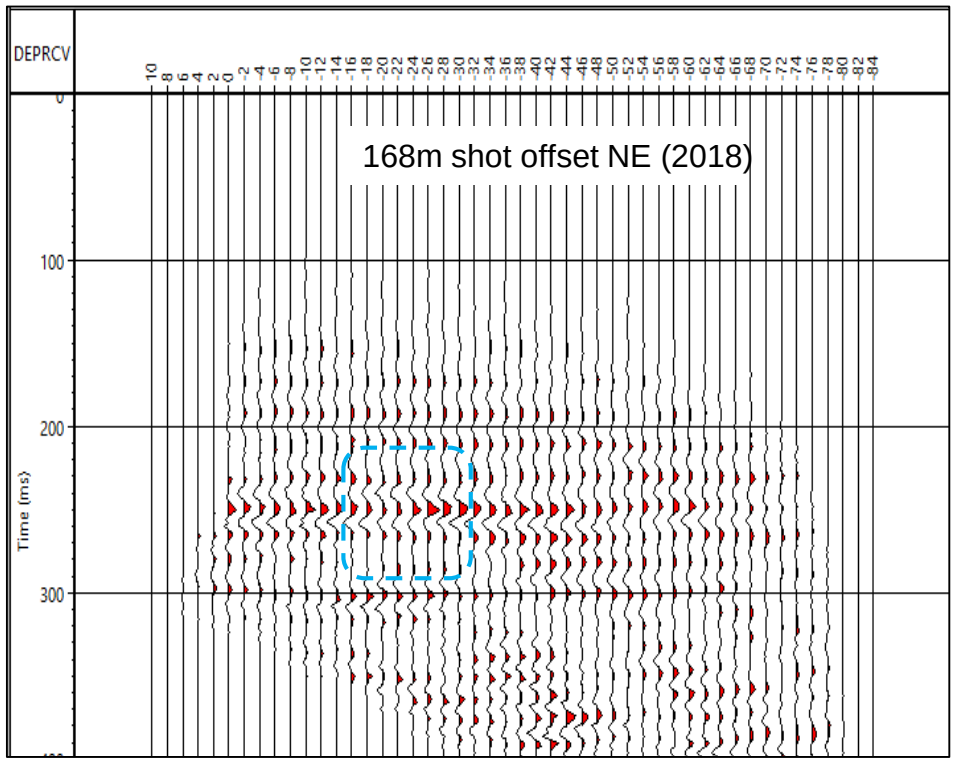
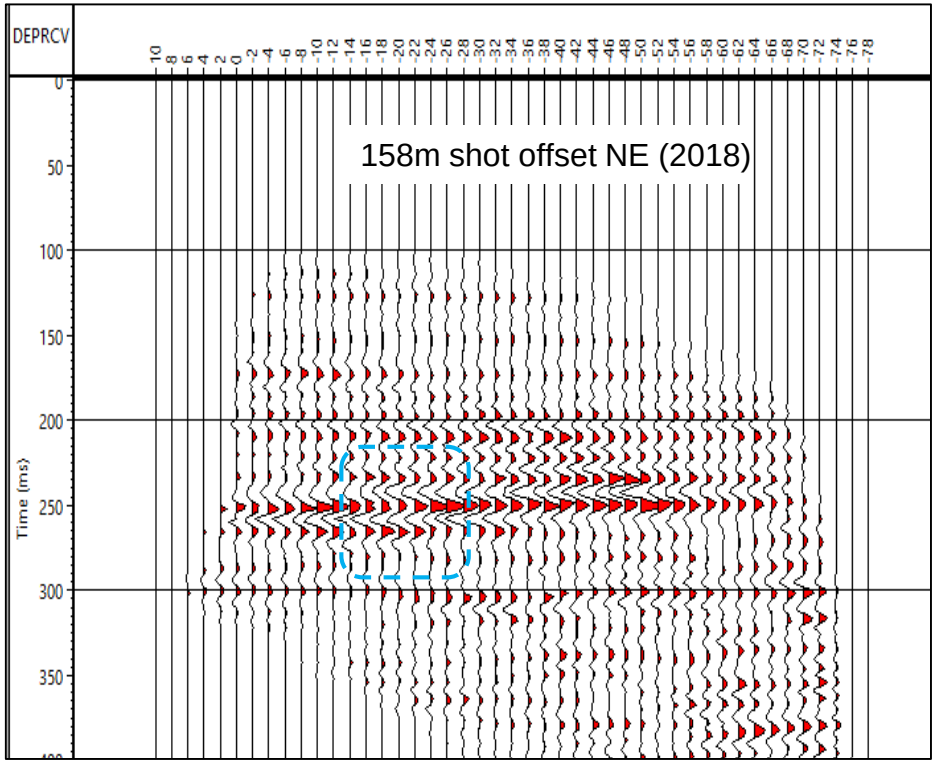




Unaltered 2018 CDP gathers show dimming of BBRS

- Consistent dimming around 16m-22m in 2018 CDP gathers
- Not evident in full- or far-offset VSP CDP stack
- AVA modeling and inspection of raw gathers should help prove or disprove





Conclusions

- Geophone data highly repeatable: NRMS = 8%-15%, PRED = 99%
- Lower repeatability scores for DAS: NRMS =25%-40%, PRED = 83%-97%
- Time-variant inverse-Q filter generally worsens NRMS and PRED by 1%-5%
- Possible CO_2 anomaly in the time-lapse geophone and pre-stack 2018 DAS: Amplitude decrease near injection well

Future work on VSP time-lapse

- Scale DAS for broadside insensitivity, particle velocity
- Attempt shaping filter on individual CDP gathers rather than TWT shot gathers
- Re-process 2018-2017 with even farther offsets
- Solve scaling/residual issues for near offset shots to improve fold and resolution
- Process 2020 monitor surveys

References

- Bancroft, J., 2002, Introduction to matched filters: CREWES Research Report, **14**, 46.1-46.8
- Cheng, A., Huang, L., and Rutledge, J., 2010, Time-lapse VSP data processing for monitoring CO2 injection: The Leading Edge, **29**, 196-199
- Daley, T., Miller, D., Dodds, K., Cook, P., and Freifeld, B., 2015, Field testing of modular borehole monitoring with simultaneous distributed acoustic sensing and geophone vertical seismic profiles at Citronelle, Alabama: Geophysical Prospecting, **64**, 1318-1334
- Gordon, A., 2019, Processing of DAS and geophone VSP data from the CaMI Field Research Station: M.Sc. Thesis, Univ. of Calgary.
- Hargreaves, N.D., and Calvert, A.J., 1991, Inverse Q filtering by fourier transform: Geophysics, **56**, 519-527
- Kragh, E., and Christie, P., 2002, Seismic repeatability, normalized rms, and predictability: The Leading Edge, **21**, 640-647
- Macquet, M., and Lawton, D., 2017, Reservoir simulations and feasibility study for seismic monitoring at CaMI.FRS: CREWES Research Report, **29**, 56.1-56.26
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