Common-Reflection-Surface stack –
a generalized stacking velocity analysis tool

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Overview

Motivation

Introduction
- Traveltime tomography
- Stacking velocity analysis & Dix inversion
- Objective

General imaging workflow

Common-Reflection-Surface stack
- Basic concepts
- Wavefield attributes

NIP wave tomography
- Principle
- Data examples

Conclusions

Acknowledgments

Motivation

Conventional depth imaging requires a macrovelocity model.

Some common approaches:

- analysis of residual moveouts in depth-migrated common-image gathers (CIGs)
  ☞ migration velocity analysis (MVA)
- direct inversion of traveltimes (and slopes) picked in prestack data
- inversion based on stacking velocities

☞ differences in applicability and complexity!

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  ⇒ often difficult, especially in 3-D
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Stacking velocity analysis:

- coherence analysis along second-order CMP traveltime approximation
- relatively coarse picking in poststack data/velocity spectra
- interpolation

Dix inversion:

- assumption of 1-D model, $v_{\mathrm{RMS}} \stackrel{def}{=} v_{\mathrm{stack}}$ or $v_{\mathrm{RMS}} \stackrel{def}{=} v_{\mathrm{DMO}}$
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- retain coherence based analysis
- allow highly automated application
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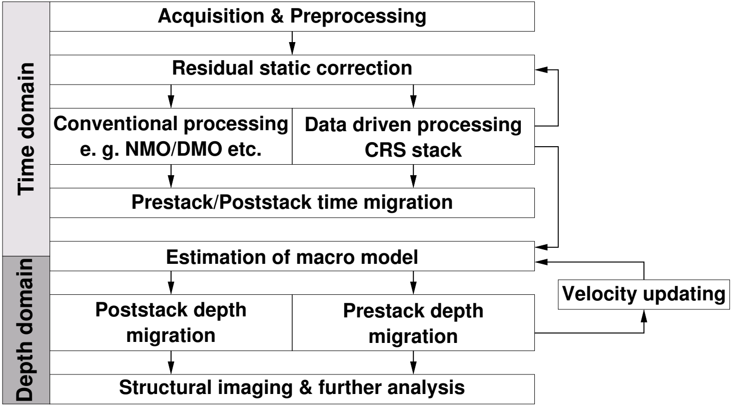

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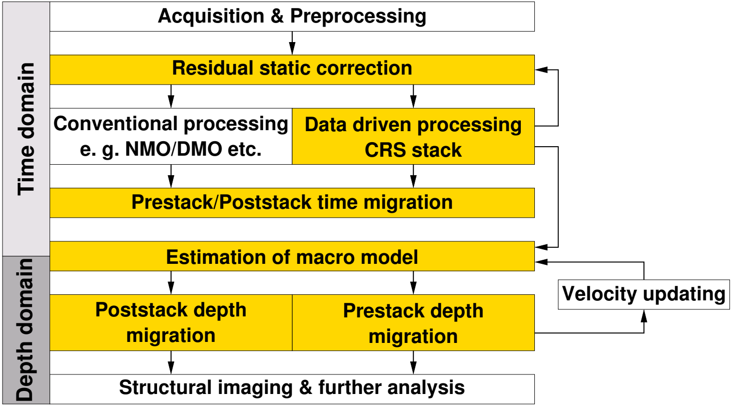

yellow = CRS-related applications

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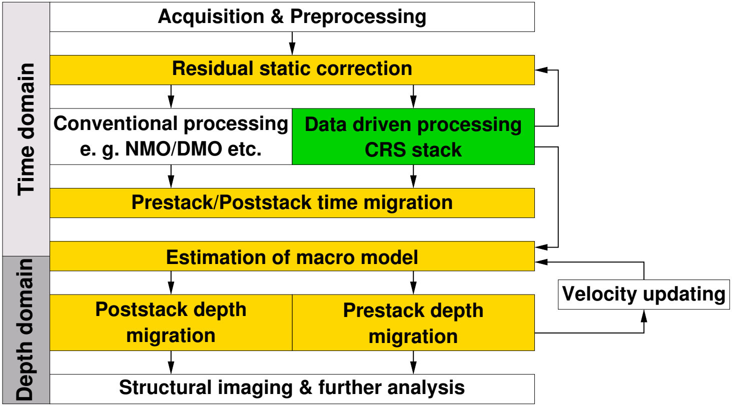

green = topics covered in this talk

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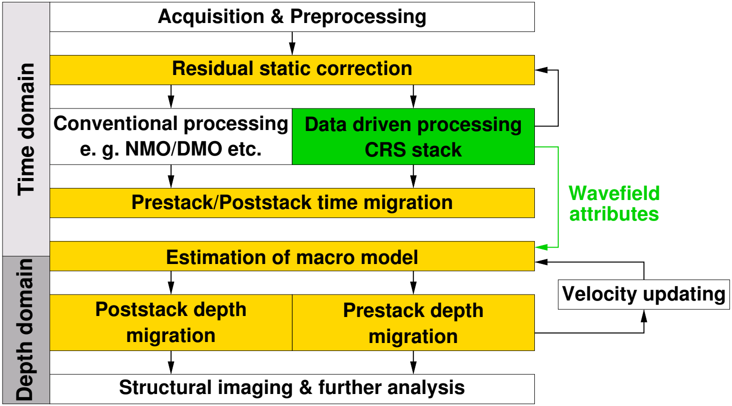

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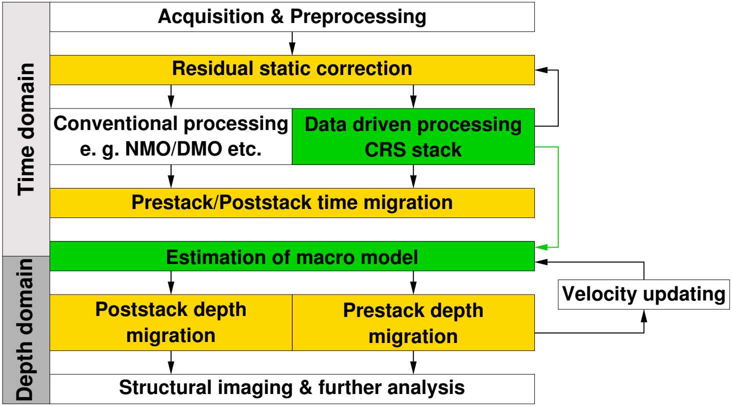

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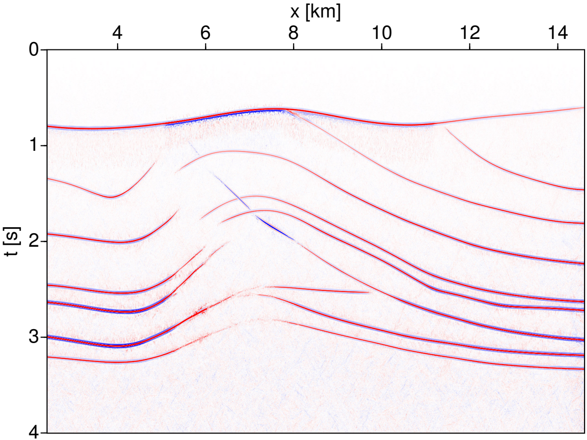

CRS-stacked section

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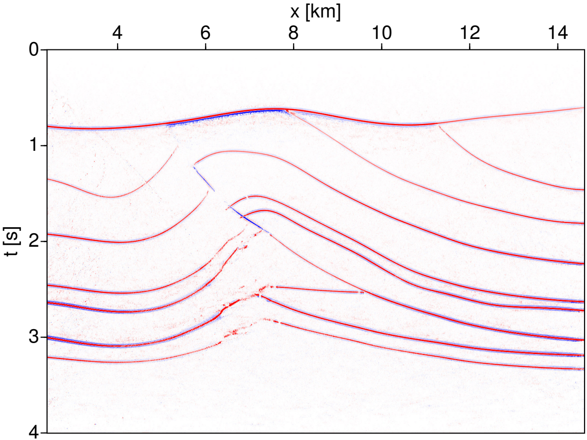

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J. Mann

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$$t^2(\Delta\boldsymbol{\xi},\mathbf{h}) = \left(t_0 + 2\,\mathbf{p}_\xi\cdot\Delta\boldsymbol{\xi}\right)^2 + 2t_0\left(\Delta\boldsymbol{\xi}^T\mathbf{M}_\xi\,\Delta\boldsymbol{\xi} + \mathbf{h}^T\mathbf{M}_h\,\mathbf{h}\right)$$

Common-Reflection-Surface stack

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t_0	zero-offset traveltime
$\mathbf{h}$	source/receiver offset
$\Delta\boldsymbol{\xi}$	midpoint displacement

Common-Reflection-Surface stack

Generalization of conventional approach:

- second-order approximation of traveltime
- fully automated coherence-based application
- high-density analysis
  ⇒ no pulse stretch, high resolution
- *spatial* stacking operator

Common-Reflection-Surface stack

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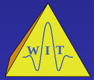
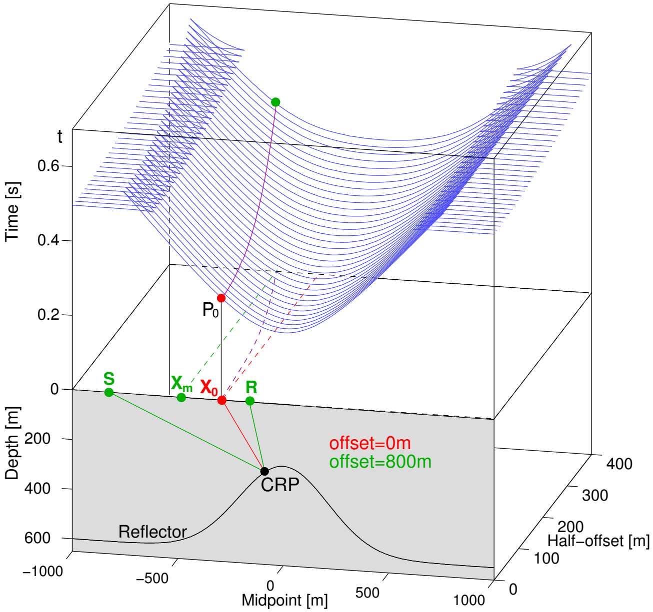
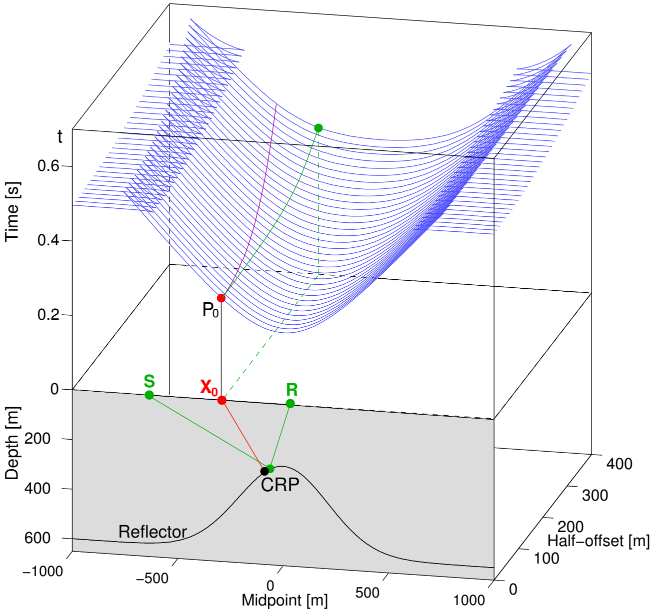


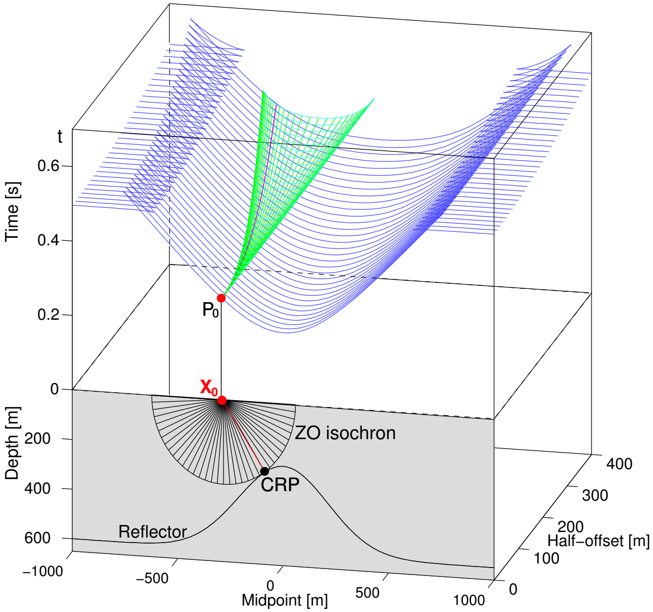
2-D stacking operators: CRP trajectory



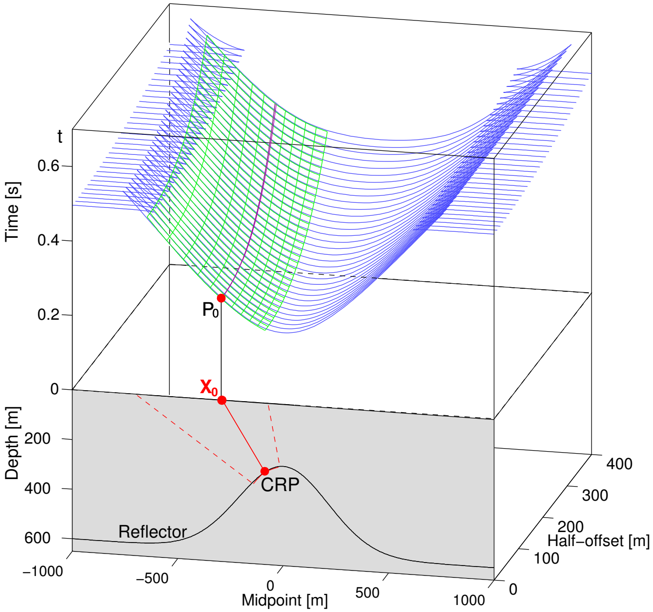
2-D stacking operators: NMO operator



2-D stacking operators: NMO plus DMO



2-D stacking operators: CRS operator



Common-Reflection-Surface stack

Generalization of conventional approach:

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  ➥ much more prestack traces used
  ➥ enhanced signal/noise ratio

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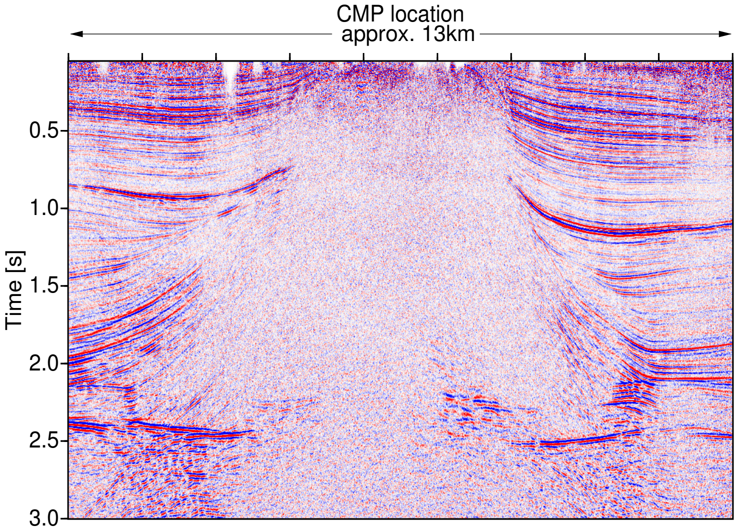
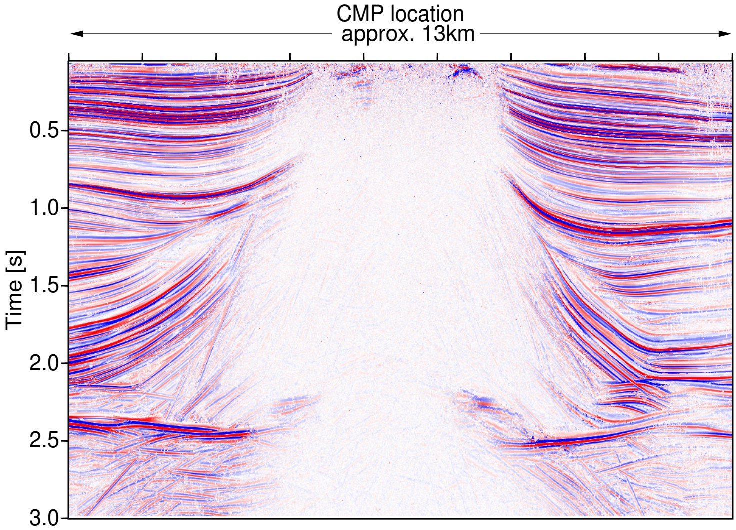
Stack results: NMO/DMO/stack



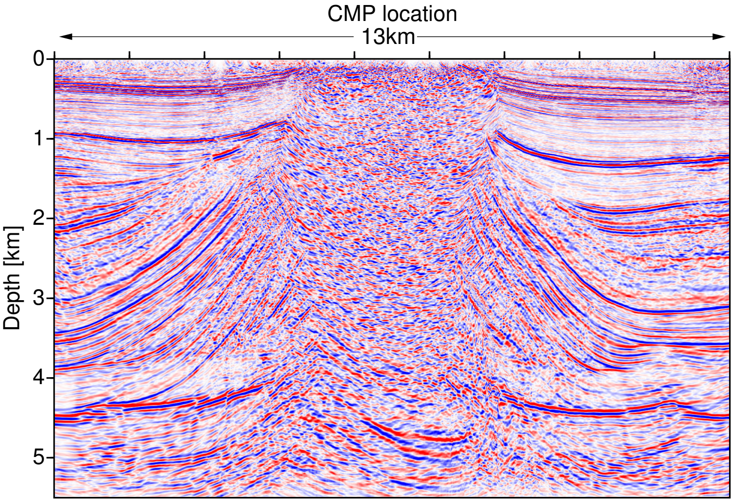
(from Müller, "The Common Reflection Surface Stack Method", 1999)

Stack results: CRS stack



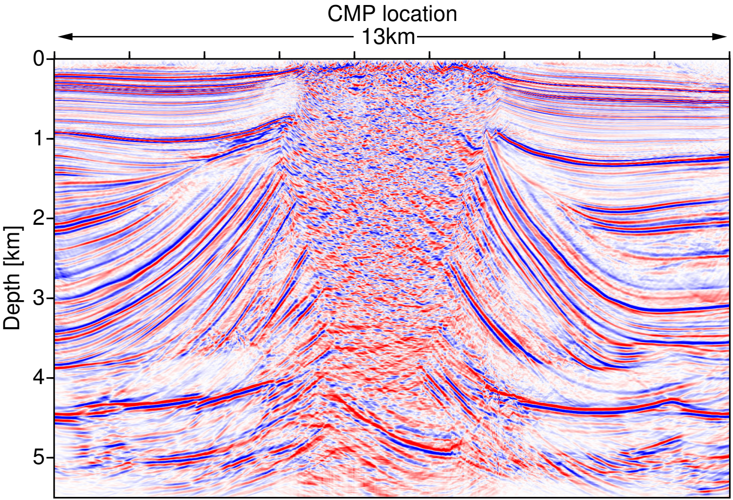
(from Müller, "The Common Reflection Surface Stack Method", 1999)

Depth migration of NMO/DMO/stack



(from Müller, "The Common Reflection Surface Stack Method", 1999)

Depth migration of CRS stack



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  ➥ geometrical interpretation

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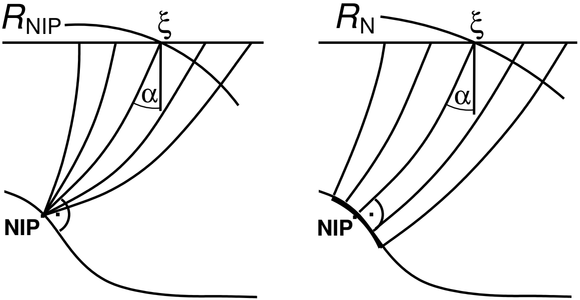
CRS wavefield attributes in 2-D

Geometrical interpretation of stacking parameters:

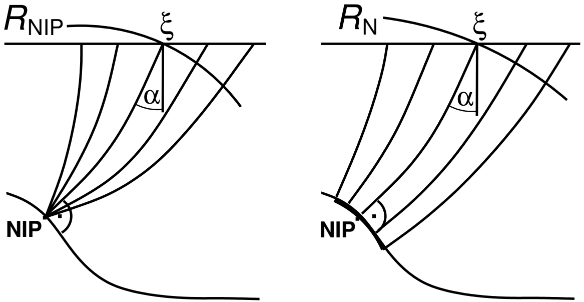


Emergence direction and curvatures of hypothetical wavefronts:

- exploding point source
  - → normal incidence point (NIP) wave
- exploding reflector

CRS wavefield attributes in 2-D

Geometrical interpretation of stacking parameters:



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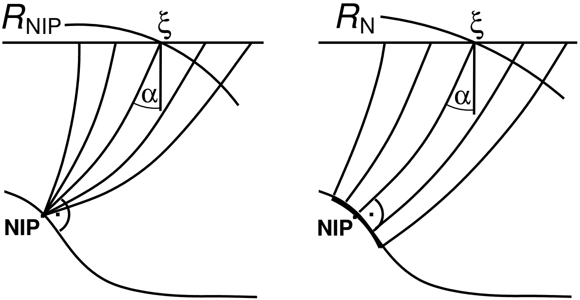

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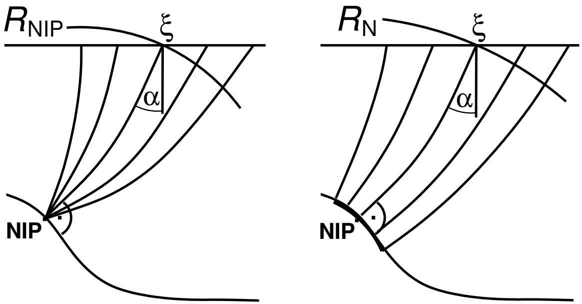

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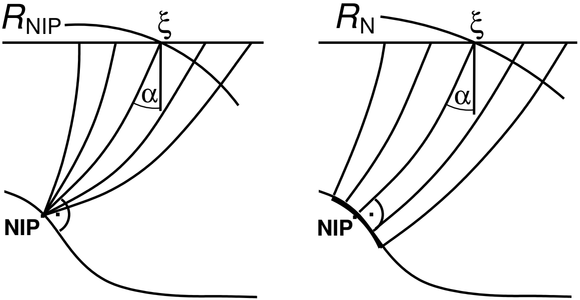

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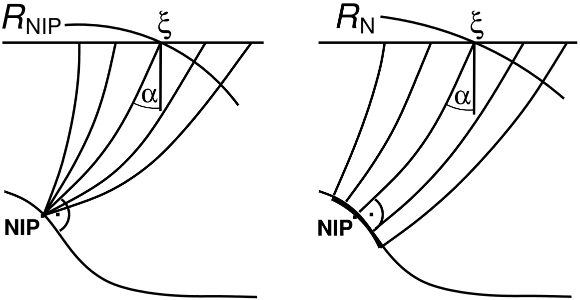

Emergence direction and curvatures of hypothetical wavefronts:

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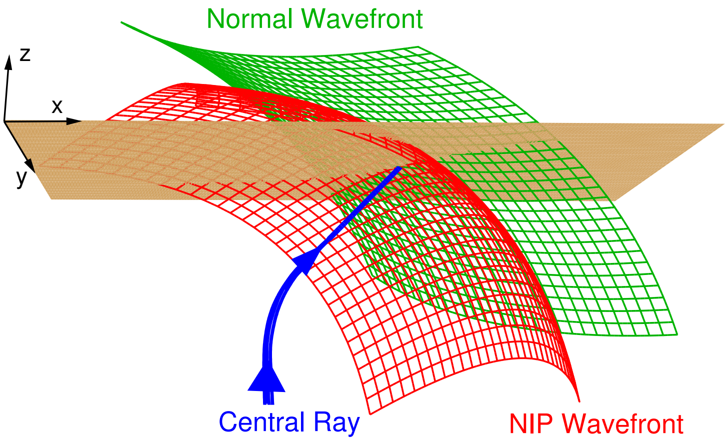
CRS wavefield attributes in 3-D



☞ slowness vector and curvature matrices!

Reformulation of traveltime formula

Reformulation of traveltime formula

In terms of traveltime derivatives:

$$t^2(\Delta\boldsymbol{\xi},\mathbf{h}) = \left(t_0 + 2\,\mathbf{p}_\xi \cdot \Delta\boldsymbol{\xi}\right)^2 + 2t_0\left(\Delta\boldsymbol{\xi}^T \mathbf{M}_\xi\, \Delta\boldsymbol{\xi} + \mathbf{h}^T \mathbf{M}_h\, \mathbf{h}\right)$$

$\mathbf{p}_\xi = \frac{1}{2}\partial t/\partial\boldsymbol{\xi}$

$\mathbf{M}_h = \frac{1}{2}\partial^2 t/\partial\mathbf{h}^2$

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t_0	zero-offset traveltime
$\mathbf{h}$	source/receiver offset
$\Delta\boldsymbol{\xi}$	midpoint displacement

Reformulation of traveltime formula

In terms of kinematic wavefield attributes:

$$t^2(\Delta\boldsymbol{\xi},\mathbf{h}) = \left(t_0 + 2\,\mathbf{p}_\xi \cdot \Delta\boldsymbol{\xi}\right)^2 + 2t_0\left(\Delta\boldsymbol{\xi}^T \mathbf{M}_\xi\,\Delta\boldsymbol{\xi} + \mathbf{h}^T \mathbf{M}_h\,\mathbf{h}\right)$$

$$\mathbf{p}_\xi = \frac{1}{v_0}(\sin\alpha\cos\psi, \sin\alpha\sin\psi)^T$$

$$\mathbf{M}_h = \frac{1}{v_0}\mathbf{D}\mathbf{K}_{\mathrm{NIP}}\mathbf{D}^T$$

$$\mathbf{M}_\xi = \frac{1}{v_0}\mathbf{D}\mathbf{K}_{\mathrm{N}}\mathbf{D}^T$$

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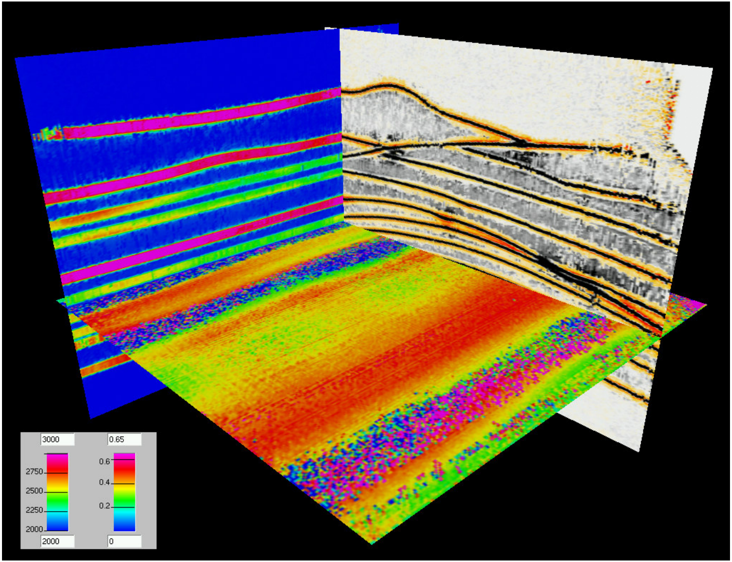
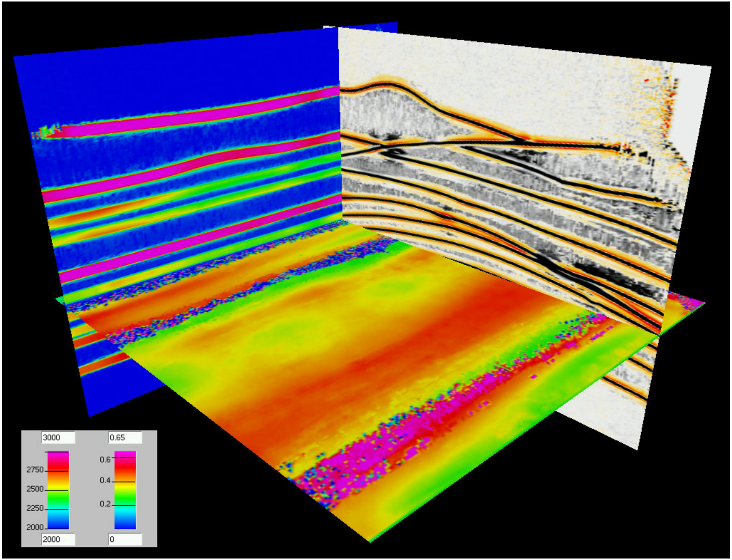
t_0	zero-offset traveltime
$\mathbf{h}$	source/receiver offset
$\Delta\boldsymbol{\xi}$	midpoint displacement

α	emergence angle of normal ray
ψ	azimuth of normal ray
$\mathbf{D}$	transformation ray-centered/global coordinates
$\mathbf{K}_{\mathrm{NIP}}$	curvature matrix of NIP wavefront
$\mathbf{K}_{\mathrm{N}}$	curvature matrix of normal wavefront
v_0	near-surface velocity

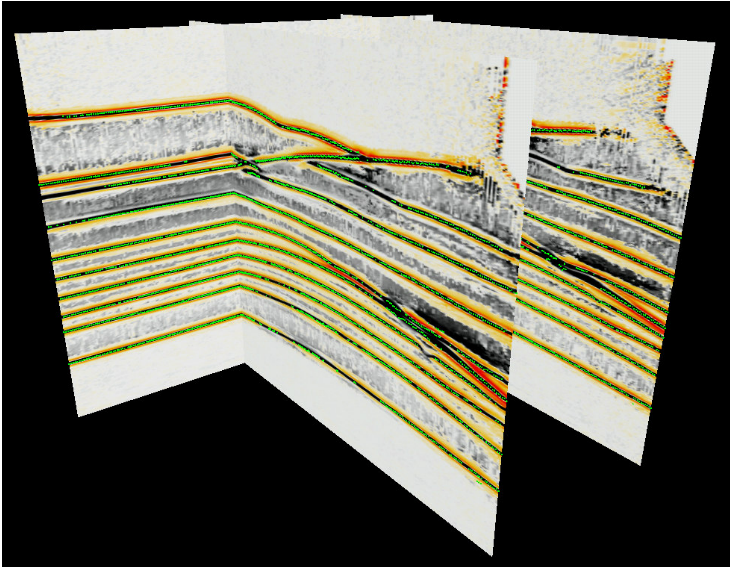
Raw wavefield attributes



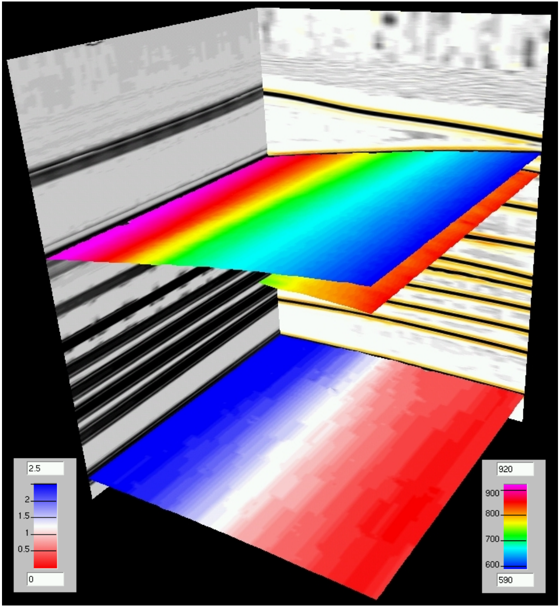
Smoothed wavefield attributes



Automatically picked events

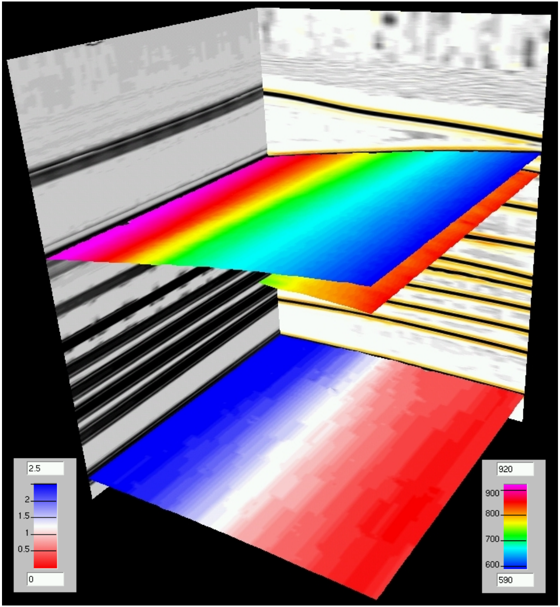


Extracted wavefield attributes



Smoothing & extraction of wavefield attributes
☞
separate presentation

Extracted wavefield attributes



Smoothing
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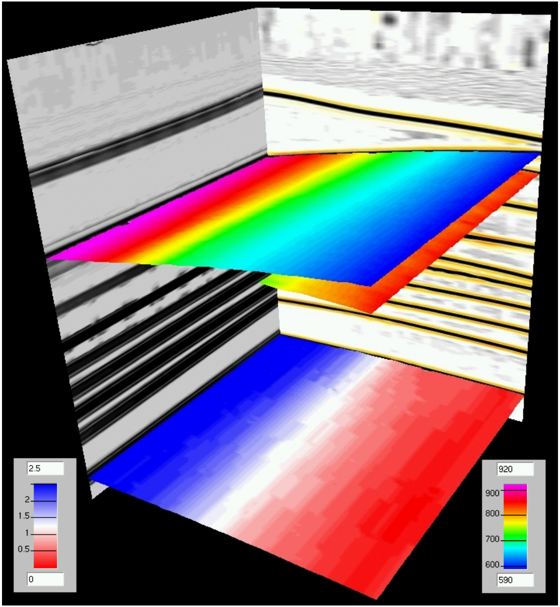

Smoothing
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separate
presentation

NIP wave tomography

Available so far:

- ZO traveltime/location picks (t_0, ξ)
- slowness vectors $\mathbf{p}_\xi(t_0, \xi)$ and second derivative matrices $\mathbf{M}_h(t_0, \xi)$
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NIP waves provide a simple and evident imaging condition for inversion!

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  $\Rightarrow$ characterizing NIP wavefronts
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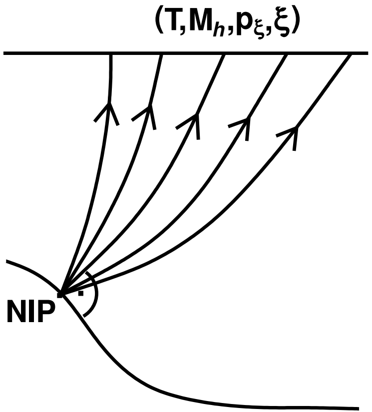
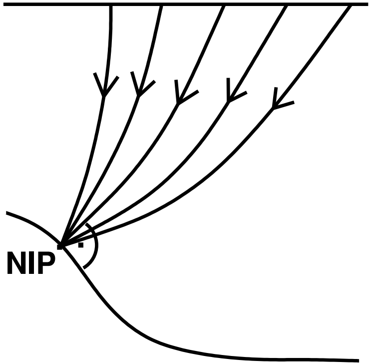


Attributes $\mathbf{M}_h$ and $\mathbf{p}_\xi$ at $(t_0, \boldsymbol{\xi})$ locally describe an emerging NIP wavefront.

NIP wave tomography



In velocity models consistent with the data,
downward-propagated NIP waves focus at $T = 0$.
☞ imaging condition

NIP wave tomography

Strategy:

- define (simple) initial model of velocity distribution and reflector segments
- forward-modeling of traveltimes and wavefield attributes by dynamic ray tracing
- solve nonlinear least-squares problem by local linearization with Fréchet derivatives
- iterative minimization of misfit between forward-modeled and picked traveltimes and attributes

➡ tomographic inversion approach, yields smooth velocity model consistent with picked data

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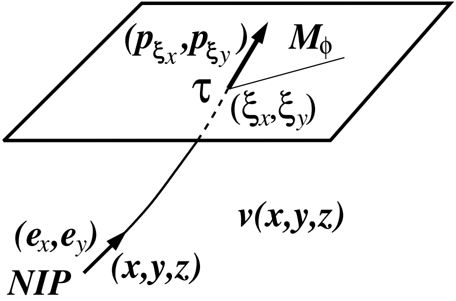
Data and model components



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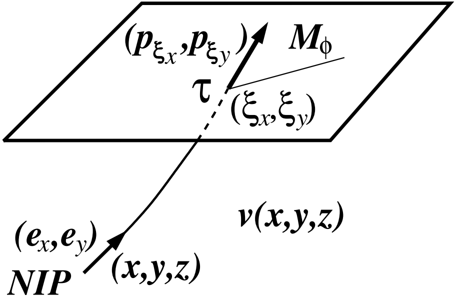


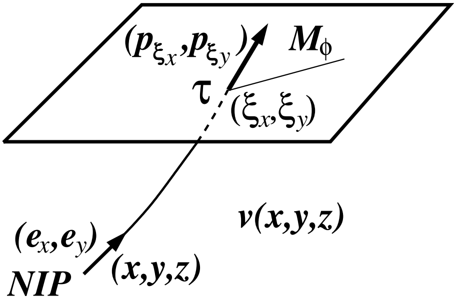
Data:

$(\tau, M_\phi, p_{\xi_x}, p_{\xi_y}, \xi_x, \xi_y)_i$

$\tau = t_0/2$

$\mathbf{M}_h$ only required for one azimuth ϕ: M_ϕ

Data and model components



Data:

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$\tau = t_0/2$

Model:

$(x, y, z, e_x, e_y)_i, v_{jkl}$

v_{jkl}: B-spline coefficients

$\mathbf{M}_h$ only required for one azimuth ϕ: M_ϕ

NIP wave tomography

Further aspects:

- Regularization:
  search for the smoothest model consistent with picked data

Optional constraints:

- velocity gradient preferably along normal rays
- consideration of well log velocities
- consideration of known velocities (e.g. marine case)

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NIP wave tomography

Advantages:

- no picking in prestack data required
- no assumptions about reflector continuity
- only few picks required due to information inherent in wavefield attributes

Limitations:

- smooth velocity model description must be applicable
- limited lateral variation within stacking aperture due to second-order approximation

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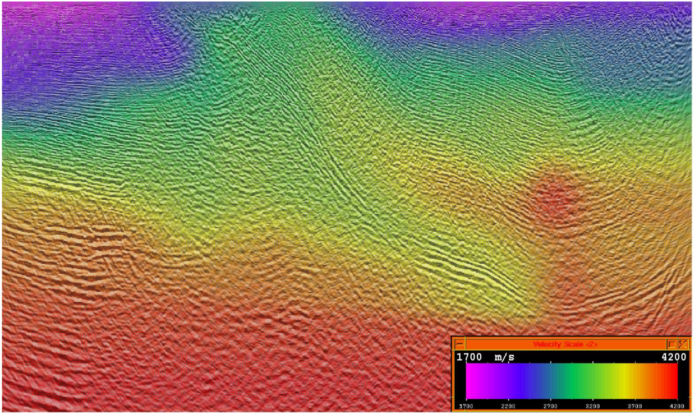
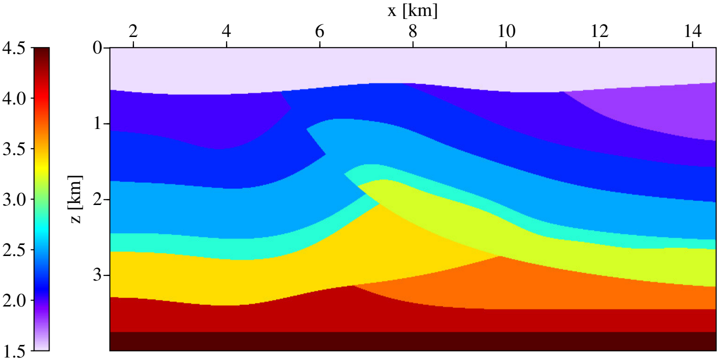
2-D real data example



Macrovelocity model from CRS tomography with corresponding PostSDM of CRS stack

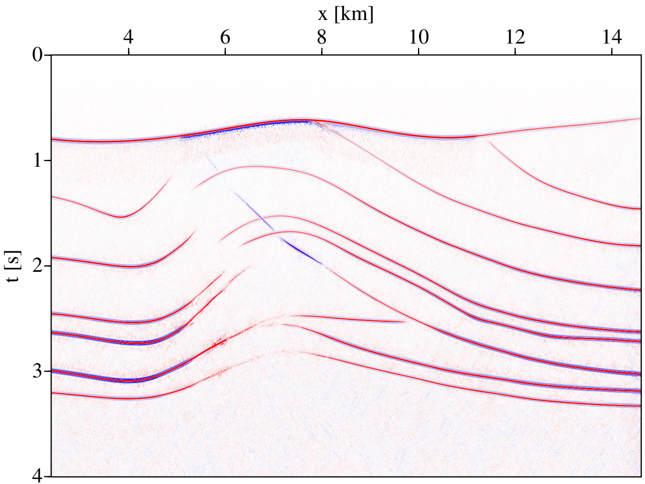
Data and image courtesy Trappe Erdöl Erdgas Consulting, TEEC

2-D synthetic data example



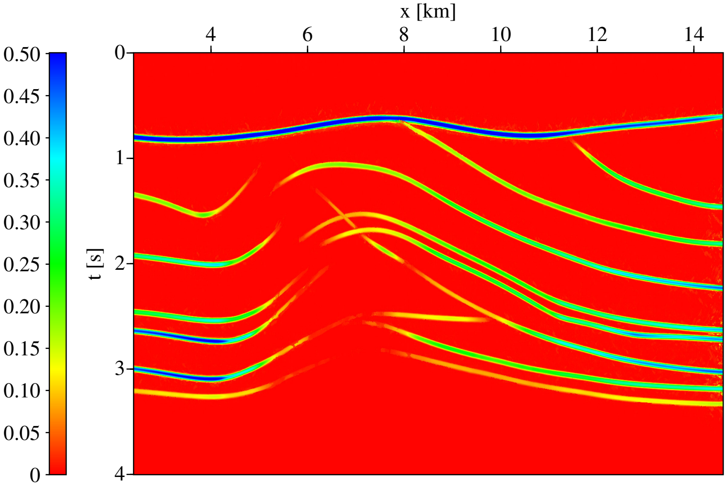
True P-wave velocity model [km/s]

2-D synthetic data example



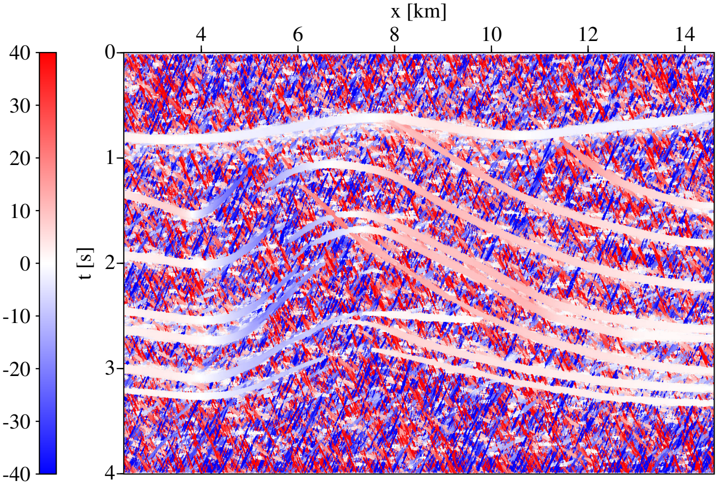
CRS stacked section

2-D synthetic data example



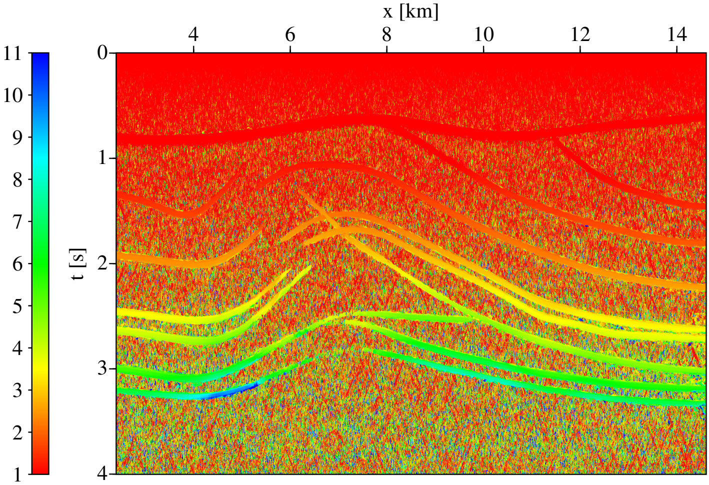
Coherence section (semblance)

2-D synthetic data example



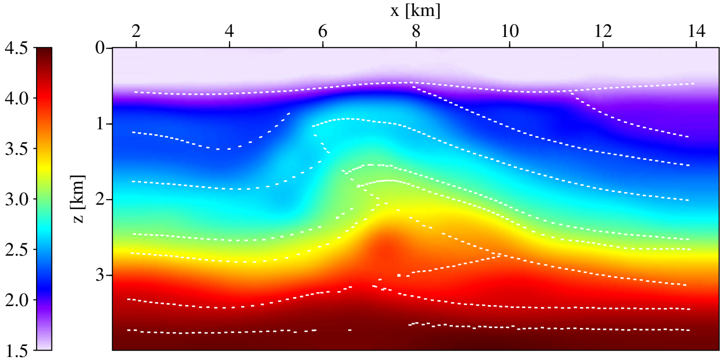
Emergence angle [°] section

2-D synthetic data example



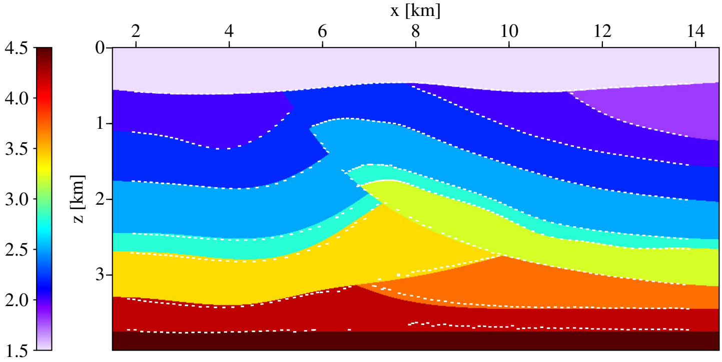
R_{NIP} [km] section

2-D synthetic data example



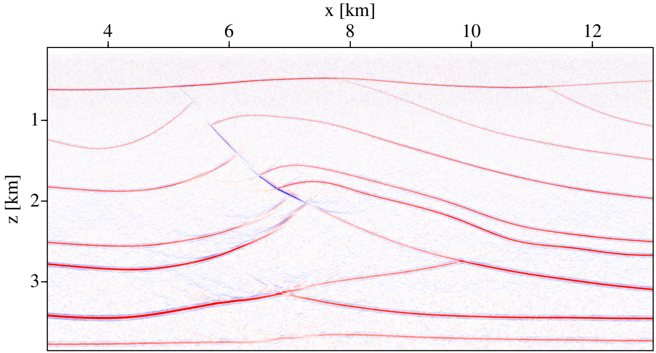
Final model [km/s] with dip bars

2-D synthetic data example



True model [km/s] with dip bars

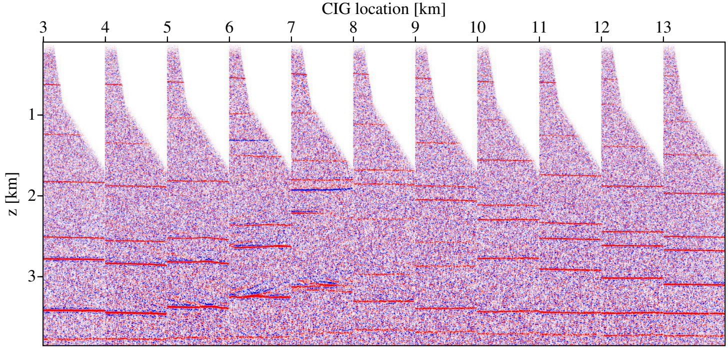
2-D synthetic data example



Prestack depth migration

2-D synthetic data example

Proof of consistency:



Prestack depth migration
(selected common-image gathers)

Conclusions

- generalization of stacking velocity analysis
- automated high-density analysis
- simple, (semi-)automatic extraction of traveltimes *and* (smoothed) wavefield attributes in poststack domain
- various applications of wavefield attributes
- tailored inversion method: NIP wave tomography
- entire workflow based on consistent assumptions

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Acknowledgments

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Related presentations

Session "Seismic Imaging", Wednesday morning:

- 09:20 Smoothing and automated picking of kinematic wavefield attributes
- 09:45 CRS-stack-based seismic imaging for land data and complex near-surface conditions
- 11:00 True-amplitude CRS-based Kirchhoff time migration for AVO analysis
- 11:25 Common-Reflection-Surface stack for OBS and VSP geometries and multi-component seismic reflection data