Raypath Interferometry
for “fun” and “profit”

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Outline

- What is raypath interferometry?
  - ***Nonstationary*** near-surface correction
- Raypath interferometry, ***mostly*** for ***'fun'***
  - ***Successful application to 2D data***, both PP and PS
    - MacKenzie Delta PP
    - Hussar PS
  - ***Extension to 3D data***, both PP and PS
    - Blackfoot PP example
- Raypath interferometry, ***partly*** for ***'profit'***
  - ***Serendipitous discovery*** of 4D seismic application
    - Elastic modeling example
    - Violet Grove field example
- Remarks

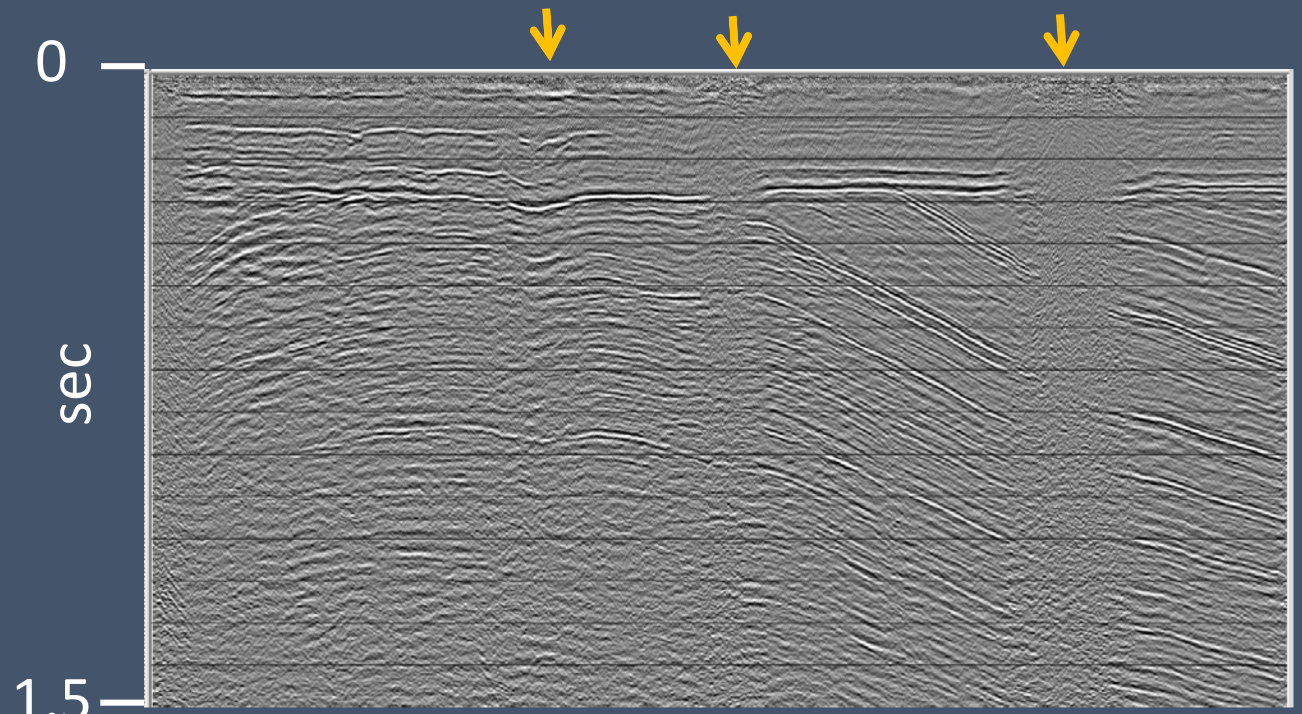
What is raypath interferometry?

- Applies ***nonstationary near-surface corrections*** to seismic data
- Static corrections ***assumptions are generalized***
  - ***Surface-consistency*** constraint generalized to ***'raypath-consistency'***
  - ***Single arrival*** constraint generalized to ***'arrival distribution'***
- ***Raypath consistency*** requires transforming X/T data to ***'raypath domain'***
- ***'Arrival distribution'*** requires ***deconvolution*** for removal, rather than simple ***time shift***
- 'Arrival distributions', or ***'surface functions'*** are estimated and removed by an ***interferometric*** process

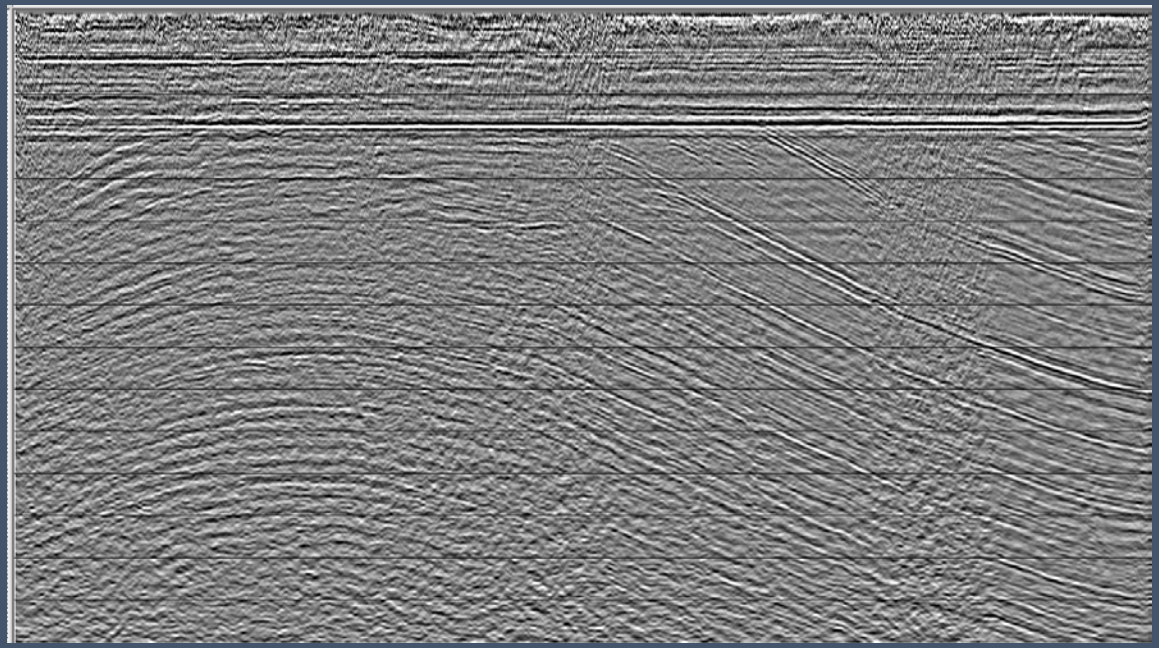
‘Fun’: MacKenzie Delta example

- High velocity near-surface layer (permafrost)—***violates surface-consistency***
- Surface river channels with abrupt edges—multi-path arrivals ***violate single-arrival assumption***

MacKenzie Delta PP



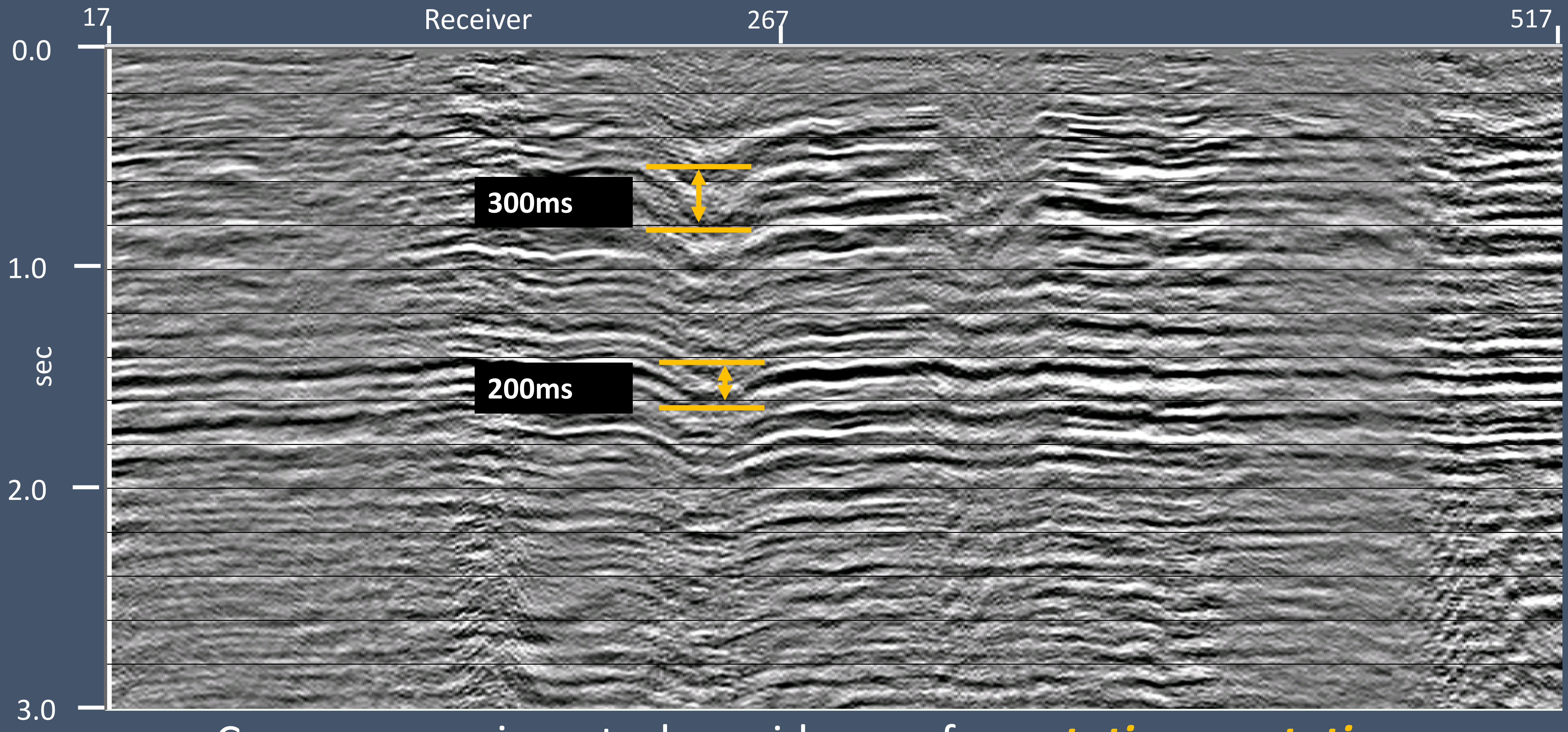
Brute CMP stack—***no statics***



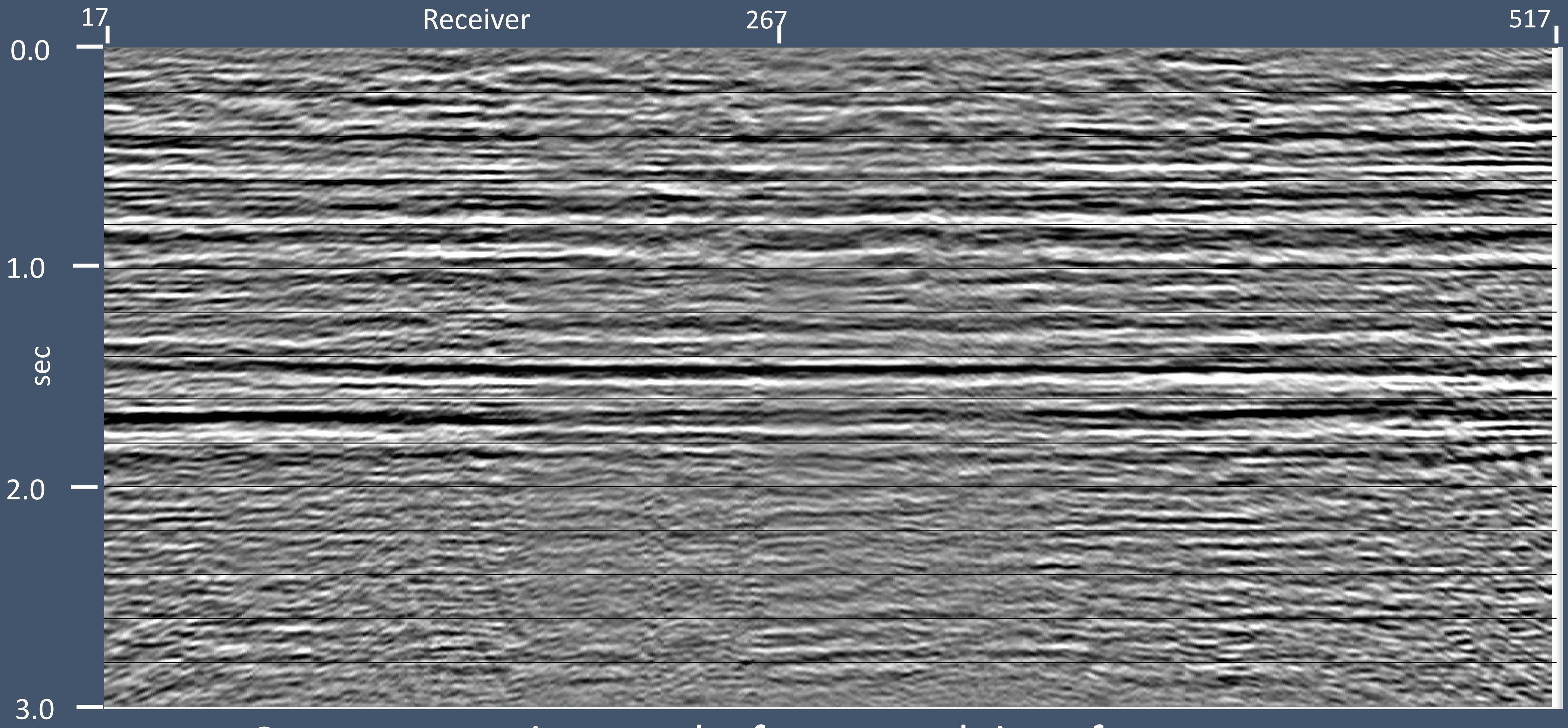
CMP stack—***raypath interferometry***

‘Fun’: Hussar PS example

- Large near-surface variations in S-wave transit time
  - Revealed on common-receiver stacks
- Apparent ***nonstationarity*** of required S-wave statics
  - Larger statics seen for shallow events than for deeper events for common surface location

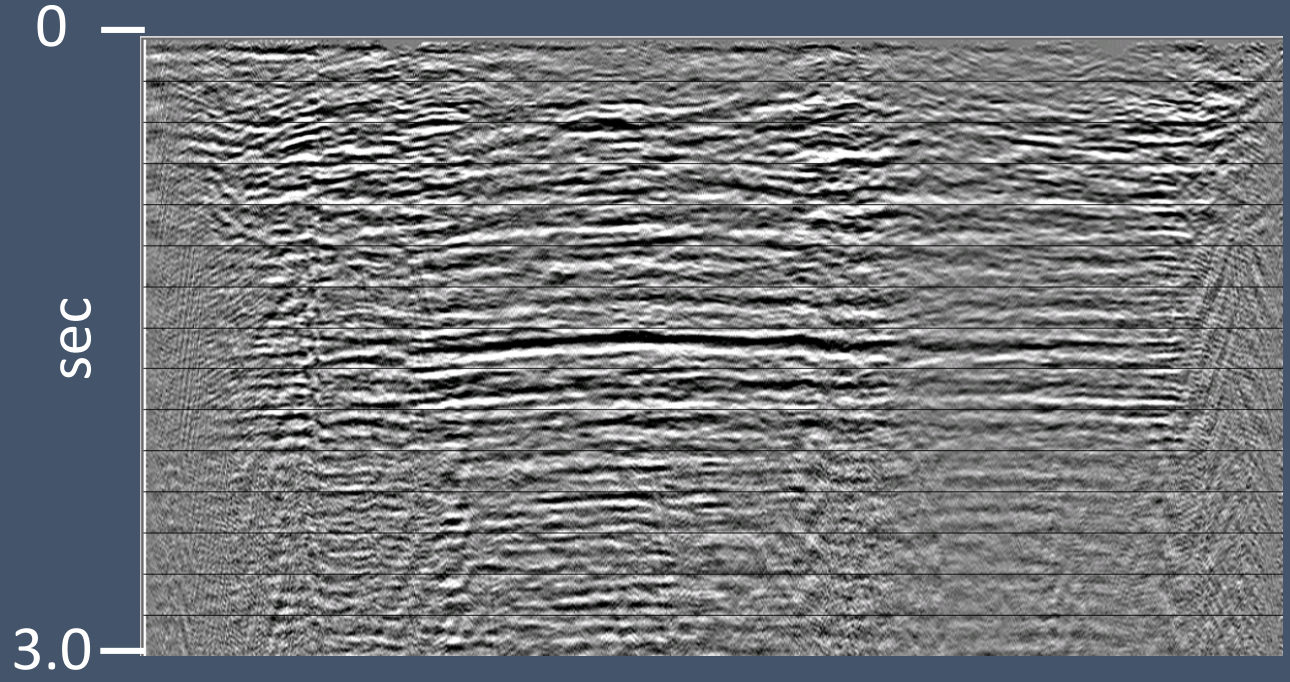


Common-receiver stack—evidence of ***nonstationary statics***

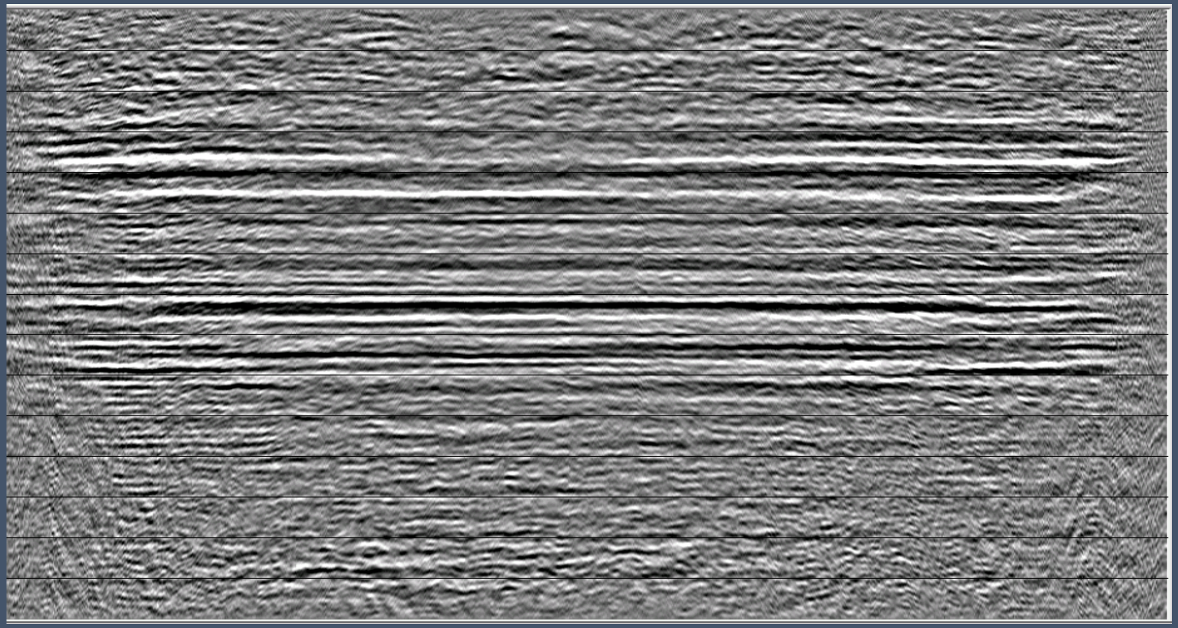


Common-receiver stack after raypath interferometry

Hussar PS



Brute CCP stack—***no statics***



CCP stack—***raypath interferometry***

Somewhat less 'fun': 3D interferometry

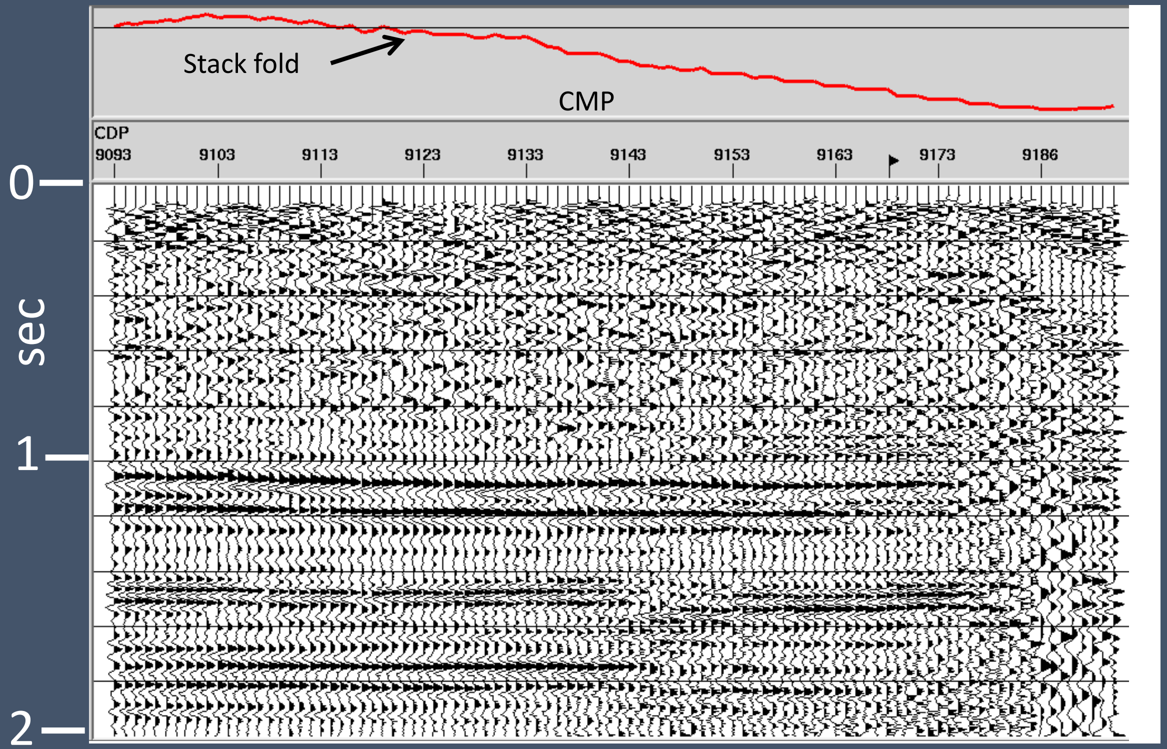
- ***3D surface functions*** required—radial geometry
- ***Sector binning*** required to gather 3D traces with cartesian geometry into appropriate ensembles
- Sector binning involves ***tradeoffs*** between trace ***population*** and ***distribution***
- 2D ***Radial Trace Transform*** ***cannot*** currently be used for X/T-raypath conversion
- 2D ***Tau-P Transform*** ***can*** be used, ***large file space required***

‘Fun’: Blackfoot 3D 3C Survey—summary

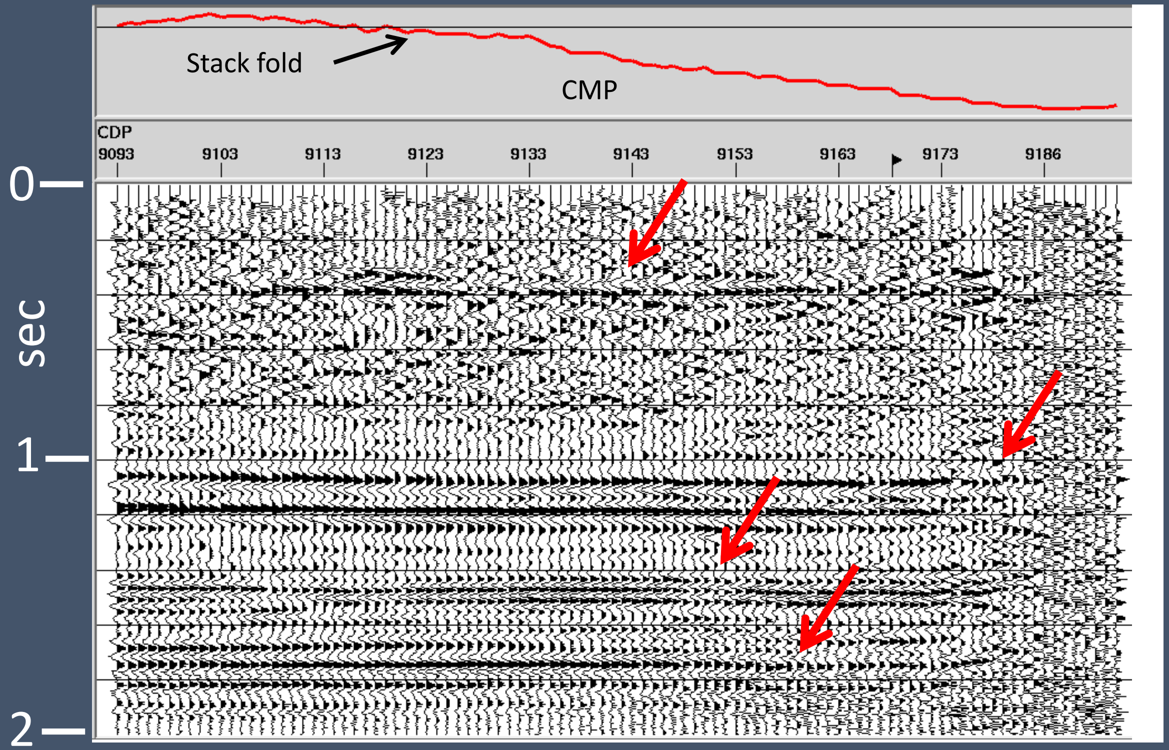
- Modest survey size ~1,000,000 traces per component
- Visible statics on unprocessed data
- Data quality good on both PP and PS components
- Data analysis bins—30deg azimuthal segments
- Tau-P Transform used
- Approximately 1Tbyte of file space required per process
- PP component processed to 3D CMP stack volume
- 2D inline CMP slices and 2D crossline CMP slices compared for results

Blackfoot 3D PP component—inline CMP stack

2D inline slice of 3D CMP stack volume—no residual statics

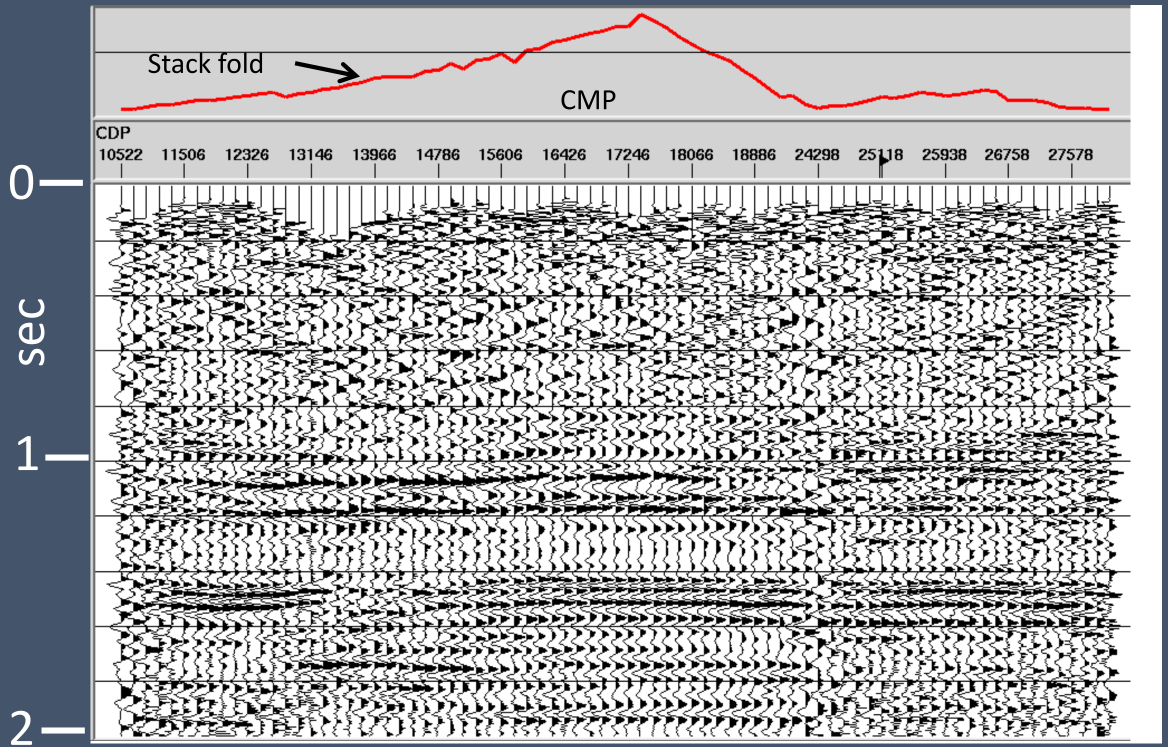


2D inline slice of 3D CMP stack volume—3D raypath interferometry

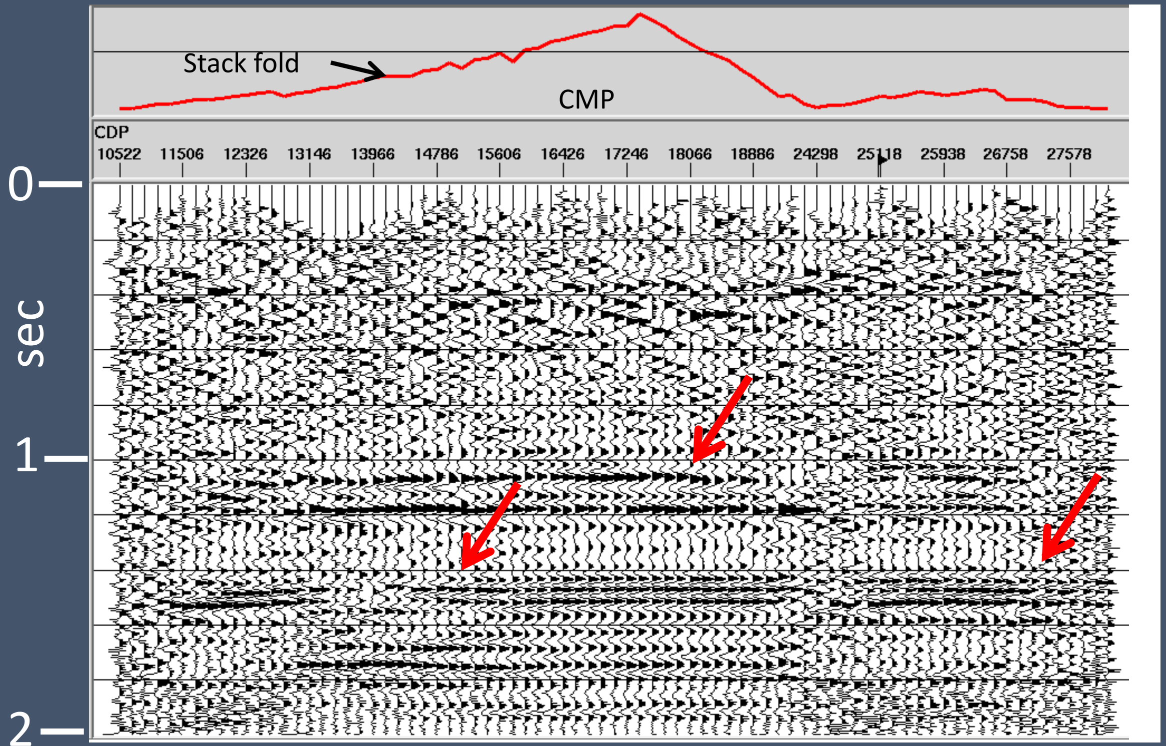


Blackfoot 3D PP component—crossline CMP stack

2D crossline slice of 3D CMP stack volume—no residual statics



2D crossline slice of 3D CMP stack volume—3D raypath interferometry



3D raypath interferometry comments

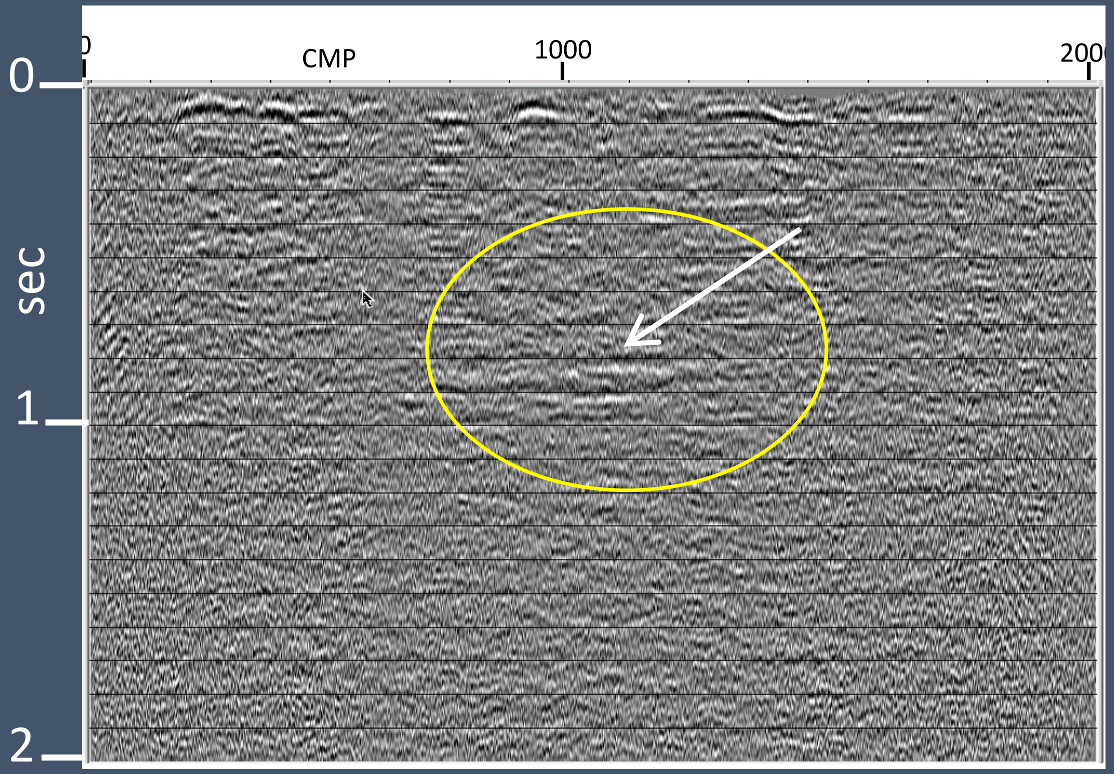
- ***Raypath interferometry*** can be successfully applied to ***both PP and PS components of 3D*** seismic surveys
- Near-surface corrections are ***truly 3D*** in nature
- ***Tau-P Transform*** preferred for conversions to/from raypath domain
  - RT Transform does not invert properly in 3D
  - Tau-P Transform requires very large file space
- Raypath interferometry probably ***not justified for most 3D PP data***
- Raypath interferometry might be ***useful for 3D PS data*** because of ***nonstationarity***

‘Fun’: Elastic modeling 4D study

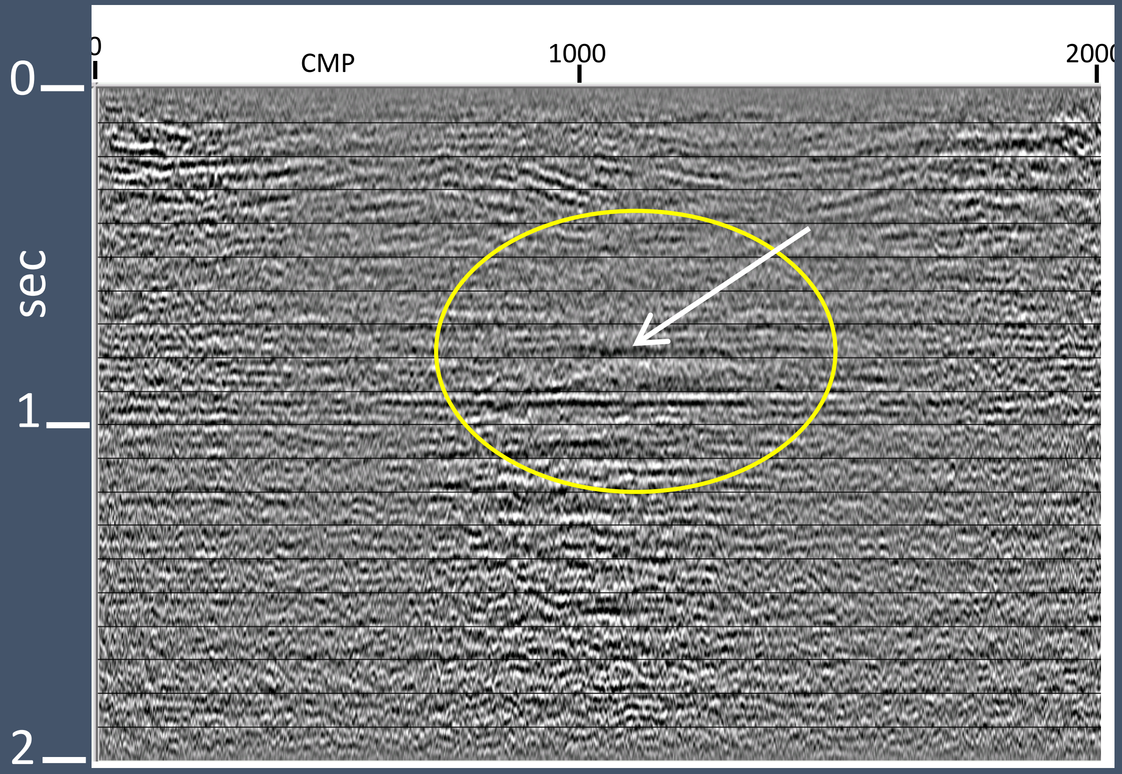
- Elastic model tested the relative effects of ***acquisition*** and ***processing*** parameters on the ***detectability*** of simulated ***fluid injection***
- Both ***reflection amplitude*** and ***time sag*** anomalies detectable on the elastic model even in the presence of noise
- With ***conventional statics***, ***reflection*** anomaly more detectable.
- With ***joint raypath interferometry***, ***time sag*** anomaly more detectable.

Elastic modeling 4D CMP image differences

Time-lapse and Baseline surveys corrected with conventional statics



Time-lapse and Baseline surveys corrected with joint raypath interferometry

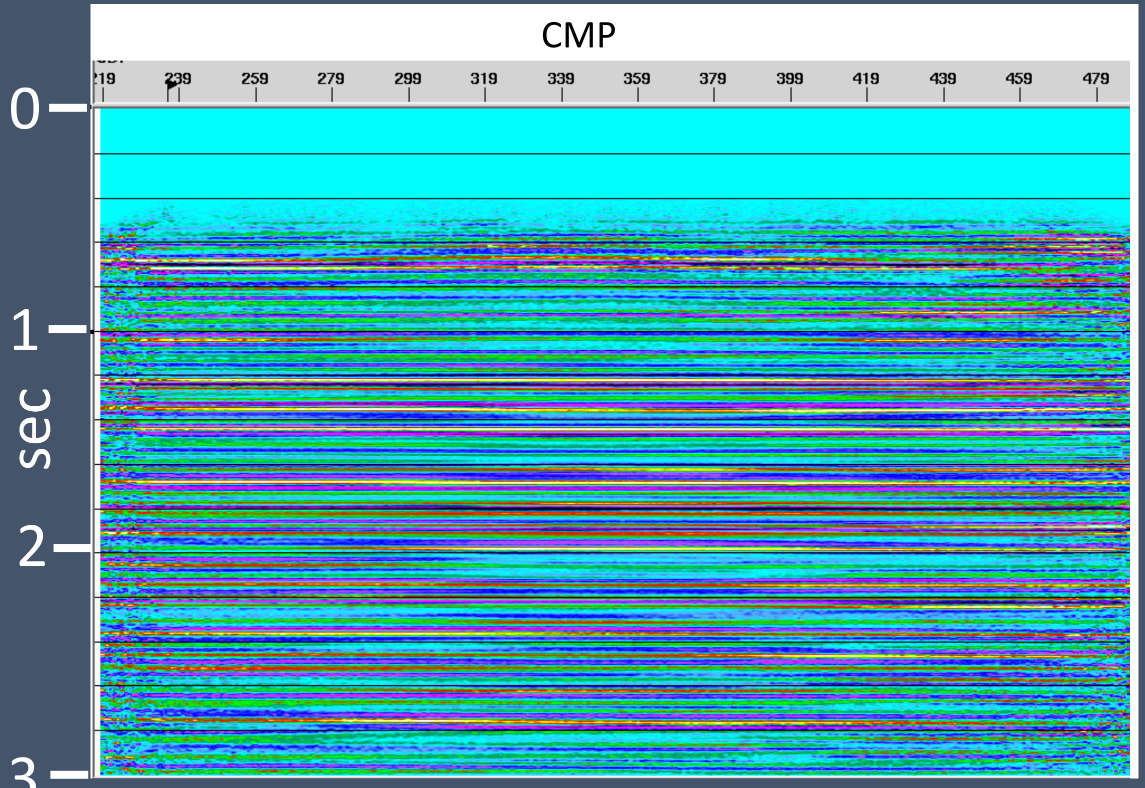


‘Profit’: Violet Grove 4D

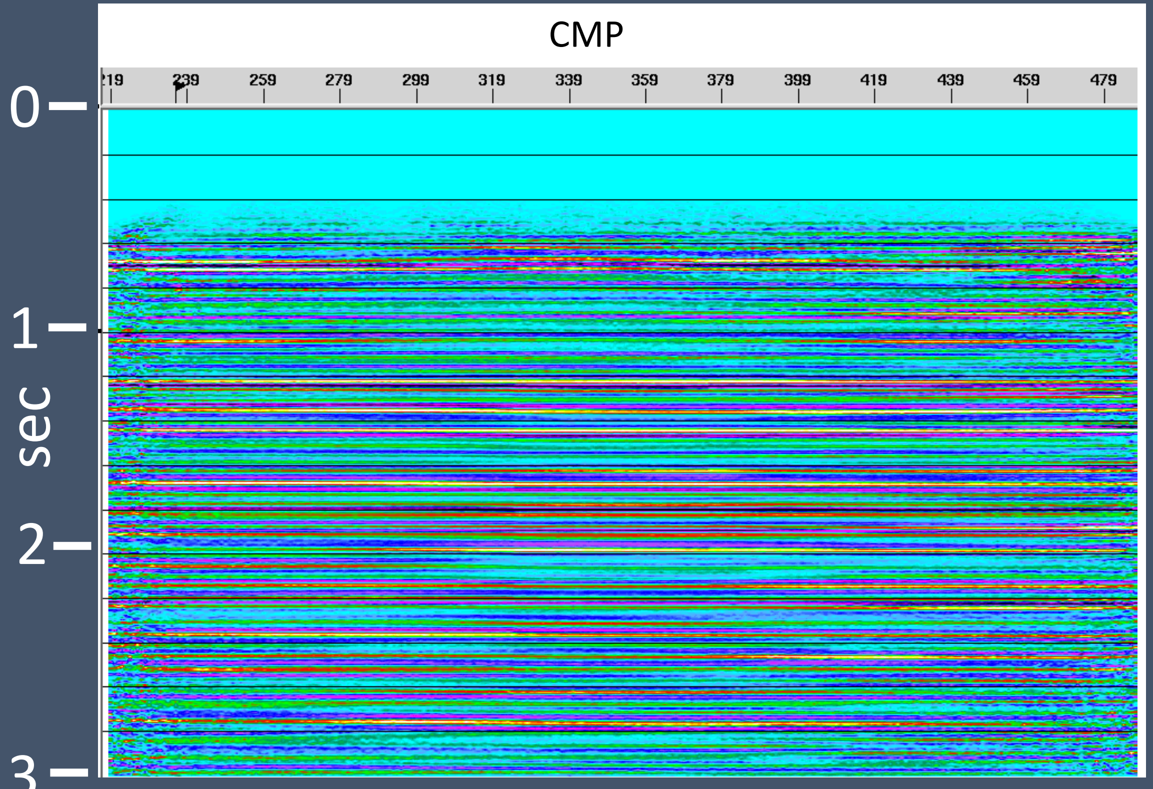
- Violet Grove experiment (2005-2007) explored ***detectability*** of ***CO2 plume*** injected into Cardium formation.
- Surface seismic profiles straddling the injection site were acquired in ***2005 (baseline)*** and ***2007(time-lapse)*** with identical acquisition and processing parameters
- ***Reflection amplitude*** anomaly for Cardium difficult to show unambiguously—***time sag*** anomaly not previously examined

Detectability test

CMP stack of noisy source gathers for 2005 baseline survey

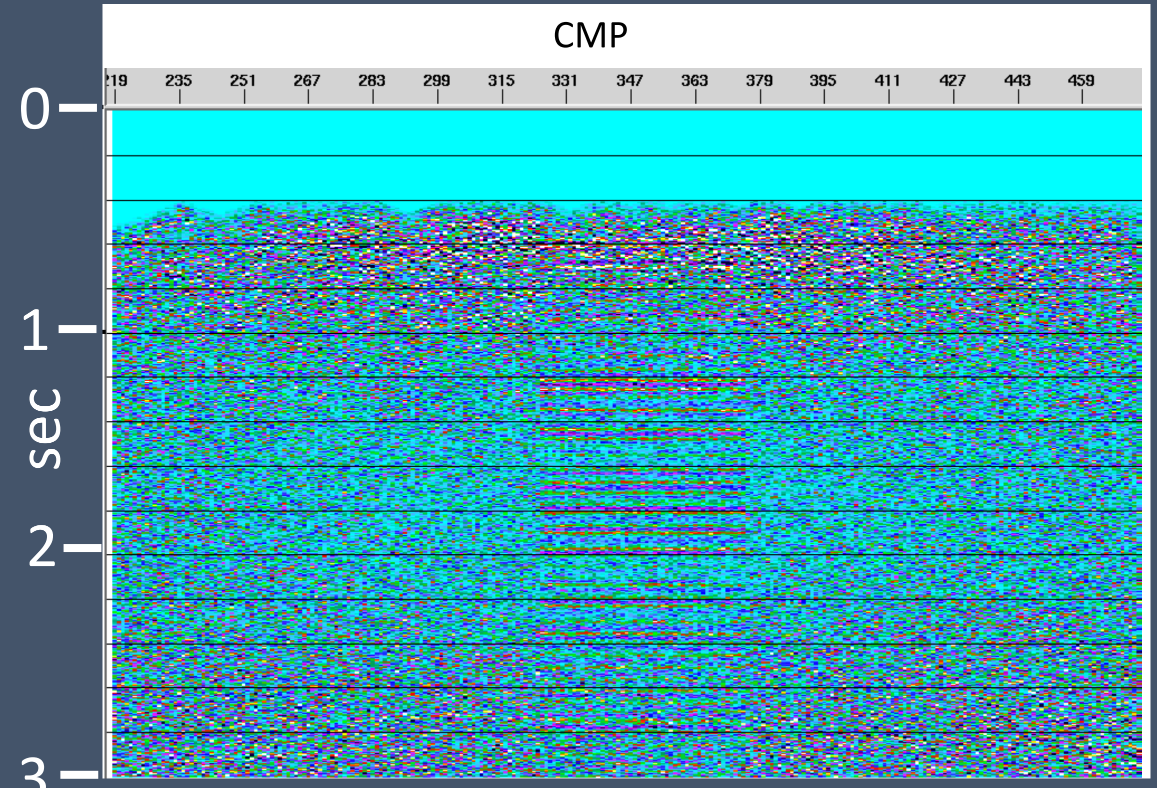


CMP stack of noisy source gathers for 2005 baseline survey—centre traces shifted 0.5ms

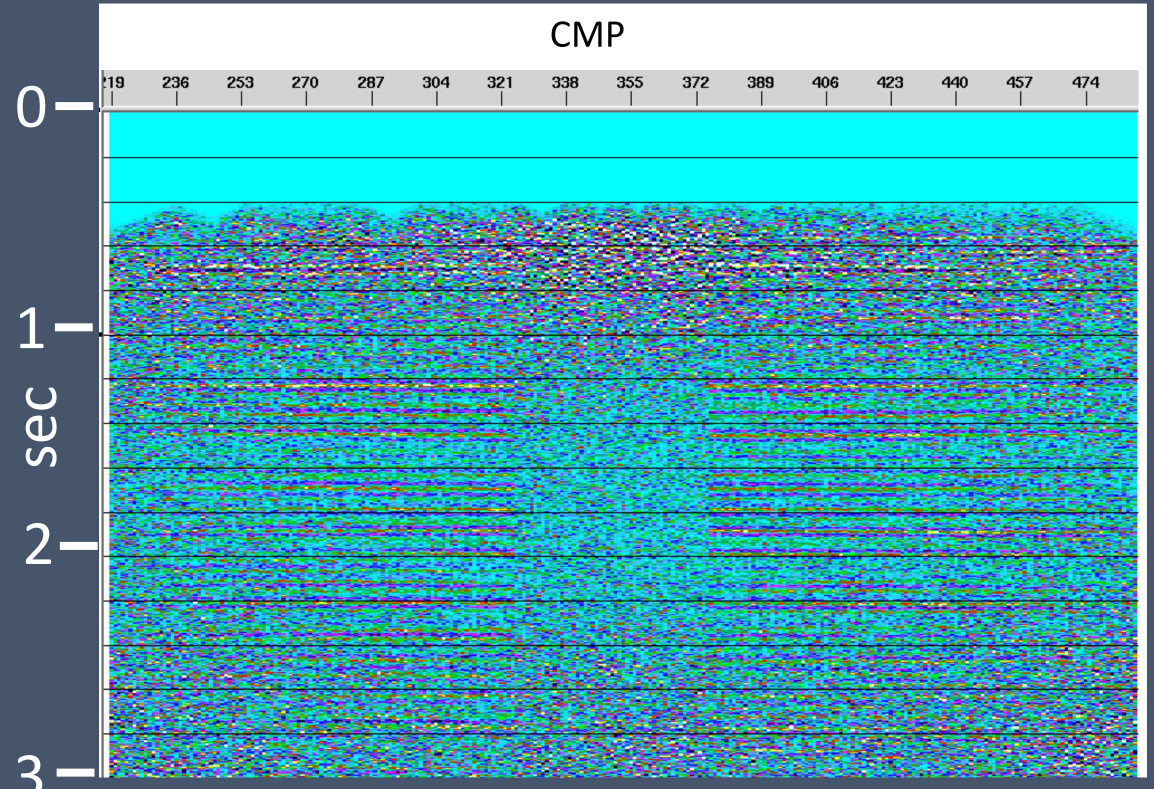


Detectability test

Difference image with no shift between images



Difference image with 0.5ms shift between images

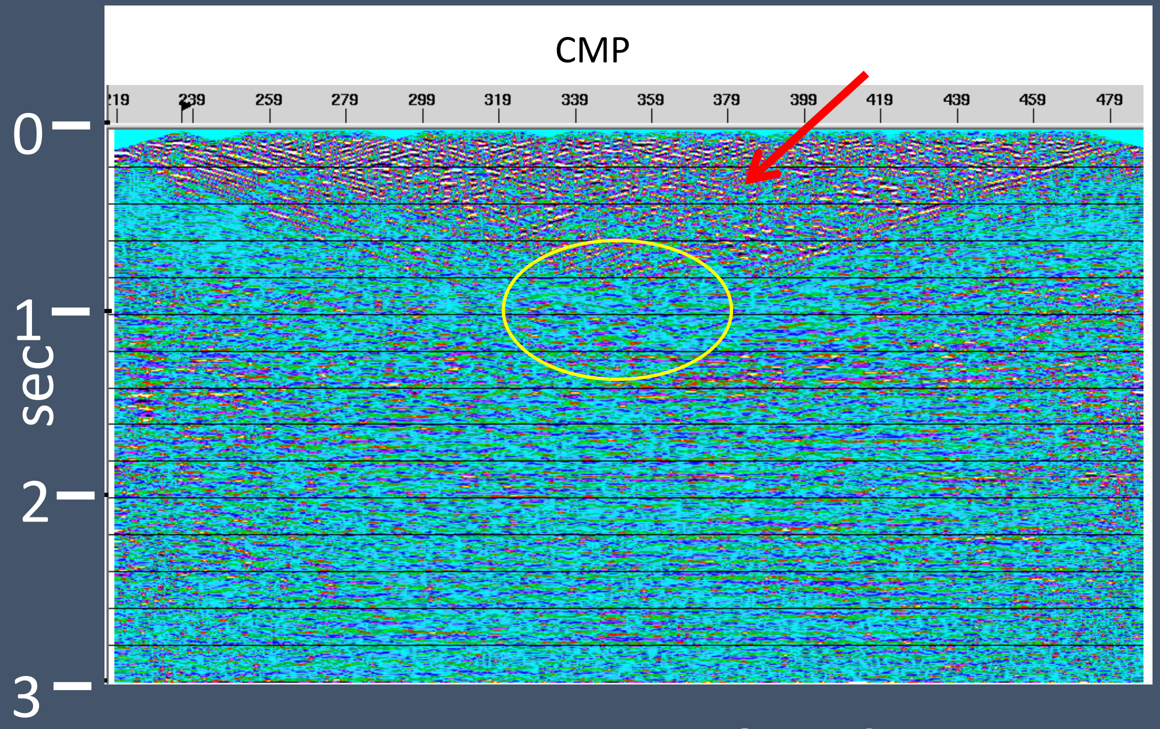


Processing for compatible CMP stack images

- Use only traces with ***common source and receiver locations*** in both surveys
- Attenuate coherent noise with ***common set of RT filters***
- Apply ***Gabor deconvolution*** using common parameters
- Apply ***zero-phase bandpass*** filters to ensure ***common bandwidth*** for both surveys
- Apply ***joint raypath interferometry***, using the ***2005 baseline reference wavefield*** for both data sets
- Remove NMO using a single common function
- CMP stack

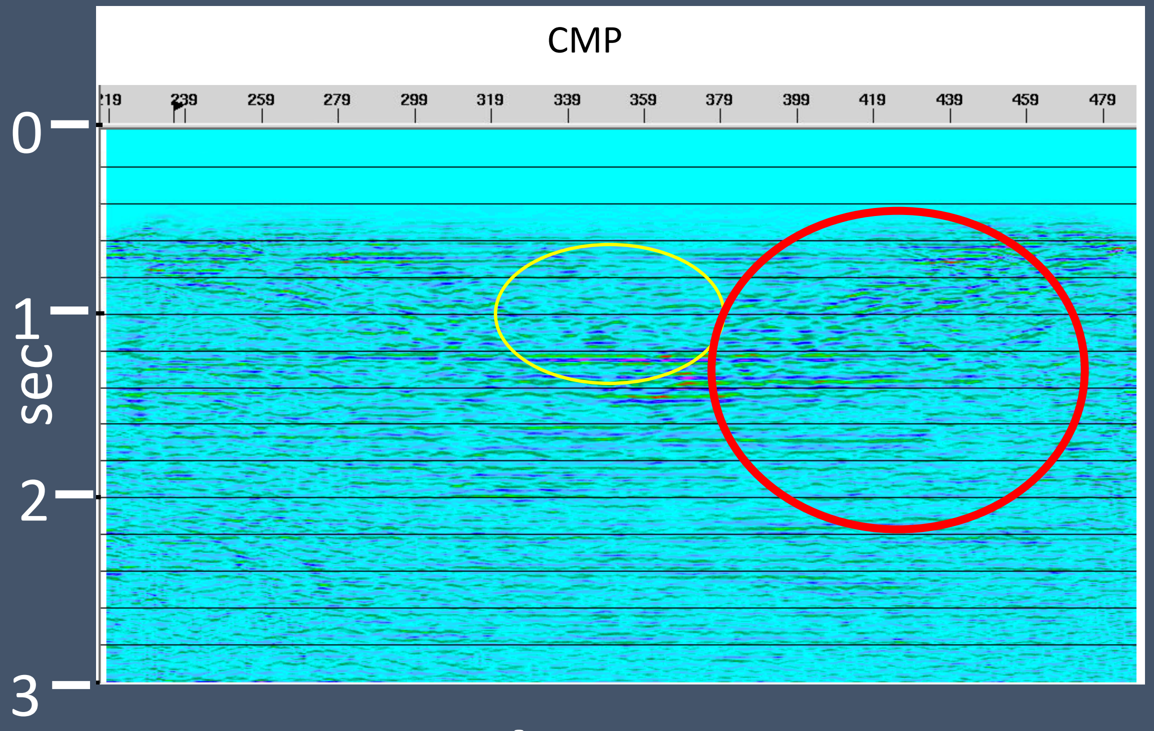
Early image difference results—more processing indicated

CMP difference image with no initial muting applied to source gathers



Large noise amplitudes

CMP difference image with initial muting to remove surface noise residuals as well as strong shallow reflections



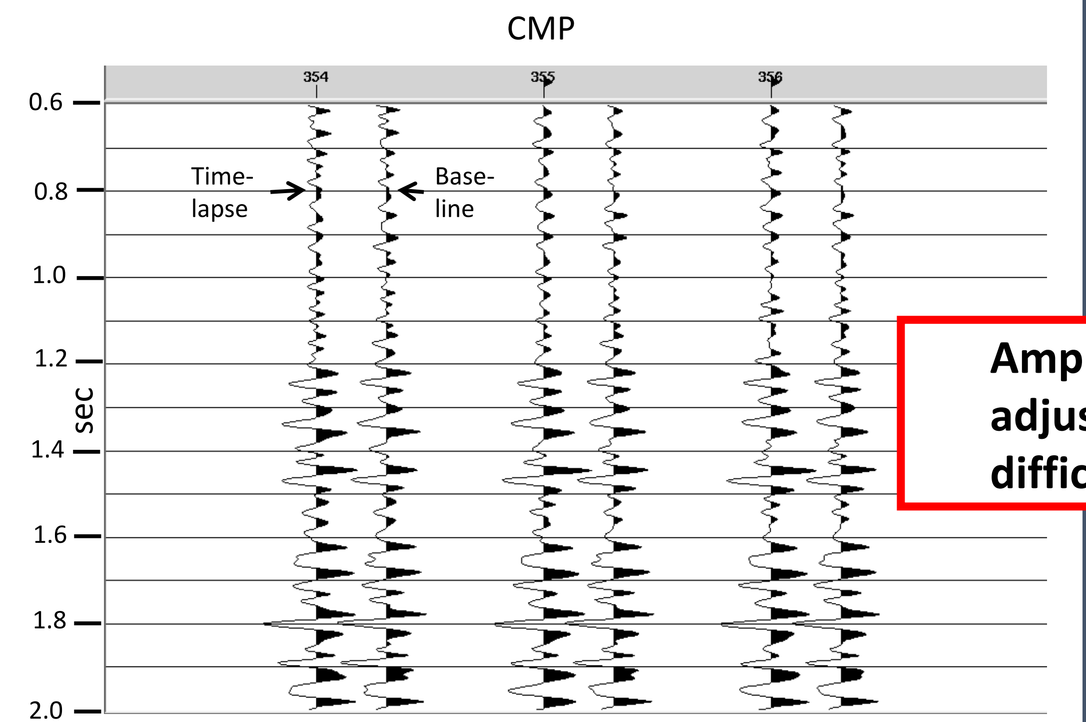
Trace equalization variations

Processing steps to enhance image subtraction

- ***Initial muting*** applied to remove residuals of surface waves
- ***Amplitude equalization*** within window applied to CMP stack images to ***minimize actual amplitude differences*** between corresponding traces
- Resulting ***background*** image difference amplitudes are due to slight event ***shape differences*** and ***random noise***
- ***Coherent*** image difference amplitudes are due to ***reflections slightly misaligned in time—time sag anomaly***

Trace amplitude equalization

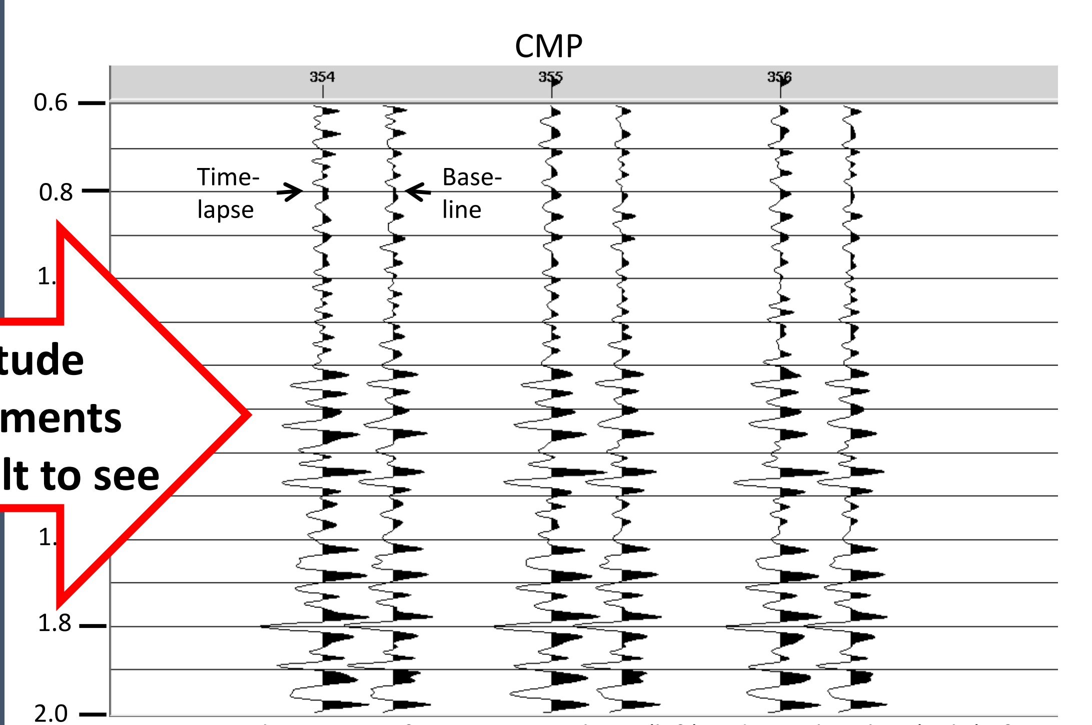
Trace pairs before amplitude equalization



CMP stack trace pairs from 2007 time-lapse (left) and 2005 baseline (right) before amplitude equalization.

Amplitude adjustments difficult to see

Trace pairs after amplitude equalization

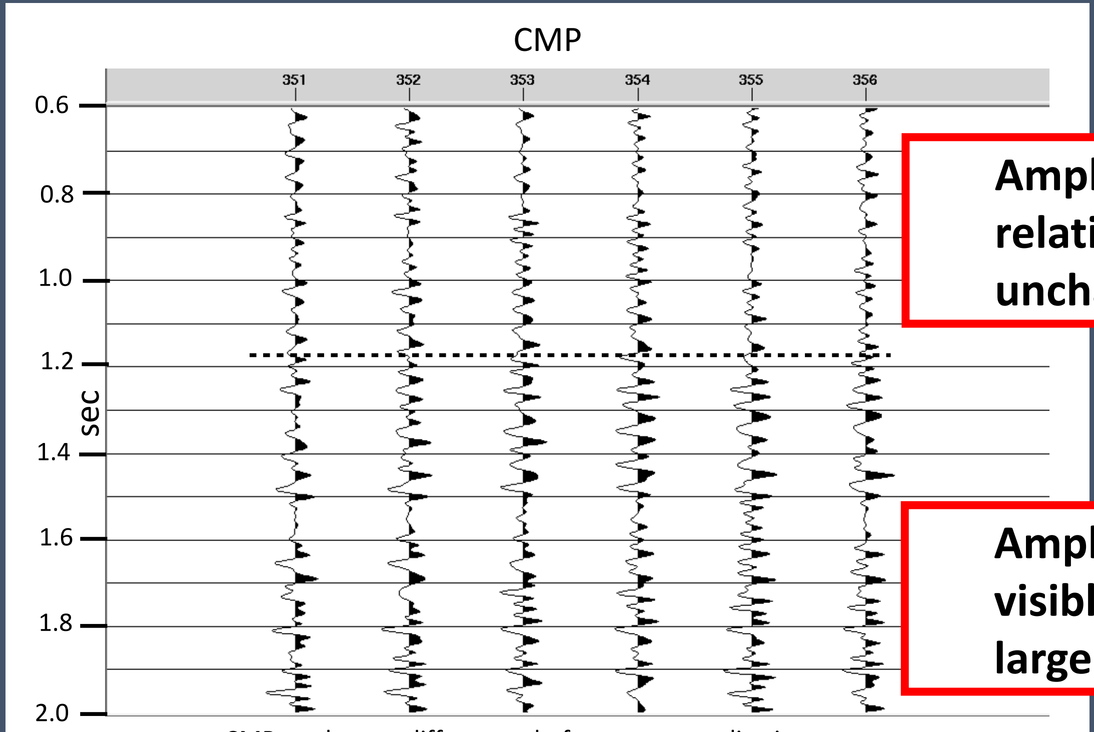


CMP stack trace pairs from 2007 time-lapse (left) and 2005 baseline (right) after amplitude equalization.

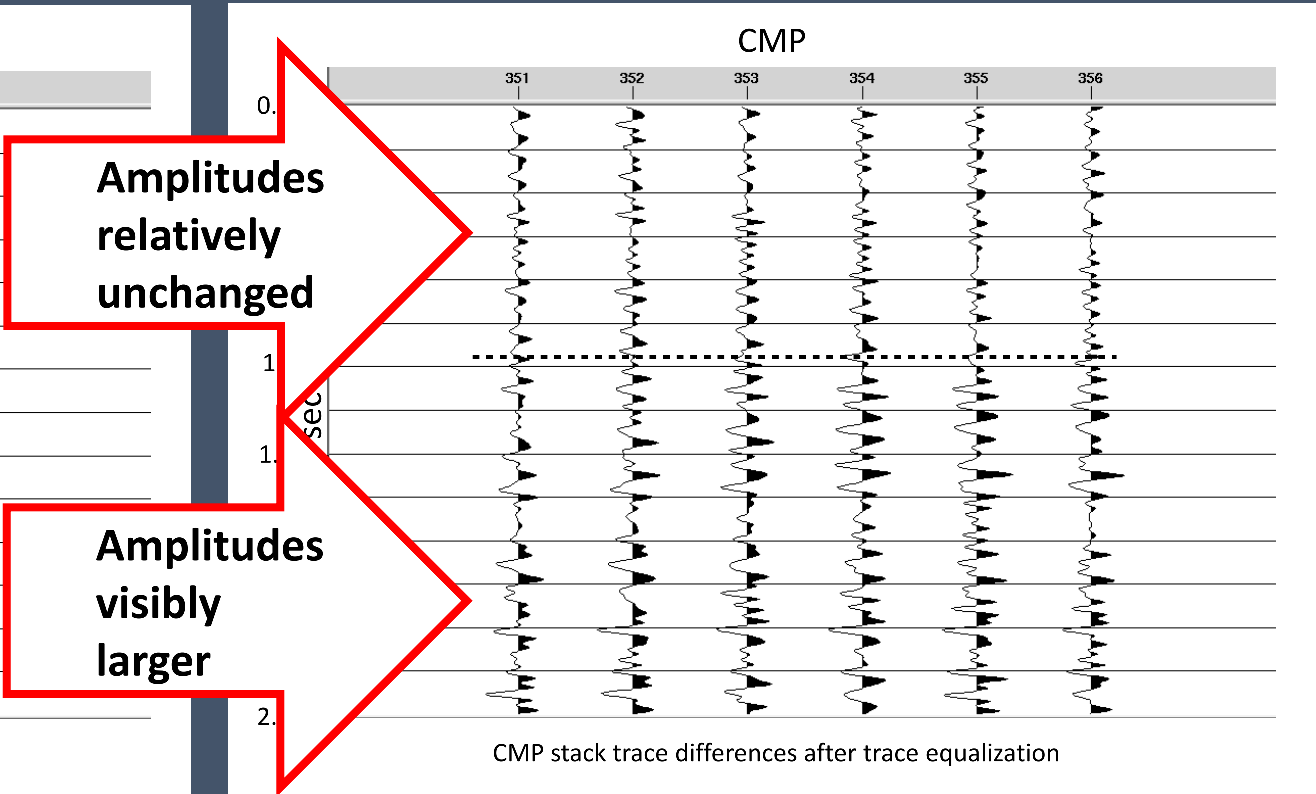
Trace amplitude equalization

Difference traces before equalization

Difference traces after equalization



CMP stack trace differences before trace equalization

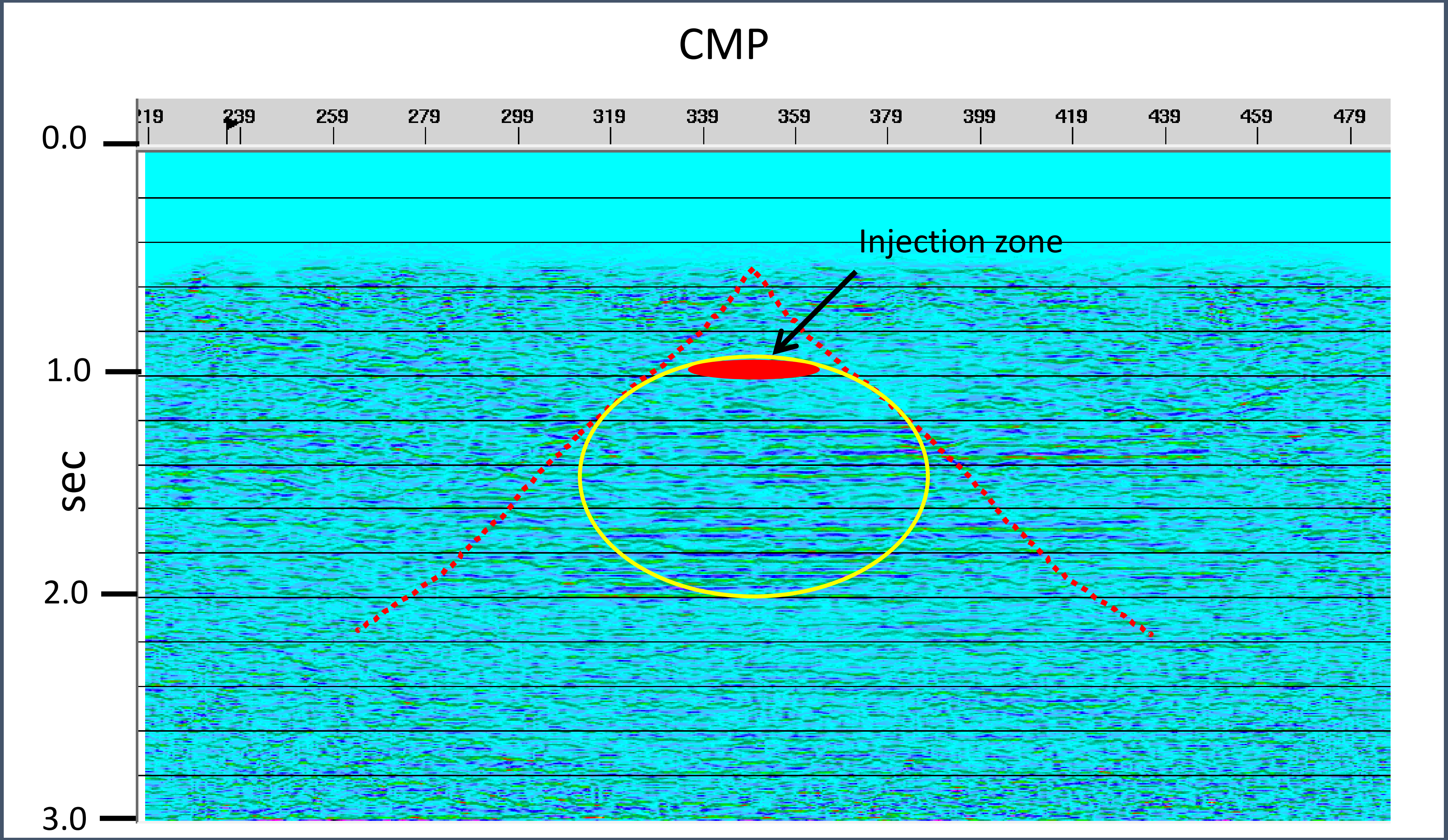


CMP stack trace differences after trace equalization

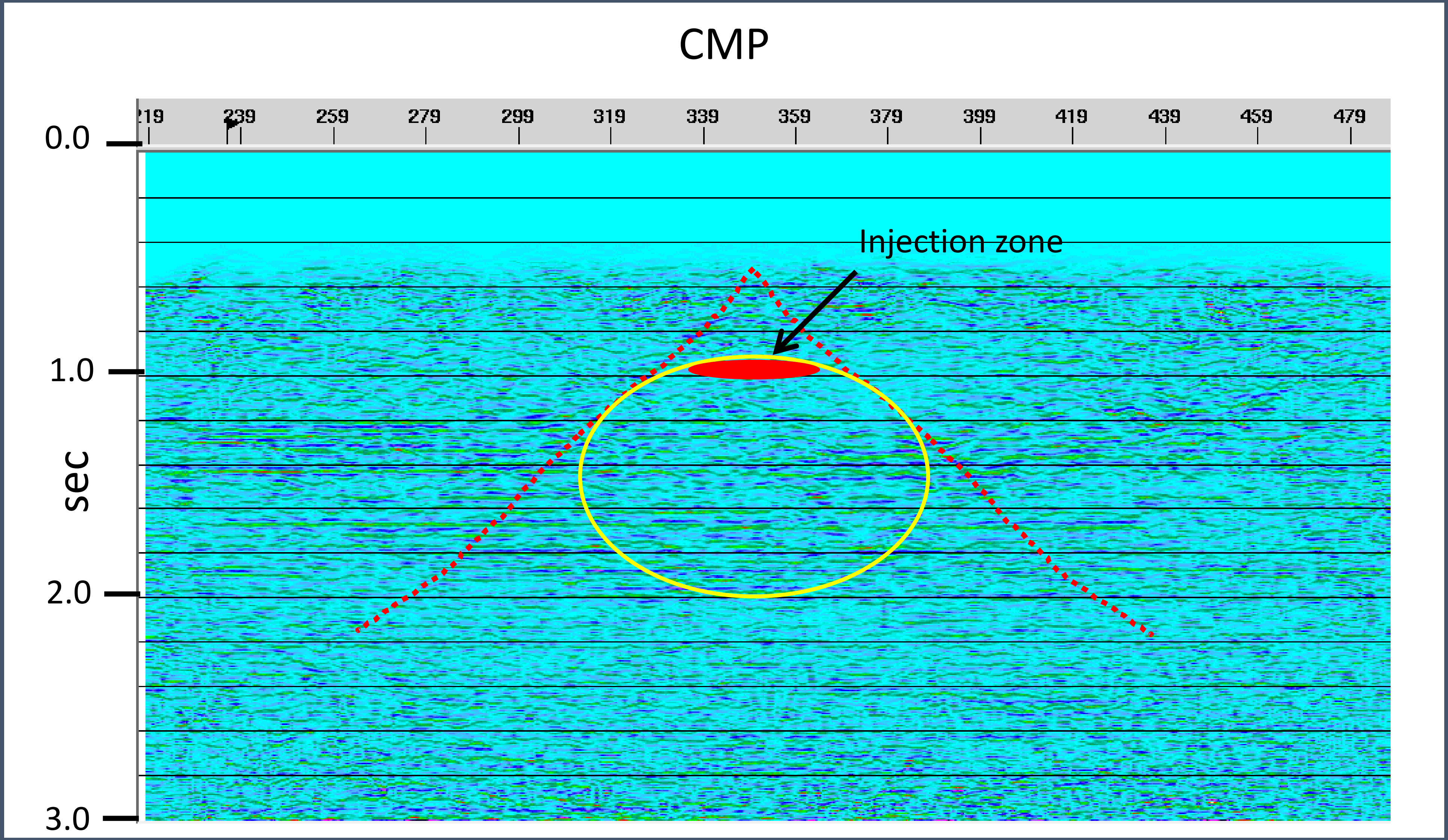
Effect of trace equalization

- Difference trace amplitudes are relatively small and incoherent, ***except*** where events on input trace pairs are slightly ***mismatched in time***

Violet Grove 2005-2007 time difference image



Violet Grove 2005-2007 time difference image—baseline shifted



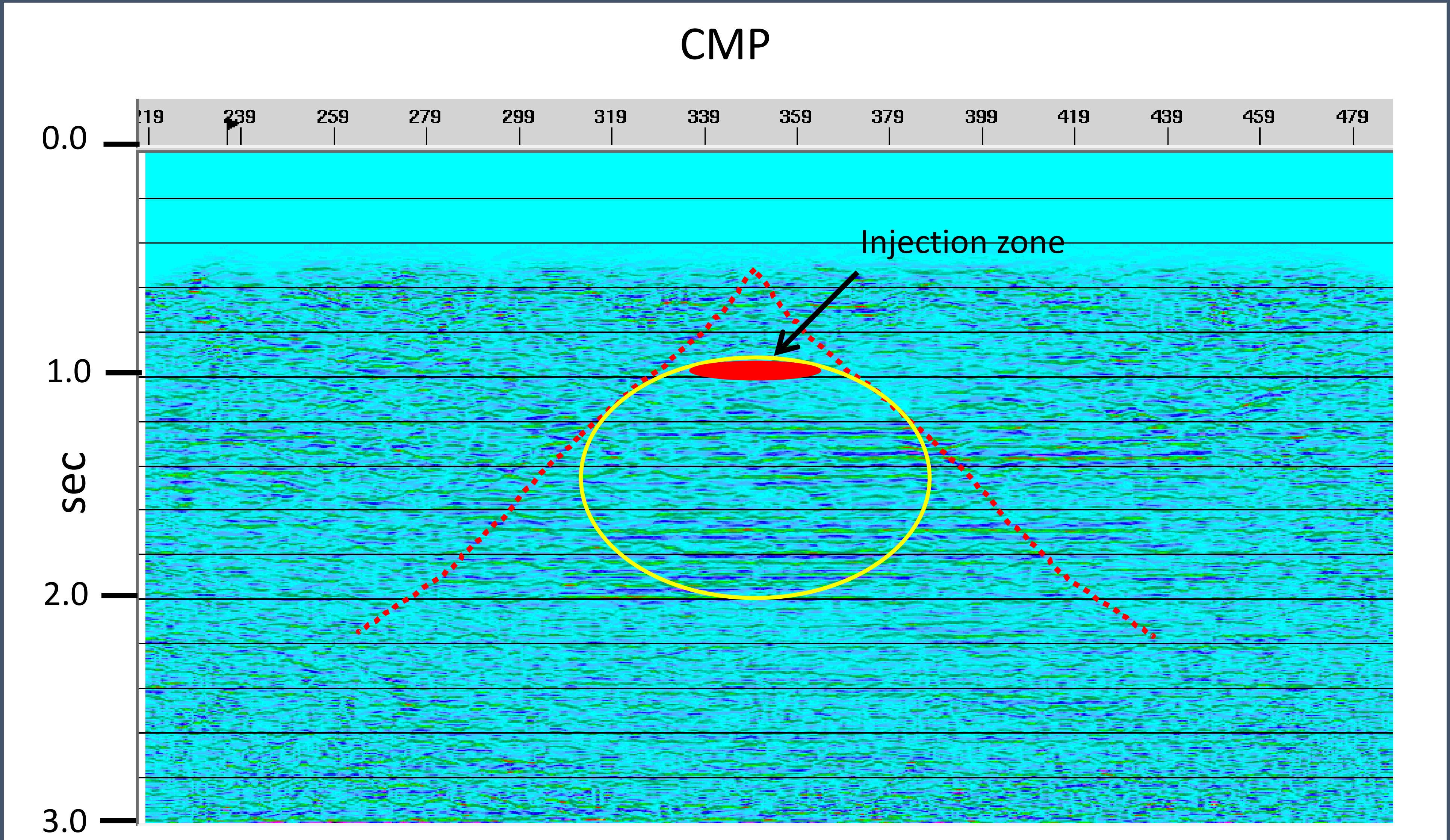
Conclusions

- With proper processing, ***time difference anomalies*** can be ***separated*** from ***amplitude difference anomalies*** in 4D time-lapse studies
- ***Time sag*** anomalies may be more readily seen in some time-lapse situations than ***reflection amplitude*** anomalies
- ***Joint raypath interferometry*** using a common reference wavefield helps find ***very small time differences*** because:
  - ***The procedure automatically registers the two images exactly***
  - ***Nonstationary surface-correction decouples shallow events from deep ones***

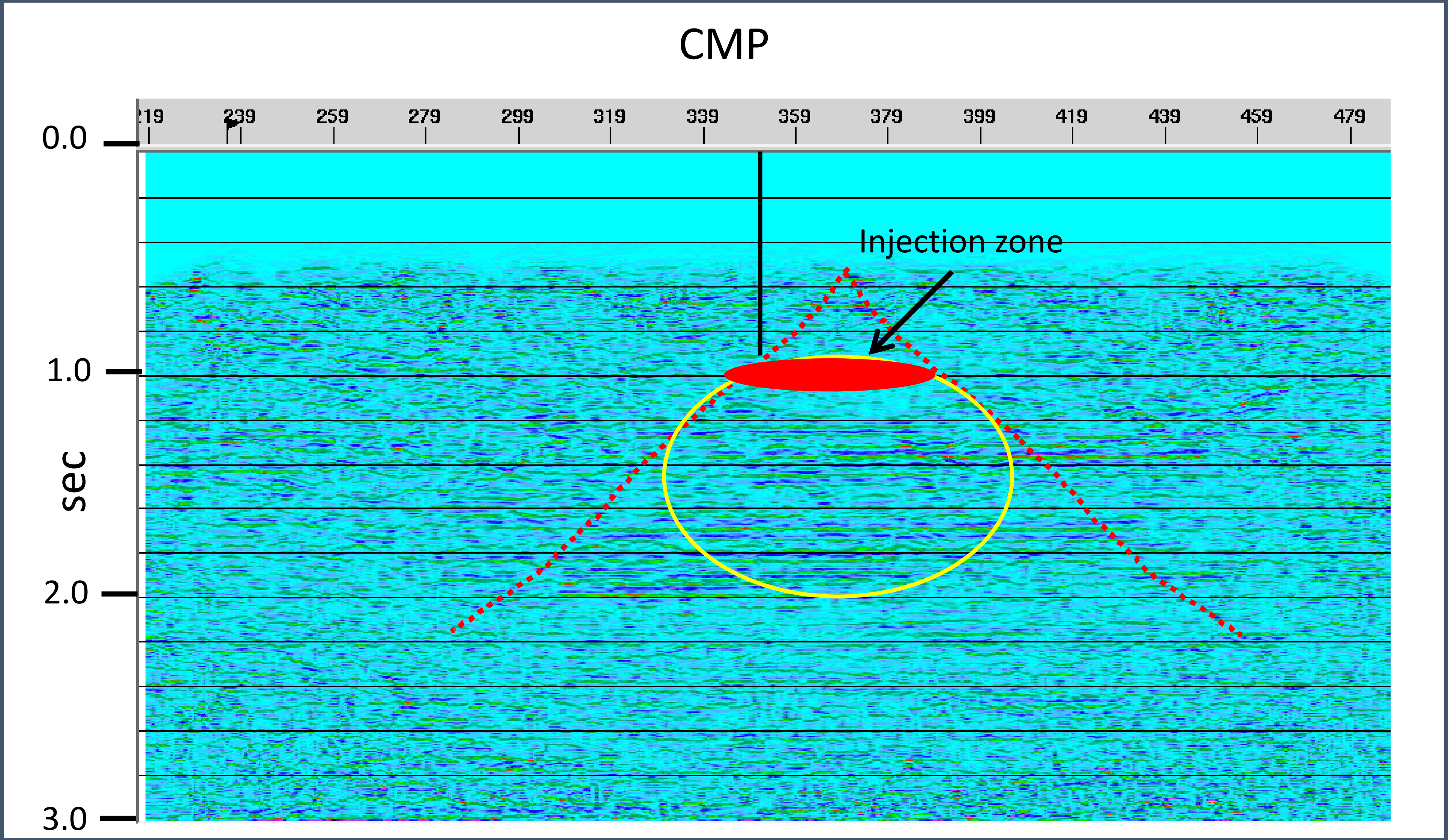
A conjecture

- The pattern of the time sag anomaly hints that ***CO_2 plume*** may have been ***asymmetric*** relative to the injection well
- The Cardium formation is well-known for its ***heterogeneous porosity and fracturing***
- A speculative interpretation allowing for this asymmetry fits the difference image better

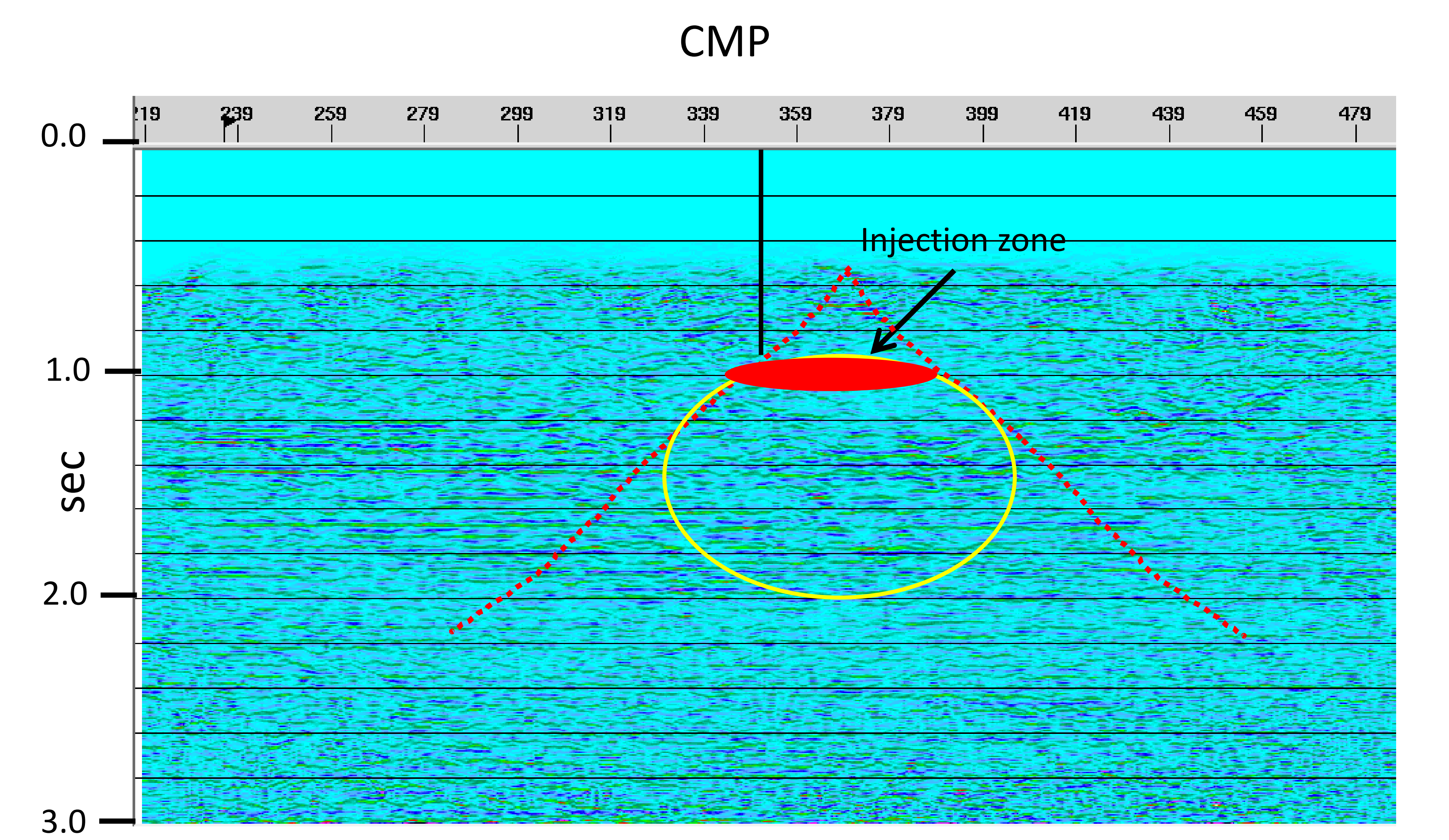
Violet Grove 2005-2007 time difference image



Violet Grove 2005-2007 time difference image—asymmetric



Violet Grove 2005-2007 time difference image—asymmetric



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