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
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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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combine advantages of different approaches
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- often difficult, especially in 3-D
- optimum model matches forward-modeled and picked traveltimes
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- picking of *locally coherent* reflection events, i.e., traveltime plus local dip
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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, $v_{RMS}^{\text{def}} = v_{\text{stack}}$ or $v_{RMS}^{\text{def}} = v_{\text{DMO}}$
- conversion of RMS velocities to interval velocities
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- avoid picking in prestack data
- retain coherence based analysis
- allow highly automated application
- go beyond the limits of Dix inversion

This requires

- a generalized stacking velocity analysis
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Time domain

Acquisition & Preprocessing

Residual static correction

Conventional processing
e.g. NMO/DMO etc.

Data driven processing
CRS stack

Prestack/Poststack time migration

Estimation of macro model

Depth domain

Poststack depth migration

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Structural imaging & further analysis

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yellow = CRS-related applications
Seismic reflection imaging

green = topics covered in this talk
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0 1 2 3 4 t [s]

4 6 8 10 12 14 x [km]

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\[ t^2 (\Delta \xi, h) = (t_0 + 2 p_\xi \cdot \Delta \xi)^2 + 2t_0 \left( \Delta \xi^T M_\xi \Delta \xi + h^T M_h h \right) \]
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p_\xi &= \frac{1}{2} \frac{\partial t}{\partial \xi} \\
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\end{align*}
\]

- \(t_0\) zero-offset traveltime
- \(h\) source/receiver offset
- \(\Delta \xi\) 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

Motivation

Introduction
Travelt. tomography
Velocity analysis
Objective

General workflow
CRS stack
Basic concepts
Wavefield attributes

NIP wave tomography
Principle
Data examples

Conclusions
Acknowledgments
Related talks
2-D stacking operators: CRS operator

![Graph showing 2-D stacking operators: CRS operator](image)

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Stack results: NMO/DMO/stack

CMP location approx. 13km

(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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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
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CRS wavefield attributes in 3-D

- Normal Wavefront
- Central Ray
- NIP Wavefront

 tanı: slowness vector and curvature matrices!
Reformulation of traveltime formula
Reformulation of traveltime formula

In terms of traveltime derivatives:

\[ t^2 (\Delta \xi, h) = \left( t_0 + 2 p_\xi \cdot \Delta \xi \right)^2 \]
\[ + 2 t_0 \left( \Delta \xi^T M_\xi \Delta \xi + h^T M_h h \right) \]

\[ p_\xi = \frac{1}{2} \frac{\partial t}{\partial \xi} \]
\[ M_h = \frac{1}{2} \frac{\partial^2 t}{\partial h^2} \]
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- \( t_0 \) zero-offset traveltime
- \( h \) source/receiver offset
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Reformulation of traveltime formula

In terms of kinematic wavefield attributes:

\[ t^2 (\Delta \xi, h) = (t_0 + 2 p_\xi \cdot \Delta \xi)^2 + 2t_0 \left( \Delta \xi^T M_\xi \Delta \xi + h^T M_h h \right) \]

\[ p_\xi = \frac{1}{v_0} (\sin \alpha \cos \psi, \sin \alpha \sin \psi)^T \]

\[ M_h = \frac{1}{v_0} DK_{NIP} D^T \]

\[ M_\xi = \frac{1}{v_0} DK_N D^T \]

\( t_0 \) zero-offset traveltime

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- \( t_0 \) zero-offset traveltime
- \( h \) source/receiver offset
- \( \Delta \xi \) midpoint displacement
- \( \alpha \) emergence angle of normal ray
- \( \psi \) azimuth of normal ray
- \( D \) transformation ray-centered/global coordinates
- \( K_{NIP} \) curvature matrix of NIP wavefront
- \( K_N \) 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 & extraction of wavefield attributes

Separate presentation
Extracted wavefield attributes

Smoothing & extraction of wavefield attributes

Separate presentation
NIP wave tomography

Available so far:

- ZO traveltime/location picks \((t_0, \xi)\)
- Slowness vectors \(p_{\xi}(t_0, \xi)\) and second derivative matrices \(M_h(t_0, \xi)\)
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NIP waves provide a simple and evident imaging condition for inversion!
NIP wave tomography

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NIP waves provide a simple and evident imaging condition for inversion!
NIP wave tomography

Attributes $M_h$ and $p_\xi$ at $(t_0, \xi)$ locally describe an emerging NIP wavefront.
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 traveltime 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

\[(p_{\xi_x}, p_{\xi_y}) \rightarrow M_\phi \tau \rightarrow (\xi_x, \xi_y) \]

\[\nabla(x,y,z) \rightarrow (e_x, e_y) \rightarrow NIP (x,y,z)\]
Data and model components

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 \(\phi\): \(M_\phi\)
Data and model components

Data:
\[(\tau, M_\phi, p_{\xi_x}, p_{\xi_y}, \xi_x, \xi_y)_i\]
\[\tau = t_0 / 2\]

Model:
\[(x, y, z, e_x, e_y)_i, v_{jkl}\]
\[v_{jkl}: \text{B-spline coefficients}\]

\[M_h \text{ only required for one azimuth } \phi: M_\phi\]
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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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
2-D synthetic data example

$R_{\text{NIP}}$ [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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This work was kindly supported by the sponsors of the Wave Inversion Technology (WIT) Consortium, Karlsruhe, Germany. I also thank the Sociedade Brasileira de Geofísica (SBGf) for its support.
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
Motivation

Introduction
  Traveltime tomography
  Velocity analysis

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  Wavefield attributes

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