Time-lapse analysis of CaMI.FRS CO_2 VSP data

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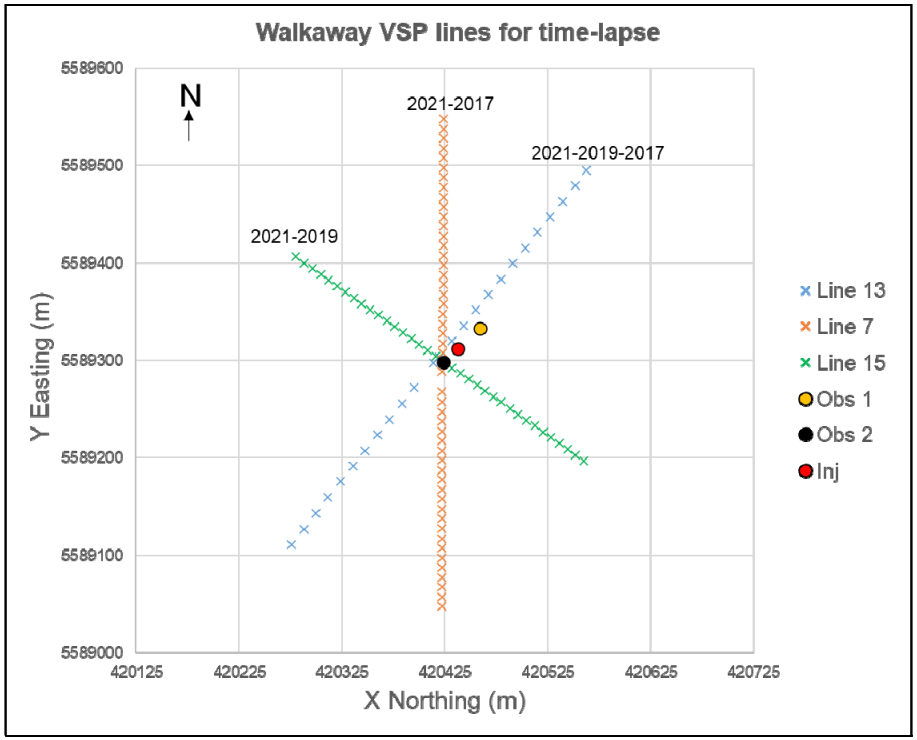
Highly repeatable walk-away lines used for time-lapse

- 3 walk-away VSP monitoring lines chosen for time-lapse VSPs
- Line 13 (NE-SW) runs parallel to injection well, observation wells, and typical 2D surface acquisition line
- Line 13 used to design time-lapse compliant processing workflow for CaMI.FRS VSP data



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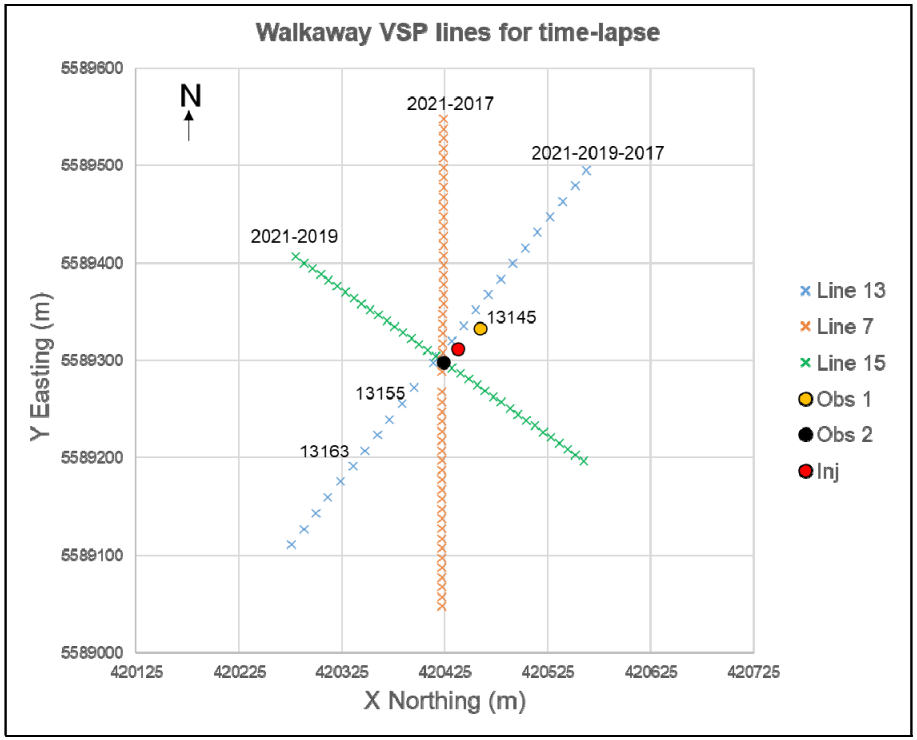
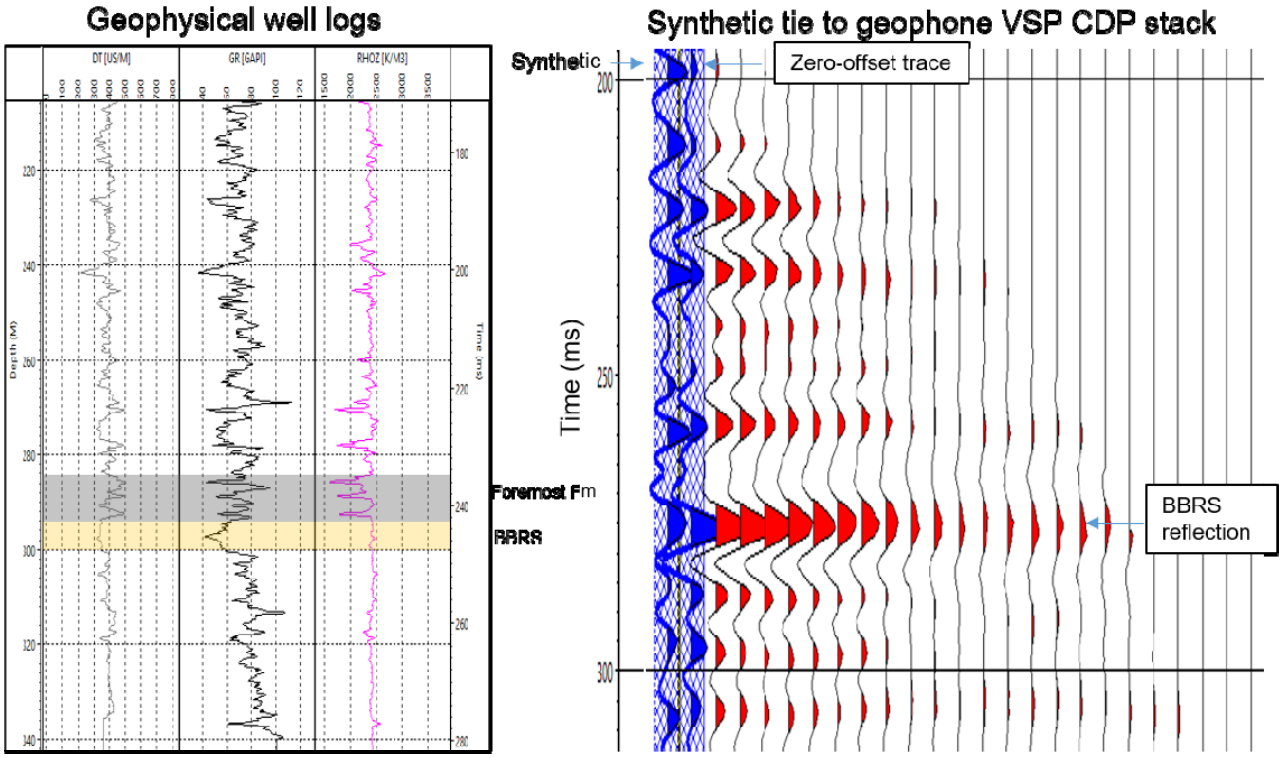


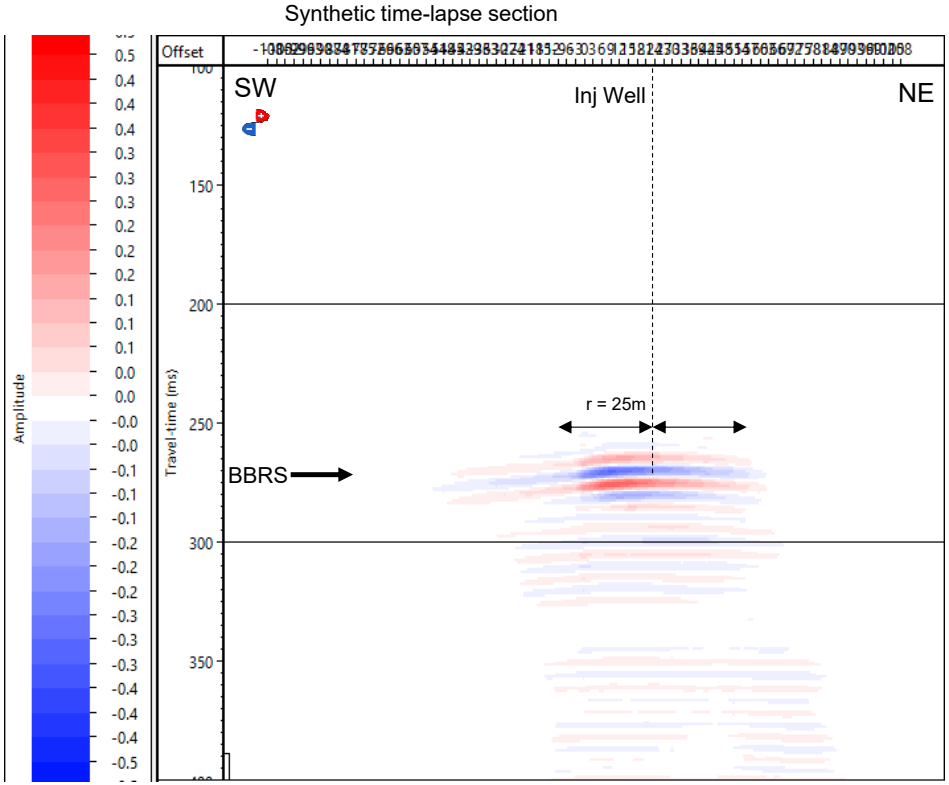
Seismic behaviour of BBRS reservoir

- Foremost Fm coals & shales cause high reflection amplitude at Basal Belly River Sandstone (BBRS) reservoir top



CO2 causes a ‘trough’ anomaly due mainly to Vp reduction

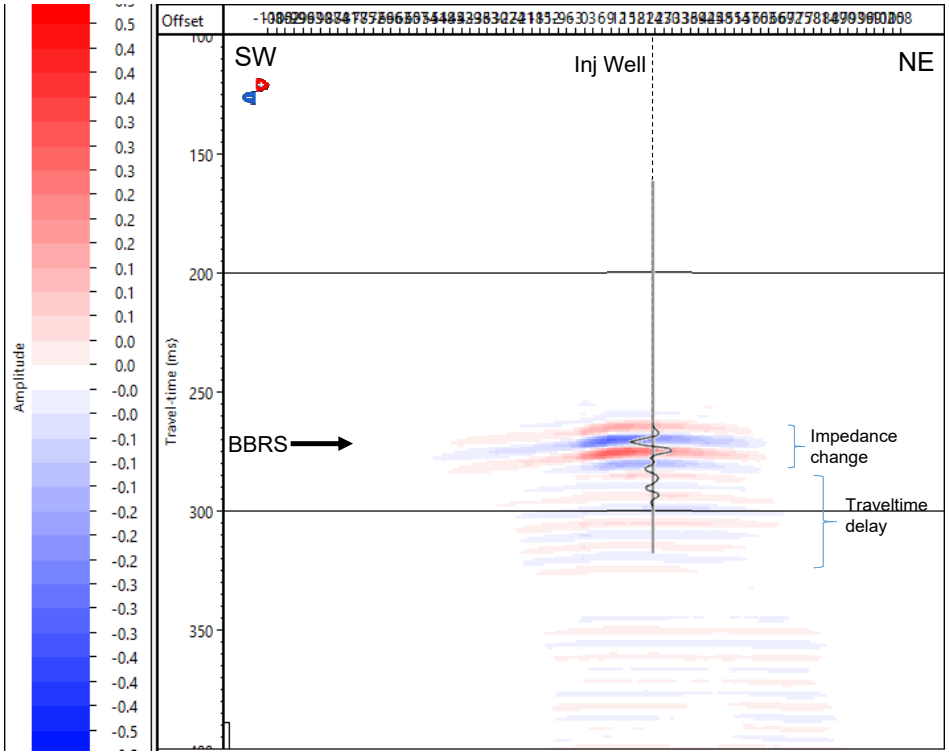
- Matlab VSP forward model (created by Marie Macquet using CaMI.FRS reservoir modeling by Seyed Jafari Raad)
- 29t (4 year) anomaly has radius ~25m, diameter ~50m
- Diffuse edges, resolution limits, noise, will complicate delineation of plume.
- Higher fold at zero offset causes asymmetrical amplitude distribution (for symmetrical anomaly)



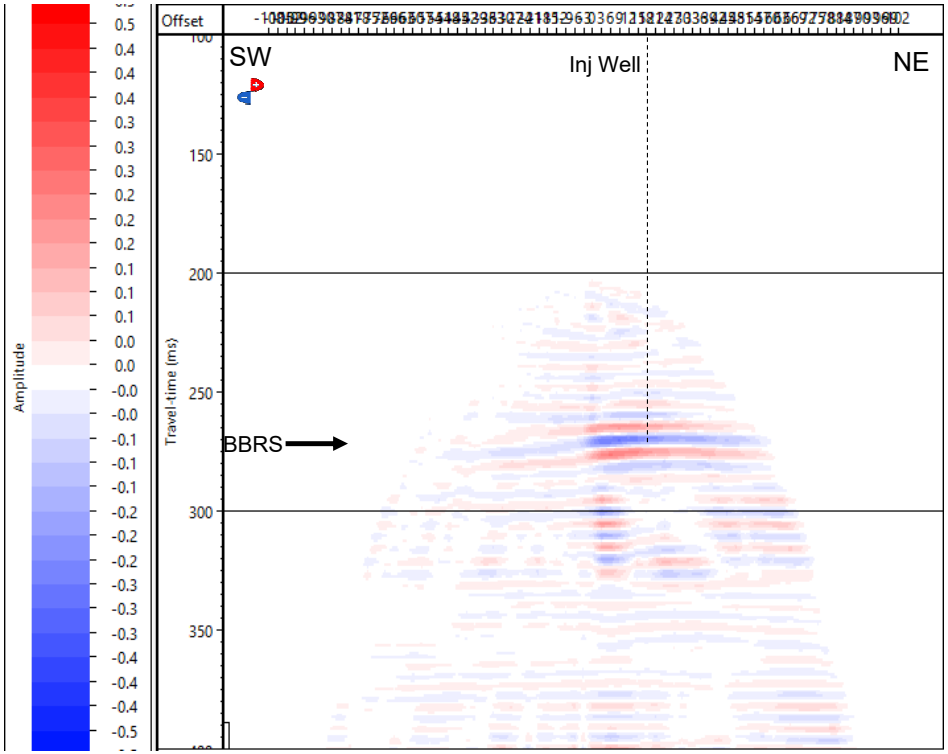
Forward modeling effects that may obscure the CO_2 anomaly

- Two-way time delay from ~5% average velocity reduction = 0.2ms
- Concern: After static corrections, monitor and baseline first breaks differ within +/- 0.25ms
- Random static errors of +/- 0.25ms do not significantly affect the synthetic anomaly, +/- 0.5ms begin to cause significant residuals. Filtering the monitor dataset also introduces residuals.

Synthetic time-lapse section



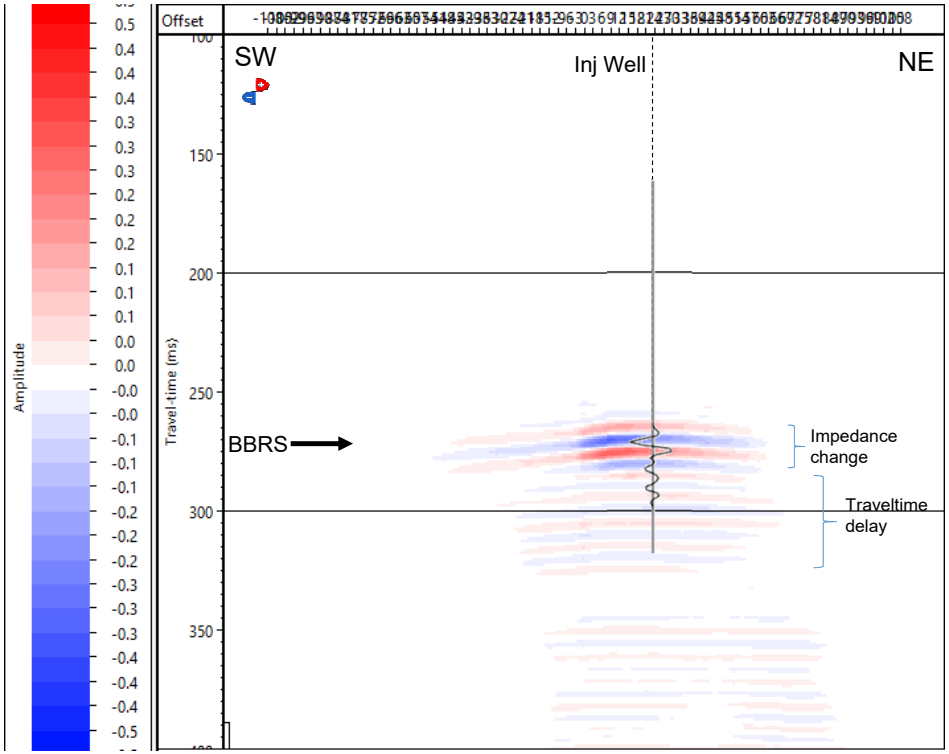
Synthetic with +/-0.5ms random static errors, high cut filter to trim ~5Hz off the high frequency range



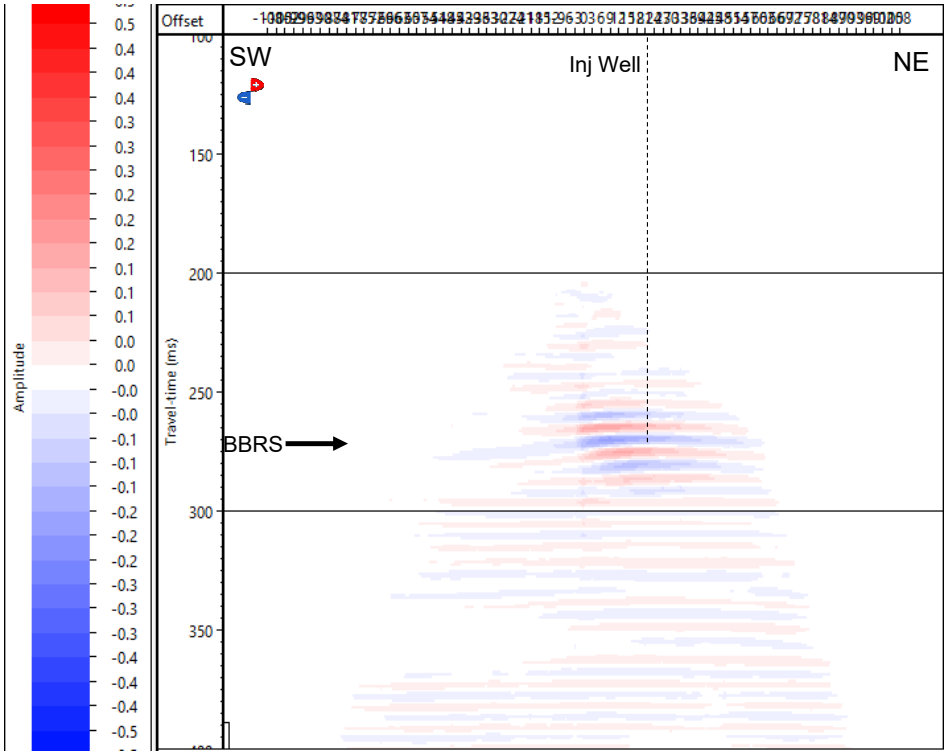
Shaping filtering ‘noisy’ monitor data does weaken the anomaly

- Shaping filter, resolved much of the artificial residuals, but also negatively affected the anomaly’s amplitude
- This indicates that in real data, the anomaly may be negatively affected by the shaping filter

Synthetic time-lapse section



Synthetic with static errors, 5Hz frequency difference, & shaping filter applied



Standard VSP workflow pared down to essentials

- 3-component data rotation removed (1C only)
- 2 mean-scaling steps removed
- Exponential gain, f-k filter, median filter removed from stack process
- RMS amplitude normalization removed from cross-equalization (no longer necessary)

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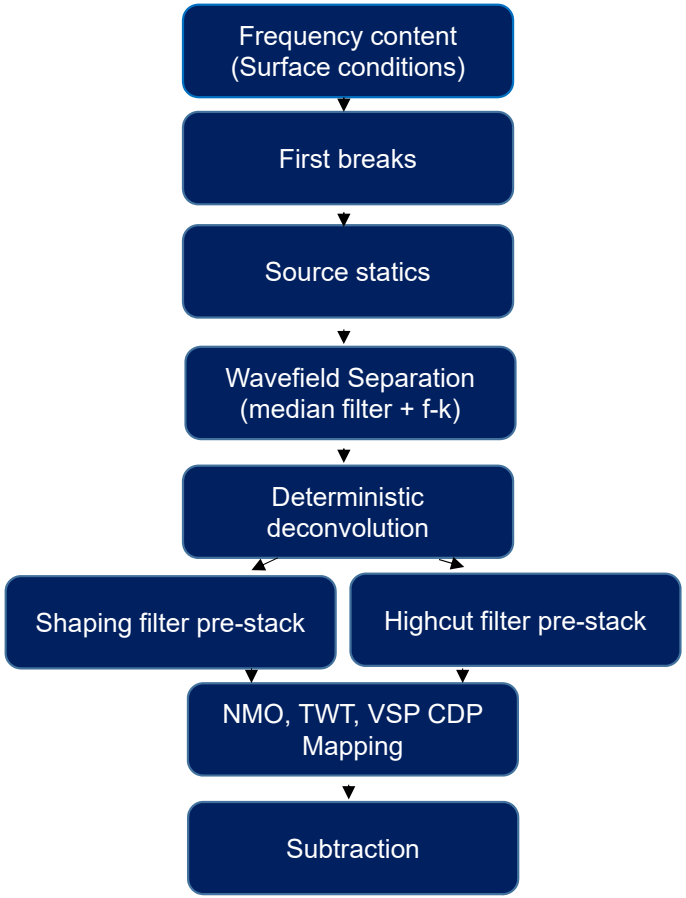
- Simple, efficient workflow without unnecessary amplitude alterations



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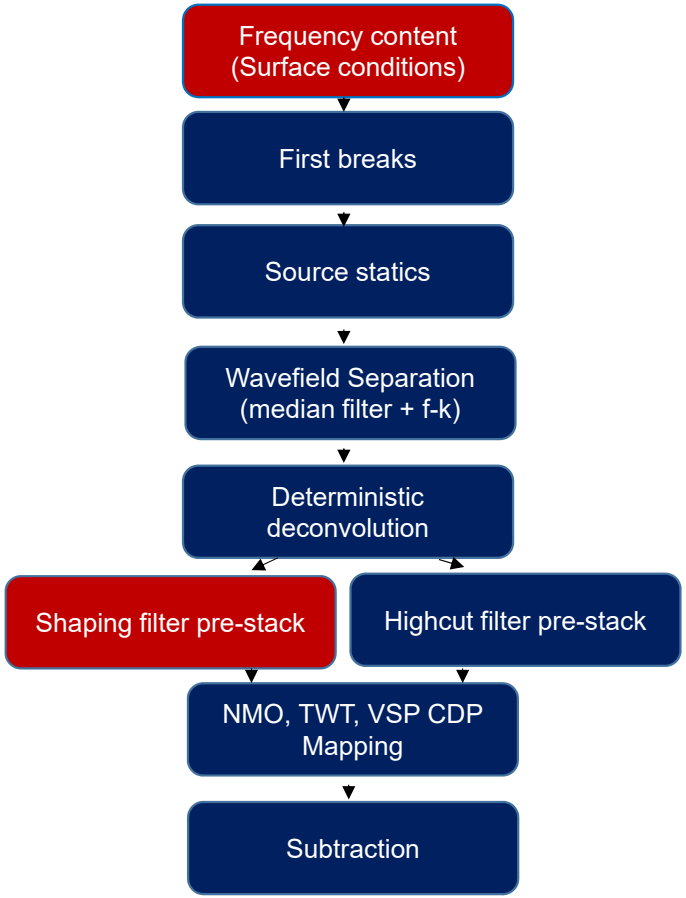
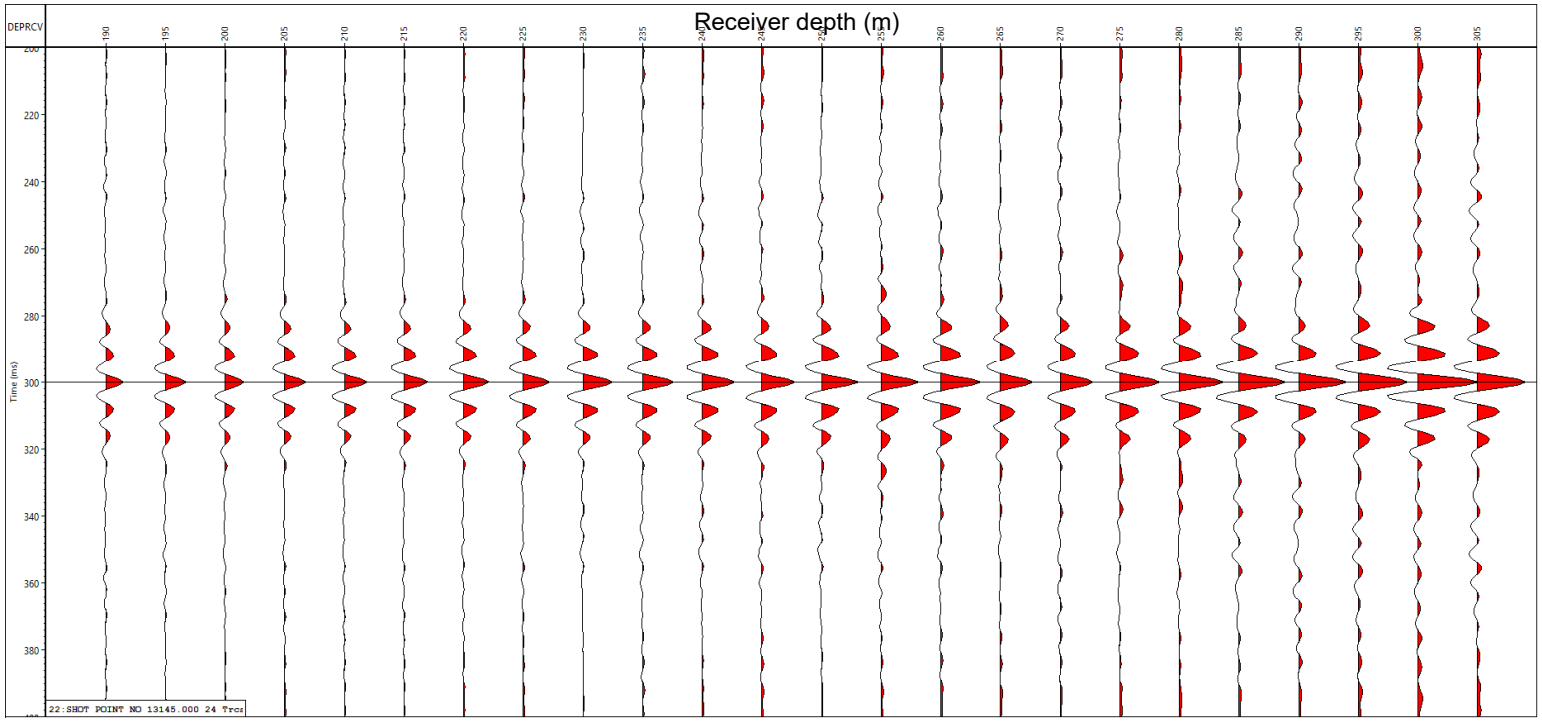
- RMS amplitude normalization removed from cross-equalization
- Simple, efficient workflow without unnecessary amplitude alterations
- Surface conditions and shaping filter introduce uncertainty



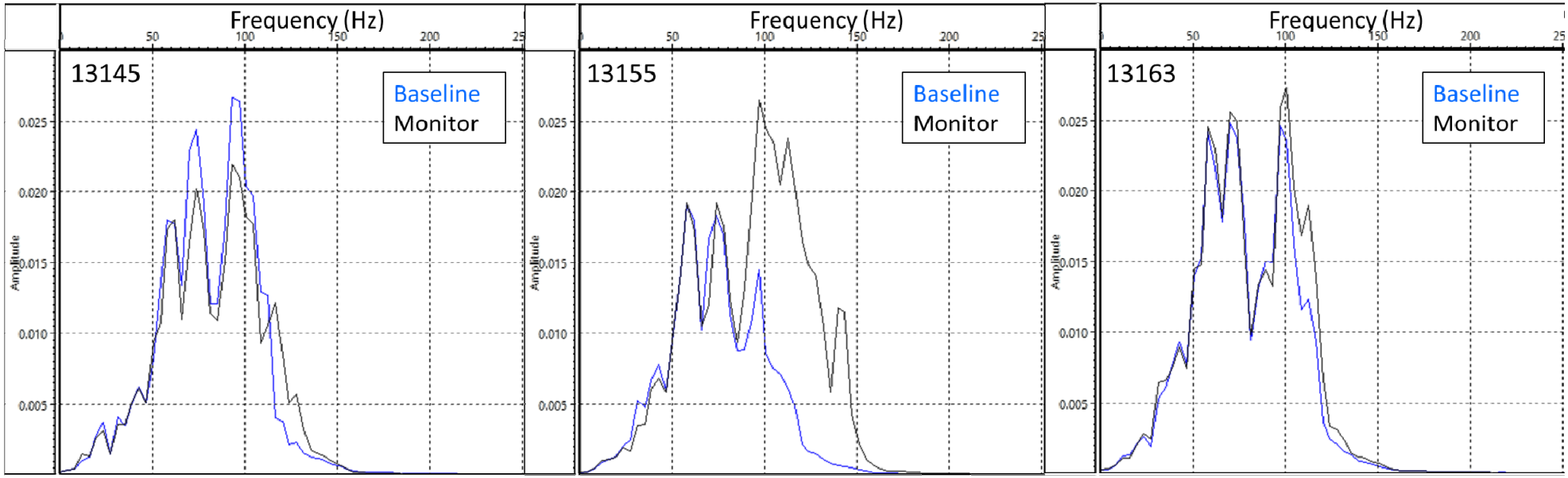
Deconvolution corrects for amplitude differences

- No scaling applied prior to deconvolution
- Deconvolution operator contains information about: filtering by the near surface (weather-related), spherical divergence, attenuation, and transmission loss.
- All major scaling needs are achieved in one step during deterministic deconvolution, except additional spherical divergence of reflected arrivals (t^1 correction) and remaining effects of near-surface filtering



Simplified workflow yields directly comparable amplitudes

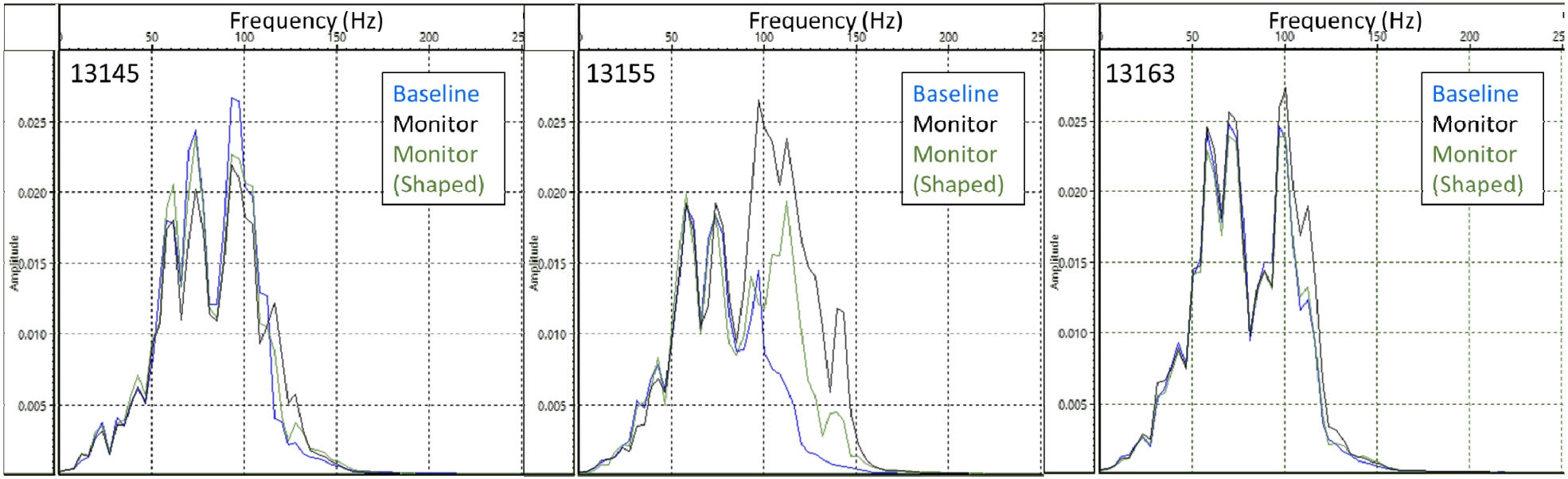
- Deconvolved shot gathers have directly comparable, normalized amplitudes up to 80Hz on average
- Remaining differences caused by different near-surface filtering between datasets, as well as CO2
- Deconvolution can not fully reverse major attenuation and band-limiting effects of near-surface
- Cross equalization required to reduce time-lapse residuals



CO_2 effect on reflectivity | Major near-surface filtering | Minor near-surface filtering

Shaping filter is an imperfect solution to spectrum differences

- Shaping filter acts as a least-squares solution to spectrum differences (Al-Mutlaq and Margrave, 2011)
- Shaping filter unavoidably alters CO2-related amplitude differences
- Minor spectrum differences were resolved easily (13163), major differences were not (13155)



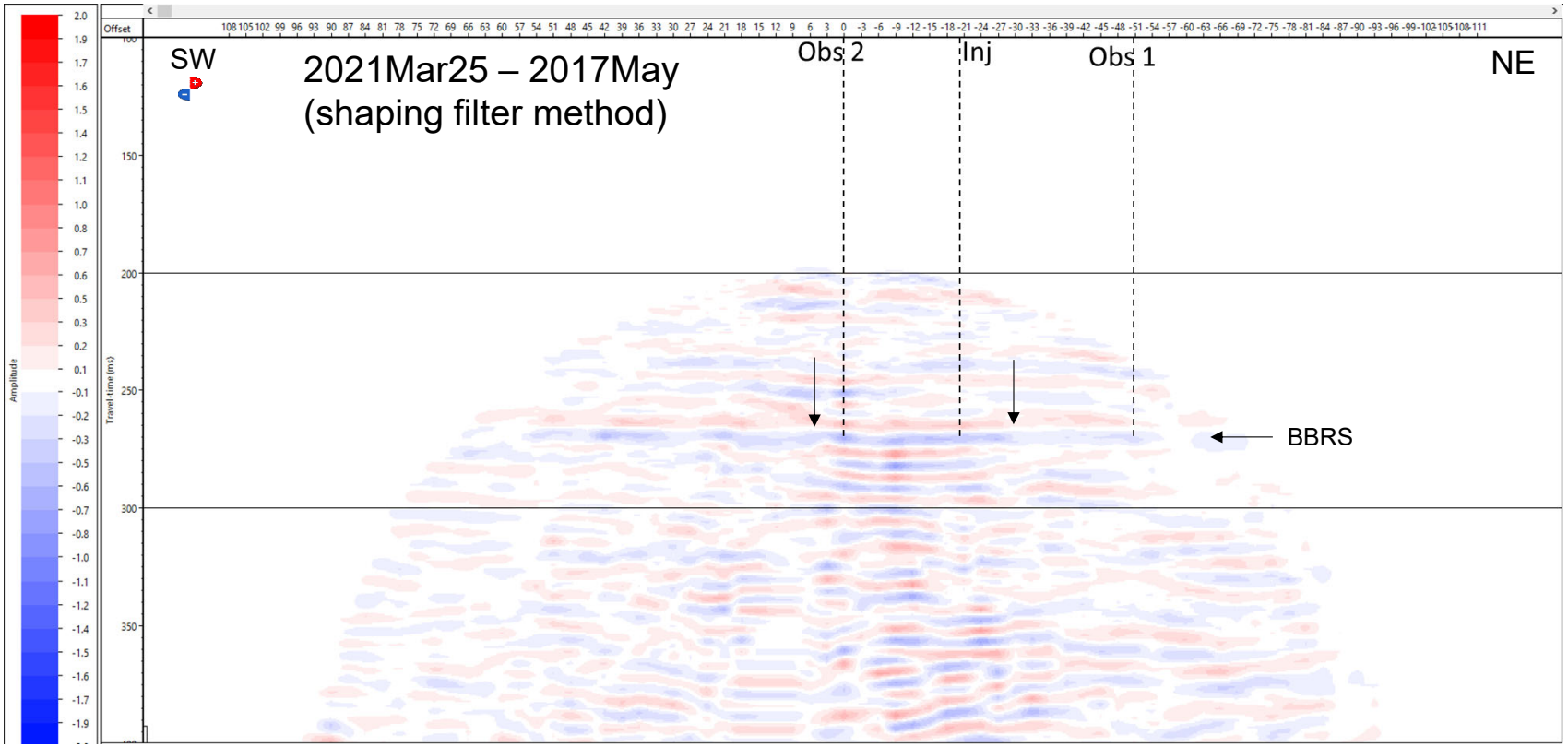
CO_2 effect altered

Residuals remain after shaping filter

Shaping filter very successful

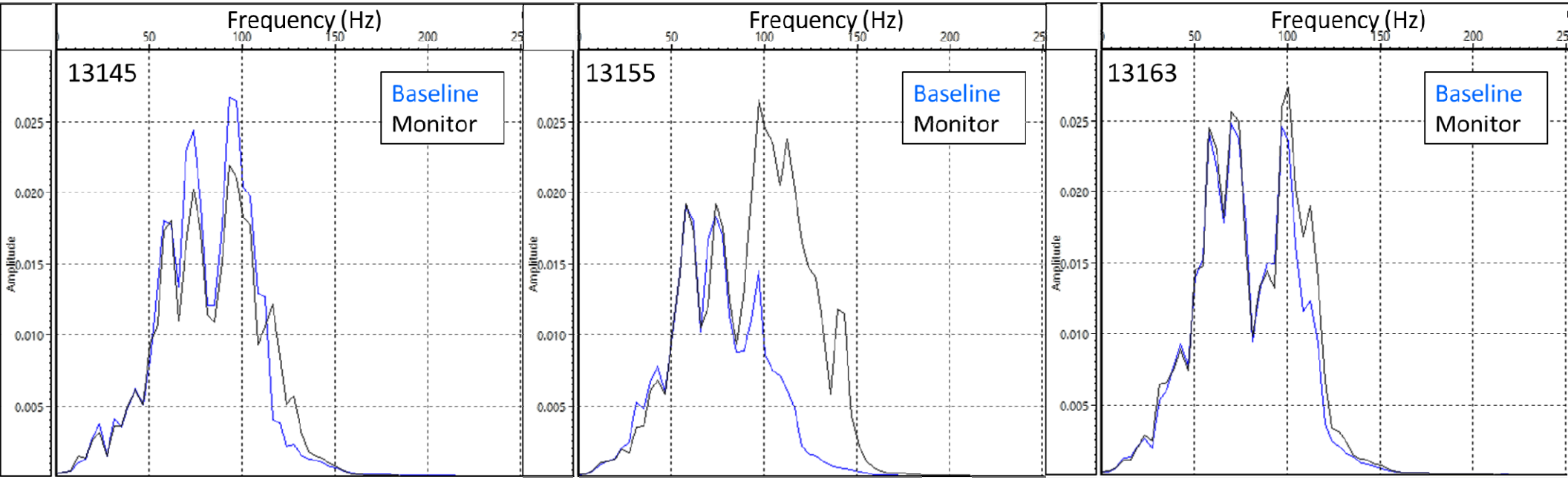
Shape-filter cross-equalization yielded weak CO_2 anomaly

- 2021 March 25th – 2017 May time-lapse showed probably CO2 anomaly weakly standing out from background
- Residuals below BBRS too strong to be travel-time delay anomaly



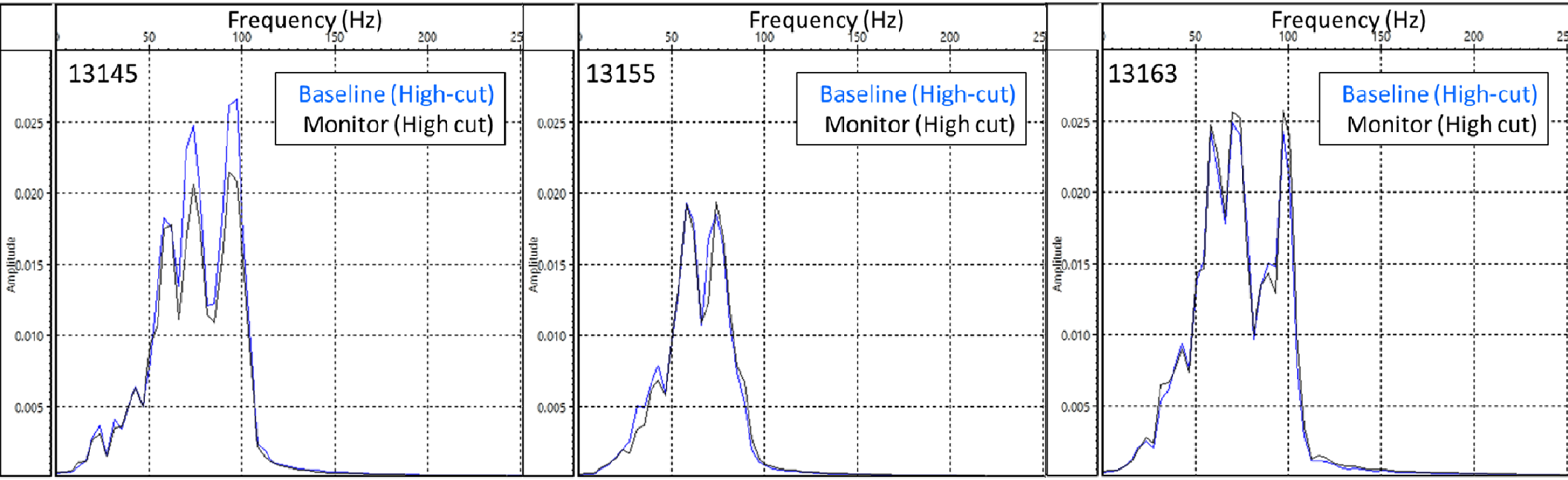
High-cut filter preserved relative amplitudes while limiting bandwidth

- Highcut filters applied to retain frequency bands where amplitudes appeared to match



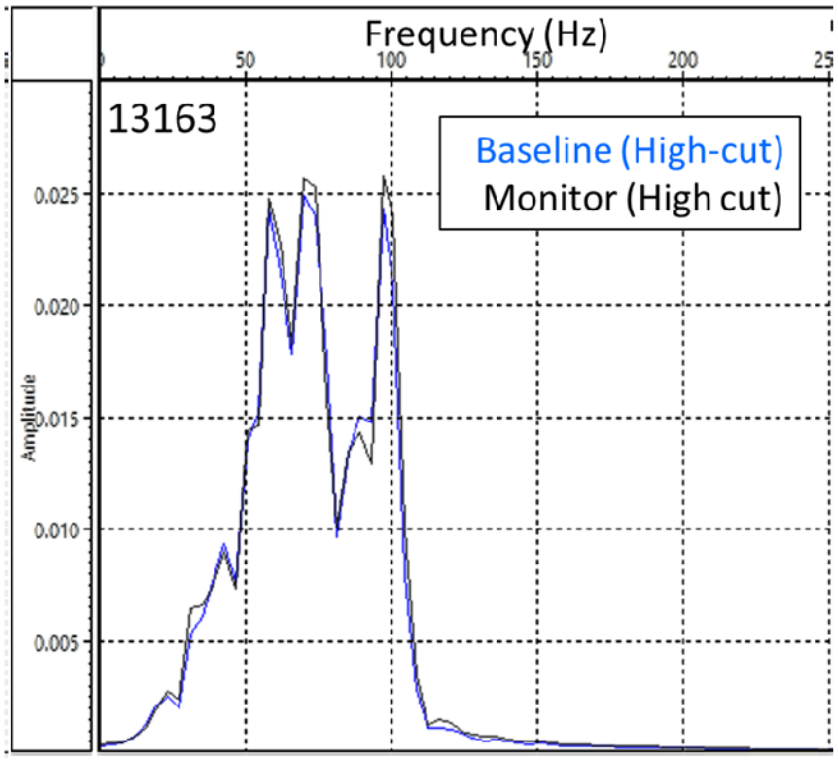
High-cut filter preserved relative amplitudes while limiting bandwidth

- Highcut filters applied to retain frequency bands where amplitudes appeared to match
- High frequency data from March 1st, 2021 was easiest to filter down
- Resulted in excellent matches between shot gathers, at the cost of bandwidth

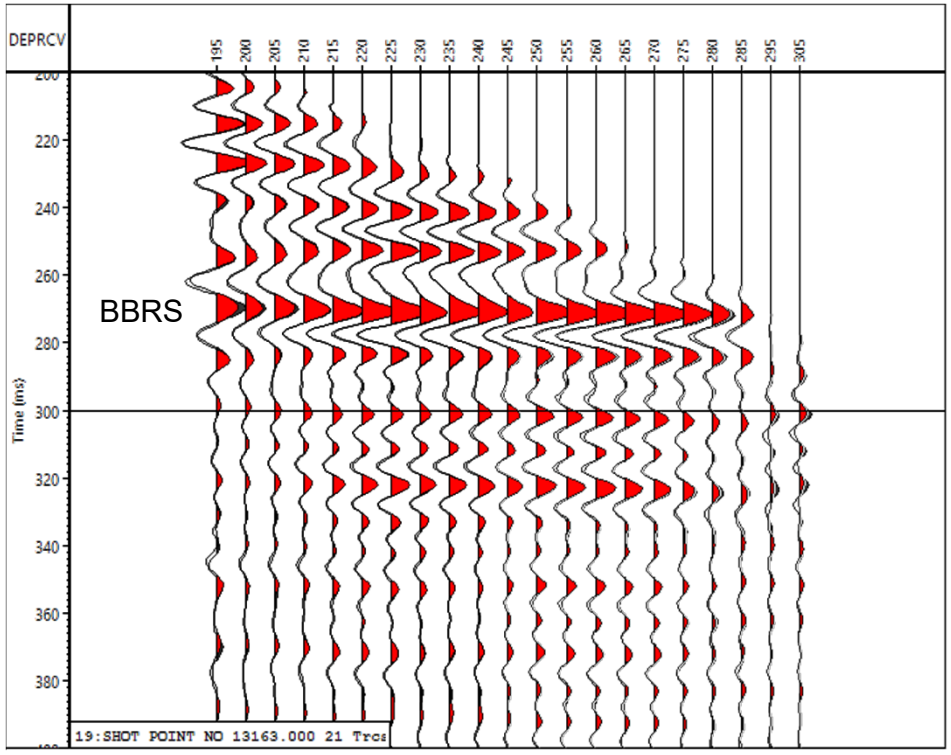


Shot gathers were very similar after high-cut filtering

- Baseline (black) and monitor (red) shot gathers matched very well after simple high-cut filtering



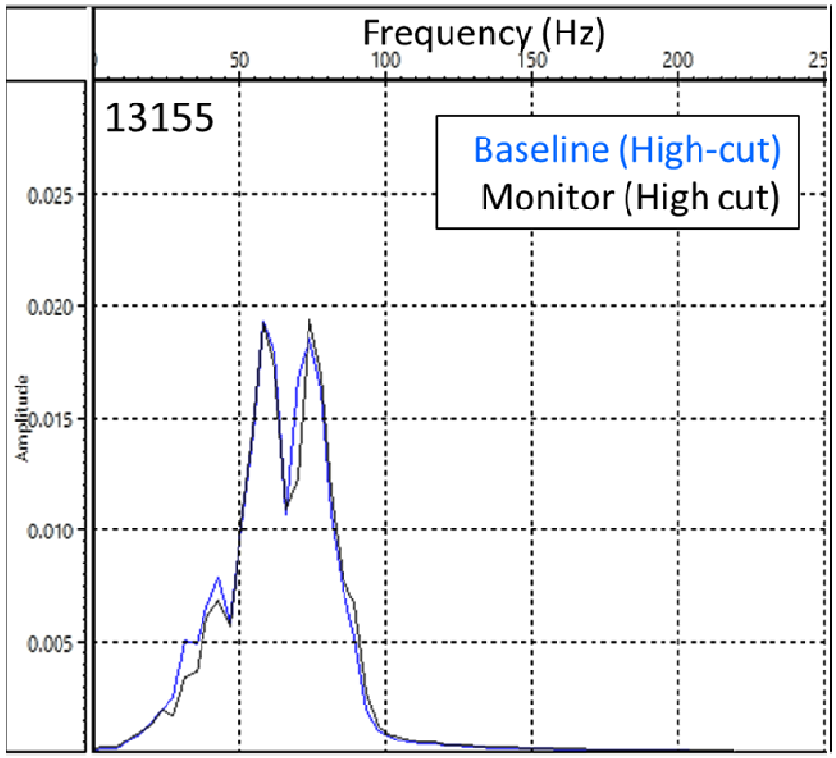
Shot 13163 Average Spectrum



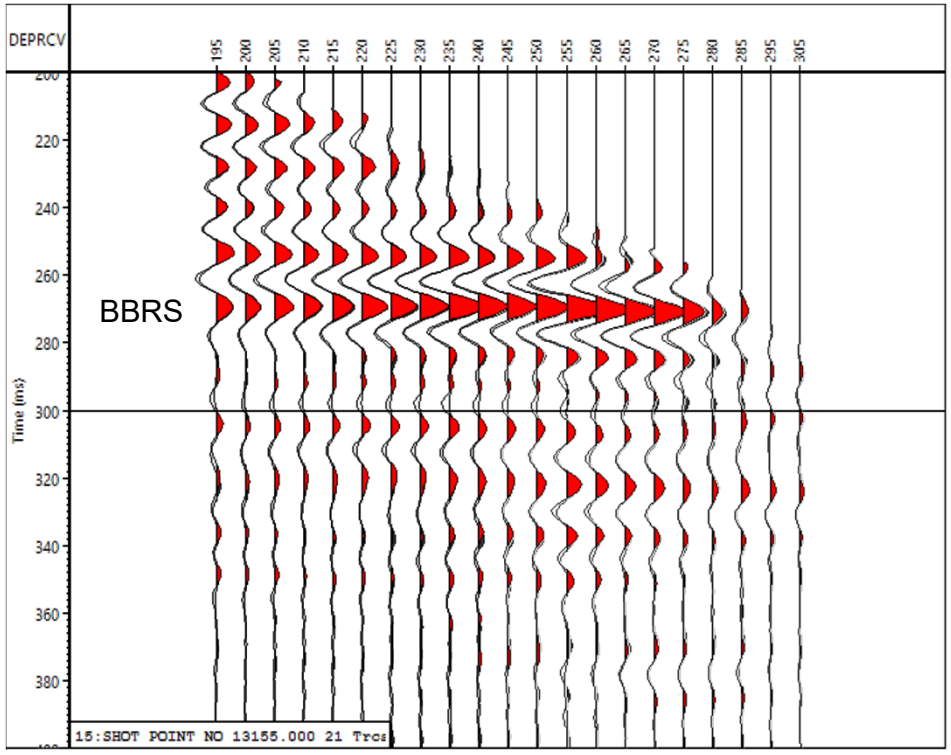
Shot 13163 matches nearly exactly

Shot gathers were very similar after high-cut filtering

- Baseline (black) and monitor (red) shot gathers matched very well after simple high-cut filtering
- Previously mismatched shots did not need to be removed



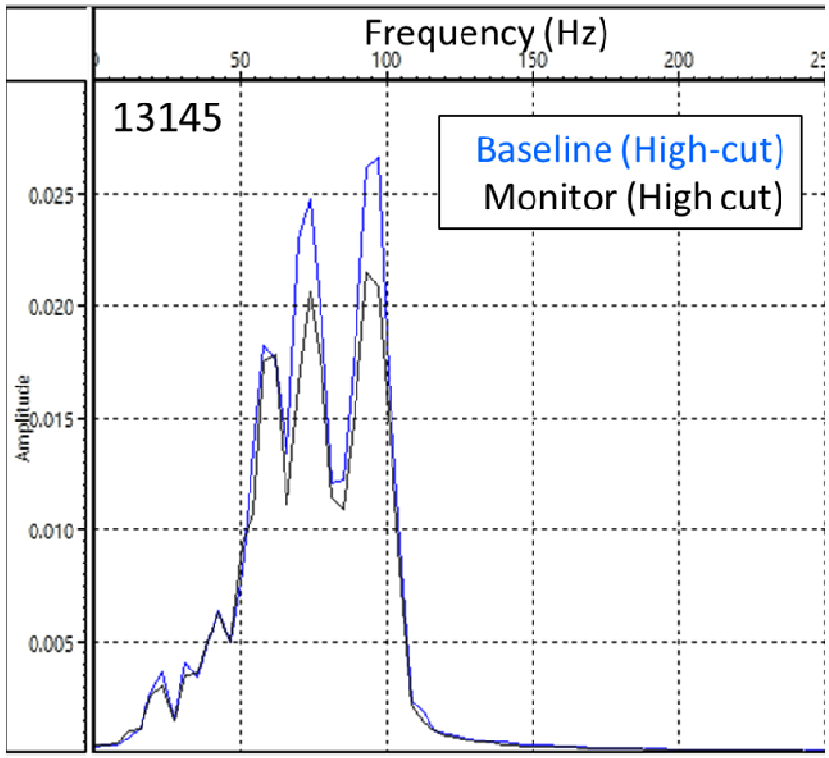
Shot 13155 Average Spectrum



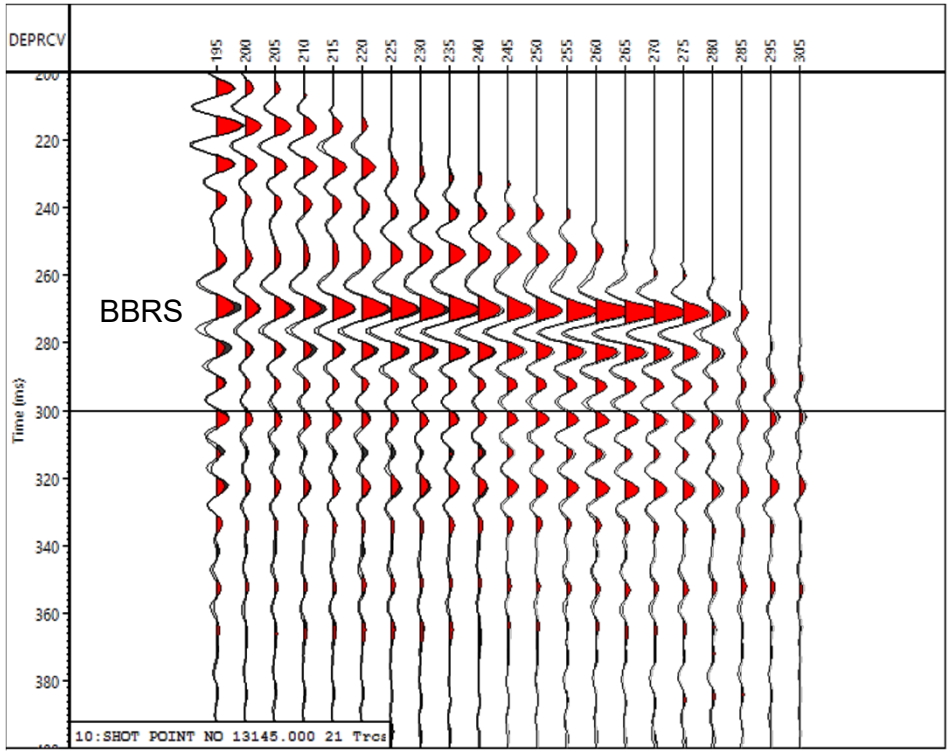
Shot 13155 has more limited bandwidth but matches well

Shot gathers were very similar after high-cut filtering

- Baseline (black) and monitor (red) shot gathers matched very well after simple high-cut filtering
- Previously mismatched shots did not need to be removed
- Similar shots retained most of their frequency content



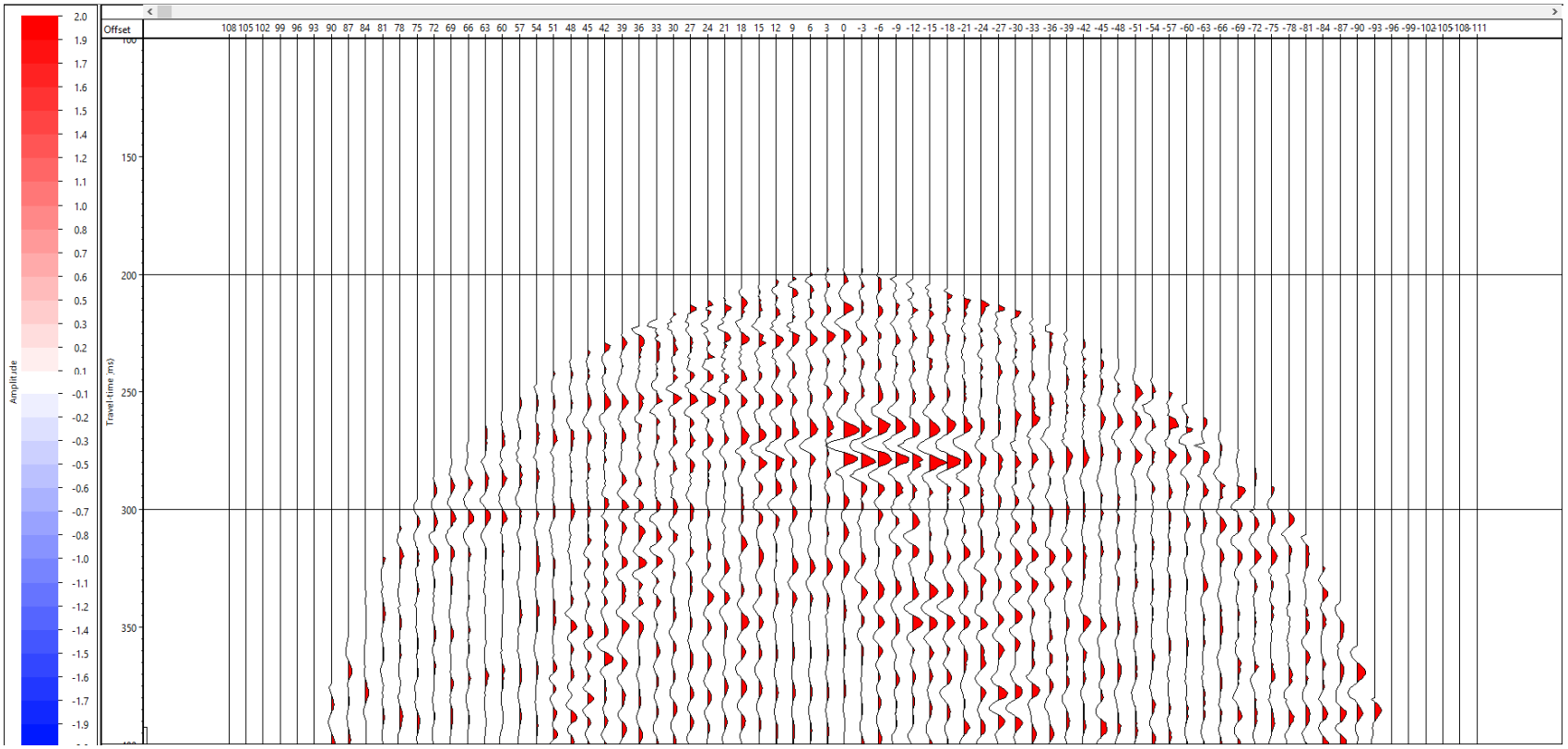
Shot 13145 Average Spectrum



Shot 13145 showing CO2 amplitude reduction at BBRS

High-cut method produced strong CO2 time-lapse anomaly

- Time-lapse anomaly clearly evident in stacked data



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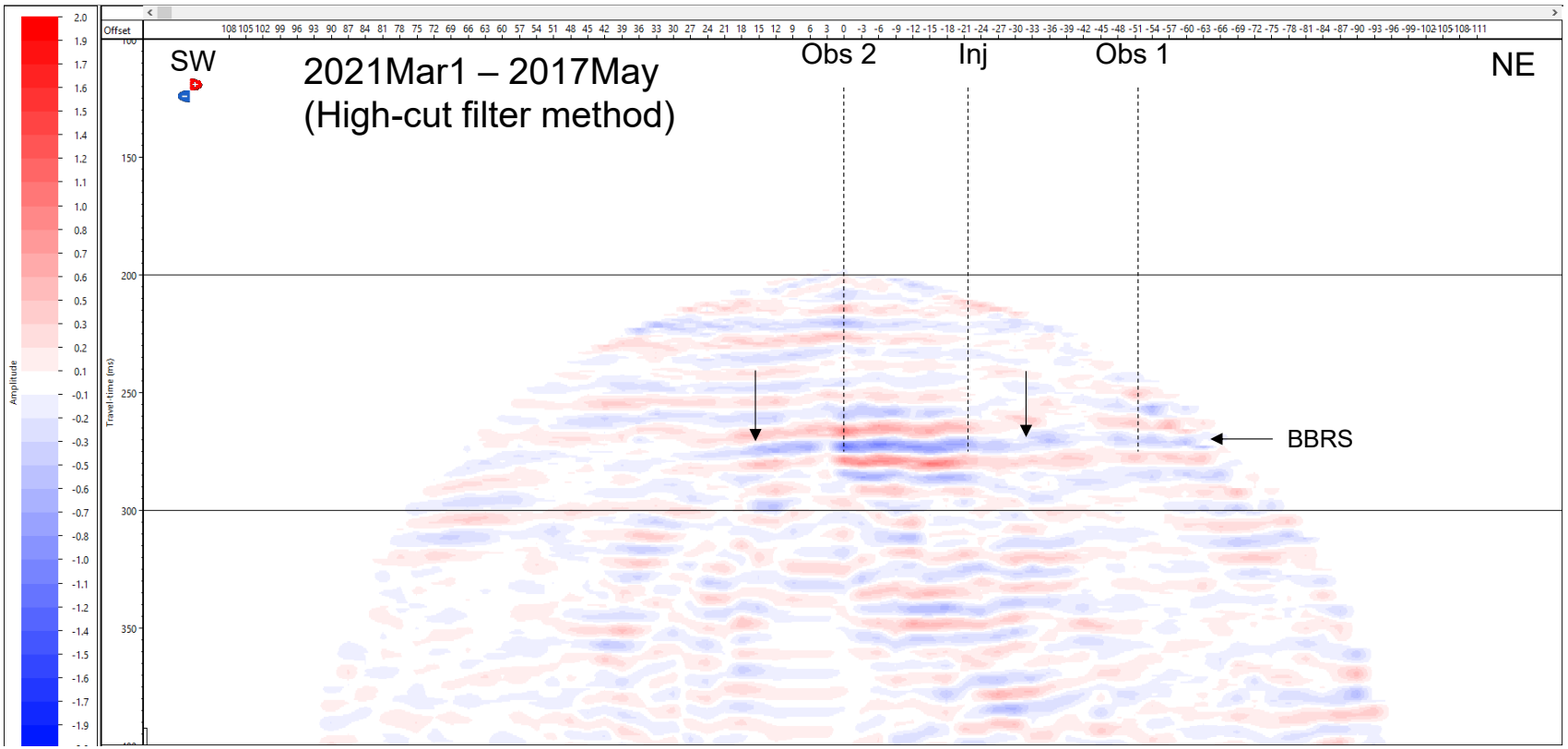
- Time-lapse anomaly clearly evident in stacked data
- 33t CO2 anomaly interpreted to be 45m-51m in lateral extent, consistent with expectations from modeling



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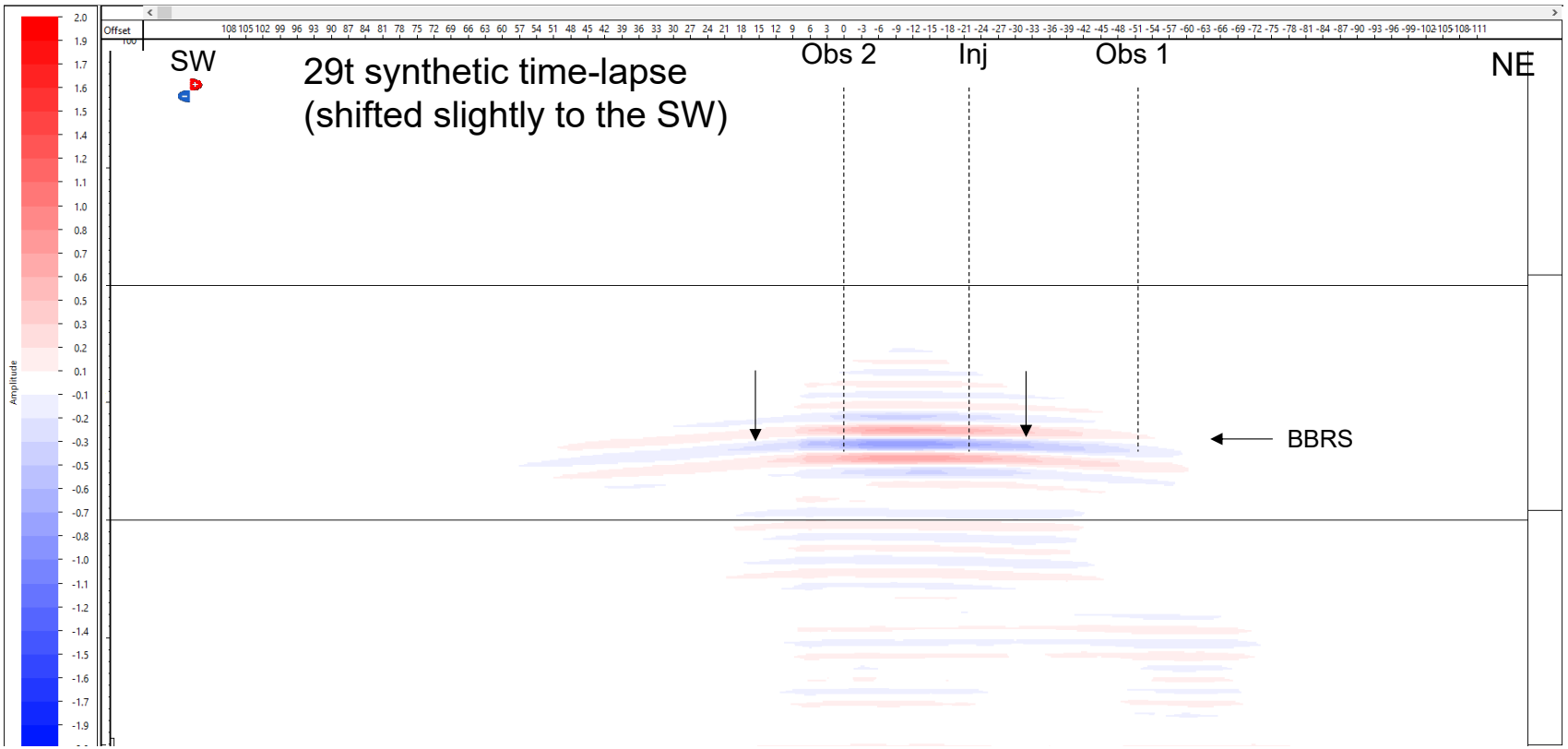
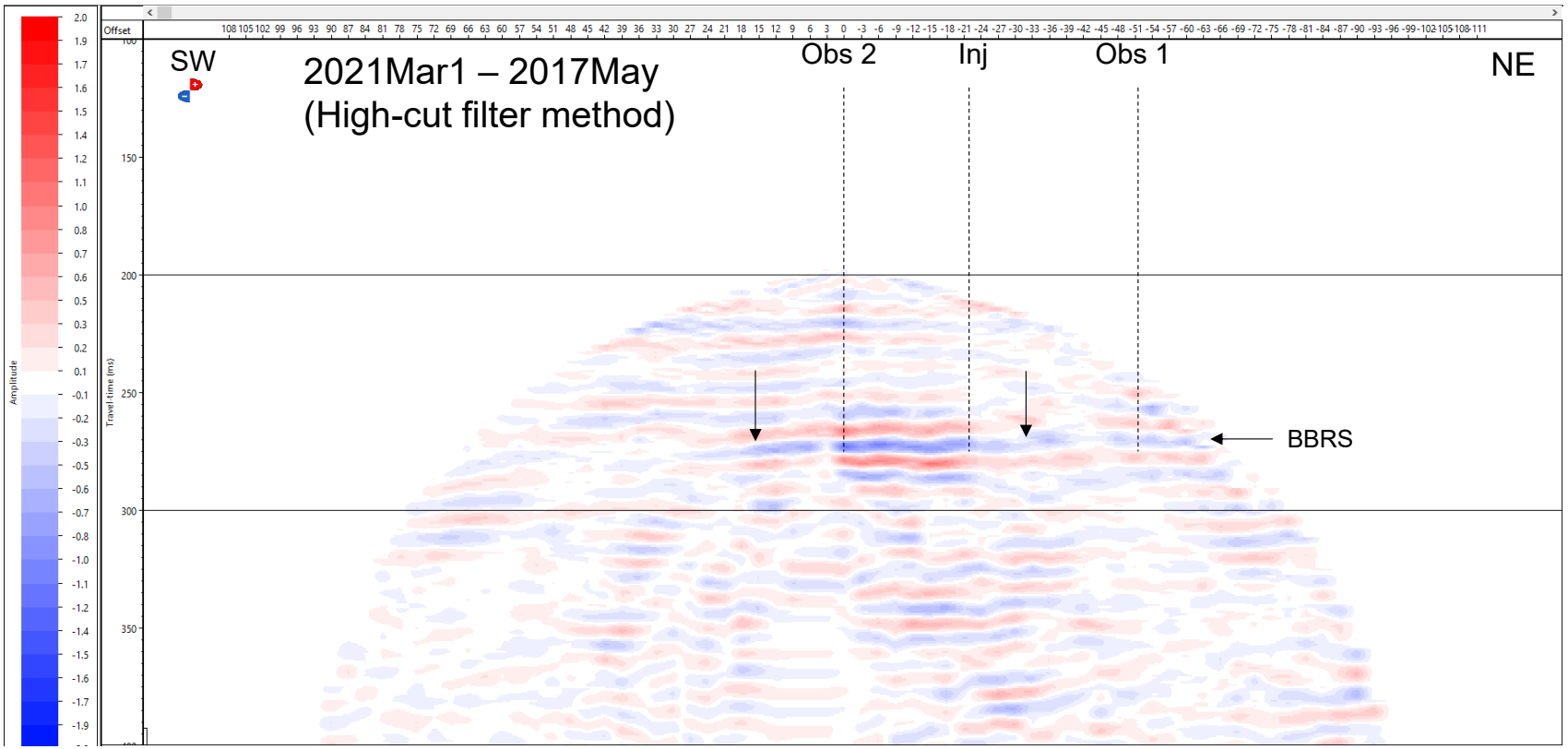


High-cut method produced strong CO2 time-lapse anomaly

- 33t CO2 anomaly is lower frequency but more distinct than shaping filter result
- Frequency and signal strength declines erratically not gradually with offset due to spatial variability in near-surface filtering effects
- Background residuals still exist, but do interfere less with interpretation



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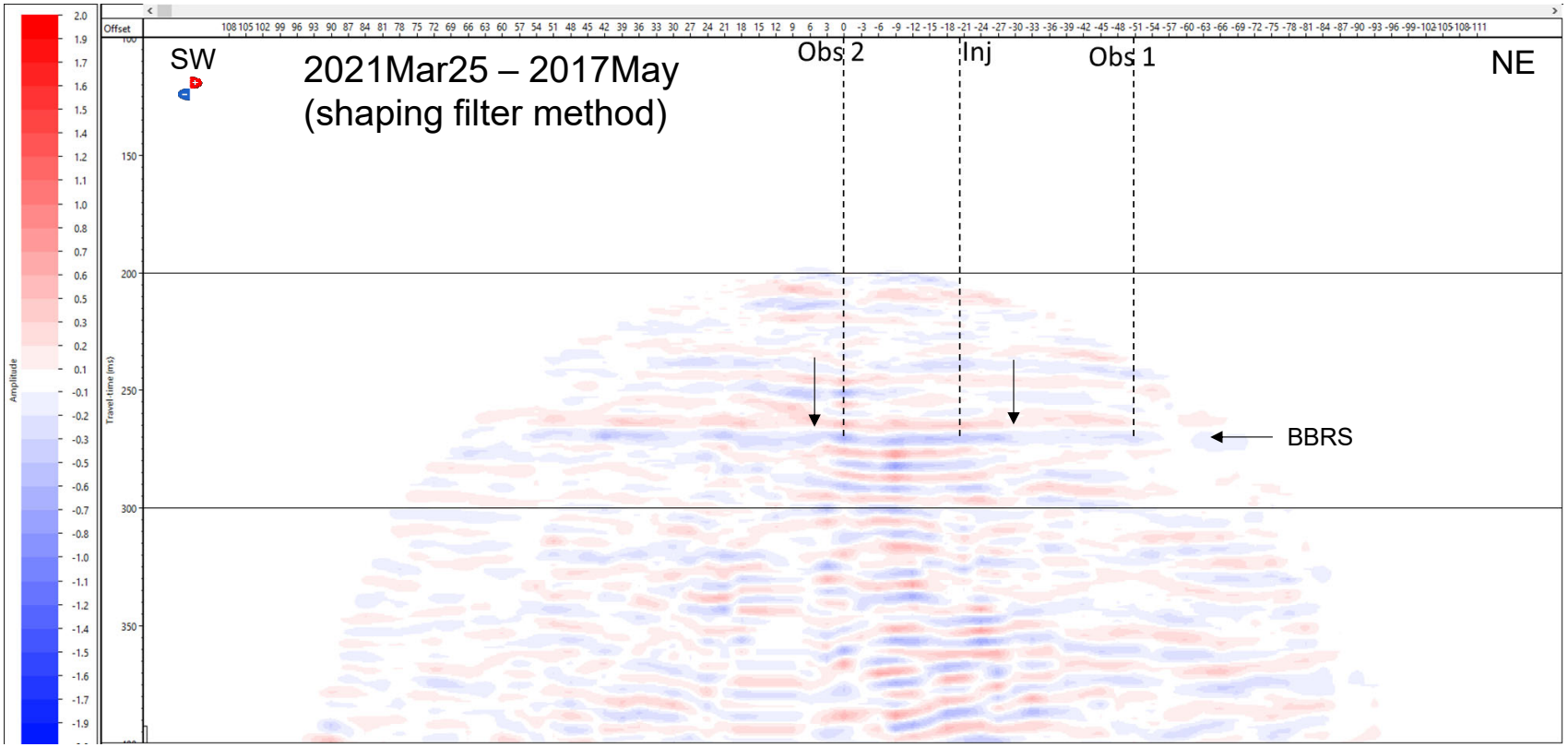

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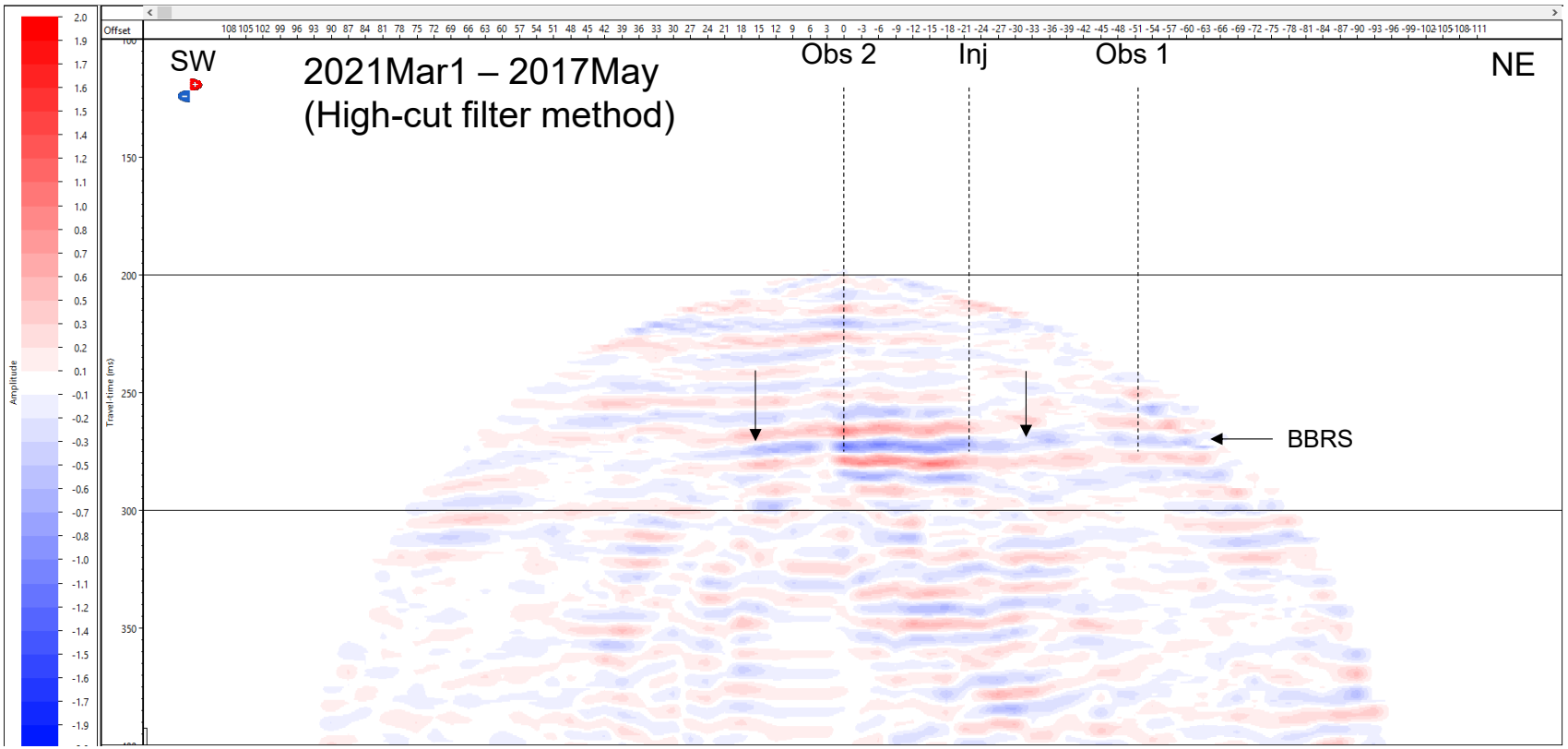

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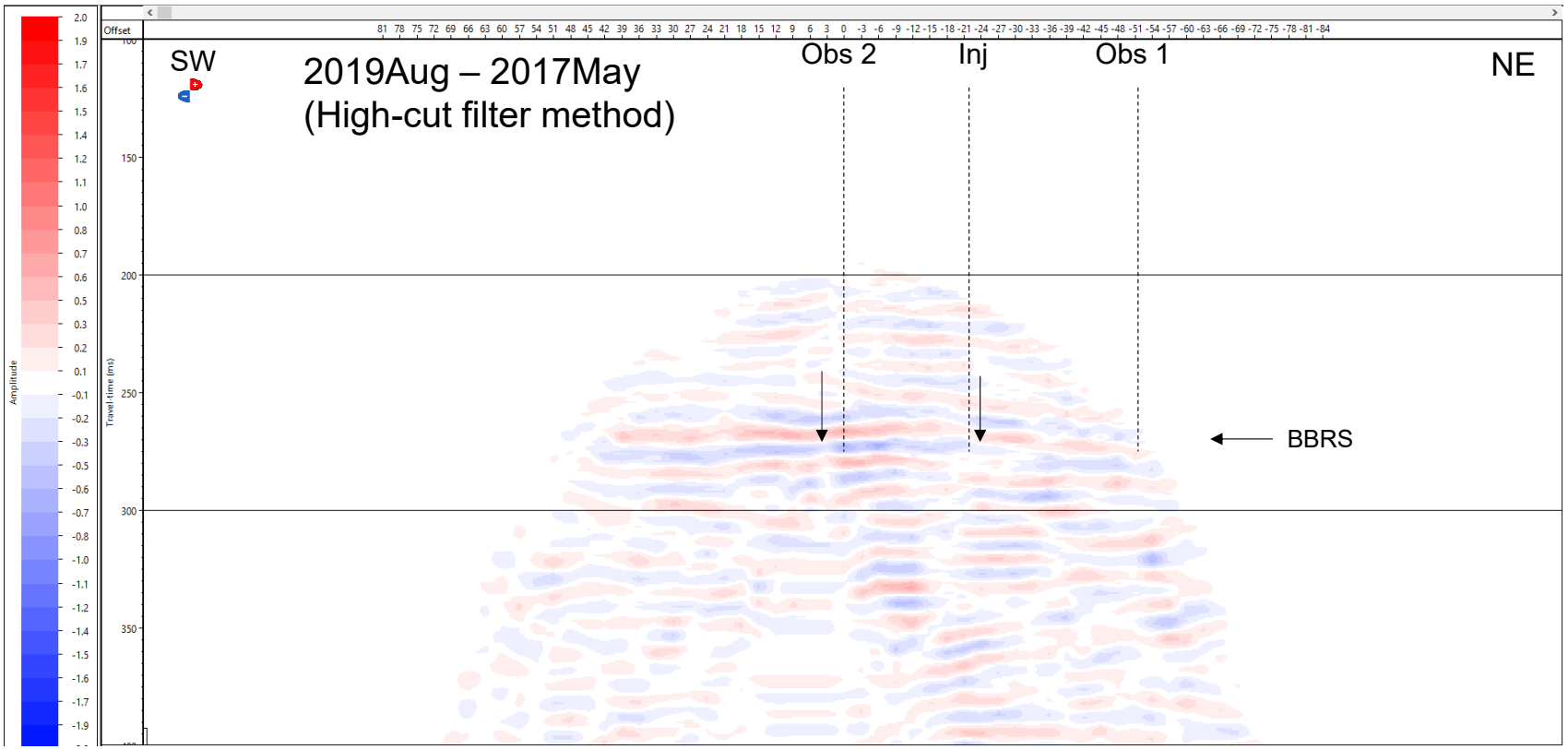
- 2019-2017 time lapse for 15t plume shows a possible anomaly, but at or below detection threshold



High-cut method produced strong CO2 time-lapse anomaly

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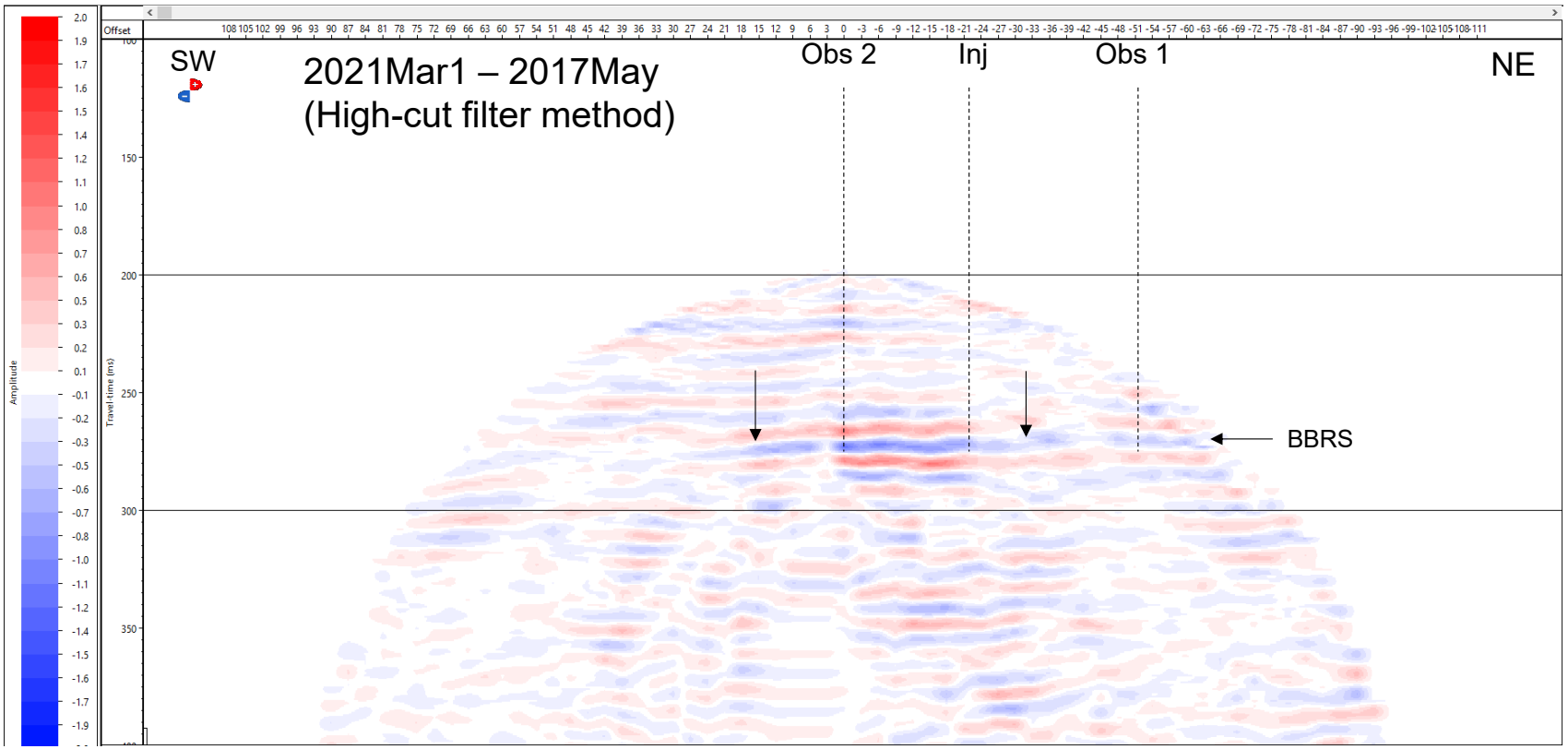
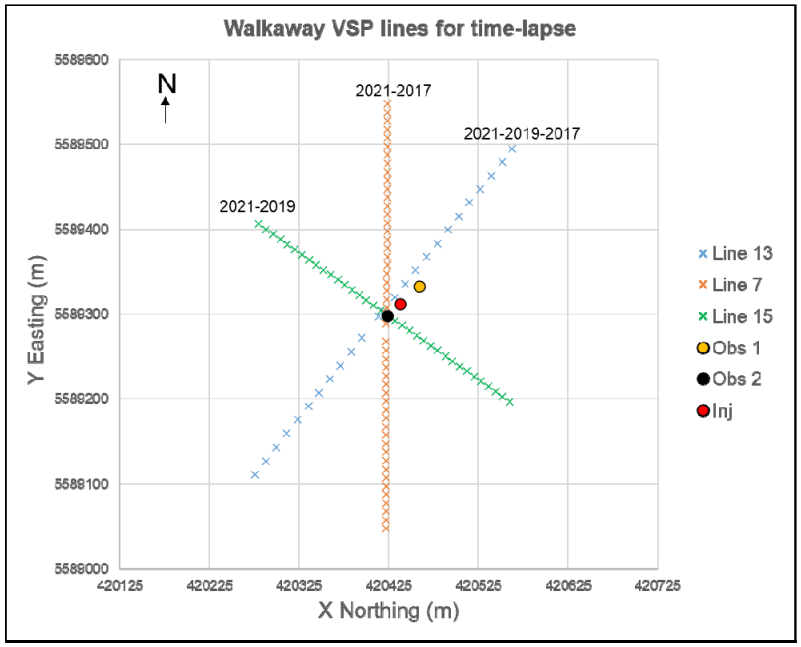
- 2019-2017 time lapse for 15t plume shows a possible anomaly, but at or below detection threshold
- CO2 not yet detected at Obs 1 well, supporting interpretation of asymmetric plume around Inj well



Conclusions

- 33t CO2 plume detected with time-lapse VSP, detection threshold established for 10% porosity 300m deep reservoir
- Time-lapse compliant workflow developed for CaMI.FRS data
- Avoided unnecessary scaling and filtering, relying on deterministic deconvolution
- Processed amplitudes were directly comparable
- High cut filters preserved effects of CO2 plume on seismic
- 1-component workflow can be applied to Line 7 and 15 to better delineate plume
- Time-lapse workflow can be adapted to DAS in Obs 1&2
- High confidence result achieved with careful processing and high repeatability – detection of CO2 leaks *early* is not trivial



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