

**TOMOGRAPHIC DETERMINATION OF STRUCTURAL  
VELOCITIES FROM DEPTH-MIGRATED SEISMIC DATA**

**A DISSERTATION  
SUBMITTED TO THE DEPARTMENT OF GEOPHYSICS  
AND THE COMMITTEE ON GRADUATE STUDIES  
OF STANFORD UNIVERSITY  
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS  
FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY**

**By  
Johannes A. van Trier  
June 1990**

© Copyright 1990  
by  
Johannes A. van Trier

printed as Stanford Exploration Project No. 66  
by permission of the author

Copying for all internal purposes of the sponsors  
of the Stanford Exploration Project is permitted

# TOMOGRAPHIC DETERMINATION OF STRUCTURAL VELOCITIES FROM DEPTH-MIGRATED SEISMIC DATA

*Johannes A. van Trier, Ph.D.*  
*Stanford University, 1990*

## ABSTRACT

One of the main goals in seismic data processing is to estimate seismic velocities of geological structures in the Earth. Structural velocities are needed for depth migration, the process that converts seismic data, recorded as a function of time, into a depth image of the subsurface. Conventional velocity-analysis methods generally assume flat-layered geology and mild lateral velocity variations. In areas with structurally complex geology, these methods often fail, and more sophisticated techniques are required. One of these techniques, seismic tomography, compares observed traveltimes, measured for each source-receiver experiment, with expected traveltimes, computed by ray tracing through an assumed velocity model; the differences are projected back over the traced ray paths to produce an update to the model.

However, traveltime tomography has some drawbacks. First, picking traveltimes can be cumbersome for data recorded in structurally complex regions. Second, in reflection seismology reflector positions are generally unknown, and ray paths cannot be accurately determined. Third, ray tracing may be complicated in areas with strong lateral velocity variation and large velocity contrasts at structural boundaries.

The tomographic velocity-analysis method presented in this thesis overcomes the above limitations. In contrast to traveltime tomography, I interpret seismic data *after* depth migration. More specifically, I pick reflectors in depth-migrated constant-offset sections, which are easier to interpret than unmigrated data gathers. Because the constant-offset sections all image the same subsurface area, they should be identical after migration if the correct velocity was used. Consequently, discrepancies between the reflectors in the different sections indicate errors in the velocity model used for migrating the data. I correct the migration-velocity model by an iterative optimization technique that minimizes these discrepancies. The optimization scheme is a conjugate-gradient method, where the

gradient operator linearly relates perturbations in velocities to changes in reflector positions. In calculating this linear operator, I use the migrated reflectors to reconstruct the rays, and, furthermore, I include ray bending effects by incorporating movement of the reflectors as a function of velocity. The calculations do not require an elaborate ray tracing scheme: instead, I use an upwind finite-difference algorithm that computes seismic traveltimes directly on a grid model of the subsurface.

The method succeeds in estimating structural velocities for a data set recorded over a salt structure in the deep Gulf of Mexico.

## Acknowledgments

I am grateful to several people for their help and guidance. I thank my advisor, Jon Claerbout, for creating an outstanding research environment at the Stanford Exploration Project (SEP), not only by providing his students with the best hardware and software tools available, but also by giving them the academic freedom to explore (possibly wild) ideas on their own. Francis Muir has been a steady mentor throughout my studies at Stanford. I appreciate both his invaluable expertise in seismic exploration and his good sense of humor, which provided some lighthearted moments on the otherwise dark fourth floor of the Mitchell Building. I also benefited from stimulating discussions with Fabio Rocca during his sabbatical year at Stanford.

All my fellow students in the SEP made my stay at Stanford a rewarding experience. Kamal Al-Yahya, Paul Fowler, Bill Harlan, Clement Kostov, Peter Mora, Rick Ottolini, Shuki Ronen, and Chuck Sword helped me get started in my early years at SEP. I had many interesting discussions on velocity analysis with Biondo Biondi, John Etgen, and Marta Woodward. Jean-Claude Dulac and Dave Nichols explained to me the subtleties of C++ and InterViews, and helped me write the interactive software that was crucial for my research. Steve Cole and Joe Dellinger often assisted me in solving graphics problems.

Francis Collino of IFP provided valuable advice in the initial stage of my research. His insights helped me formulate the linear theory of Chapter 4. Bill Symes of Rice University brought upwind finite-difference techniques to my attention, and gave me useful ideas on how to apply them to the eikonal equation.

Financial support for my work came from the sponsors of the SEP. Rodney Calvert facilitated an enjoyable summer at Shell's research facilities in Rijswijk, the Netherlands, during which time I learned many invaluable facts about seismic data processing in the oil industry. Arco Oil and Gas Co. provided the Gulf of Mexico data set through the kind efforts of Paul Fowler and Bruce Verwest.

Paul Fowler, Bill Harlan, and Marta Woodward critically read an early thesis draft, and suggested useful improvements. Fannie Toldi edited the final version of the thesis with great care and expertise.

Finally, I want to thank my wife, Joyce. Her patience, love, and support gave me the strength to complete this work.

# Table of Contents

<b>Abstract</b>	<b>iii</b>
<b>Acknowledgments</b>	<b>v</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Goal . . . . .	1
1.2 Problems with imaging salt structures . . . . .	2
1.3 Tomography after depth migration . . . . .	6
1.4 Comparison with travelttime tomography . . . . .	7
1.5 Overview . . . . .	8
<b>2 Structural interpretation and velocity estimation</b>	<b>11</b>
2.1 Introduction . . . . .	11
2.2 What is a seismic event? . . . . .	11
2.2.1 Normal moveout . . . . .	12
2.2.2 Dip moveout . . . . .	13
2.2.3 Kinematics of an event point . . . . .	13
2.3 Complex structure . . . . .	16
2.3.1 Migrating the prestack data . . . . .	16
2.3.2 Interpreting the migrated data . . . . .	20
2.4 Pitfalls . . . . .	22
<b>3 Finite-difference travelttime calculations</b>	<b>25</b>
3.1 Introduction . . . . .	25
3.2 Eikonal equation . . . . .	26
3.2.1 Hyperbolic conservation law . . . . .	26

3.3	Finite-difference scheme . . . . .	28
3.3.1	Initial and boundary conditions . . . . .	29
3.4	Example . . . . .	30
3.5	Limitations . . . . .	32
<b>4</b>	<b>Residual event migration</b>	<b>35</b>
4.1	Introduction . . . . .	35
4.2	Prestack depth migration . . . . .	36
4.3	Event modeling . . . . .	38
4.3.1	Triplications . . . . .	41
4.3.2	Operator notation . . . . .	41
4.4	Event migration . . . . .	43
4.4.1	Algorithm . . . . .	44
4.5	Residual event migration . . . . .	45
4.6	Field data example . . . . .	46
4.7	Residual event migration as a linear operator . . . . .	47
4.7.1	Calculating the linear residual-migration operator . . . . .	49
4.7.2	Example . . . . .	50
4.8	Summary . . . . .	52
<b>5</b>	<b>Velocity estimation</b>	<b>53</b>
5.1	Introduction . . . . .	53
5.2	Model parametrization . . . . .	54
5.2.1	Parametrizing horizons? . . . . .	55
5.3	Objective function . . . . .	55
5.3.1	Pseudo-depth perturbations after NMO and DMO . . . . .	56
5.3.2	Minimizing the objective function by least squares . . . . .	57
5.4	Backprojection operator . . . . .	59
5.4.1	Computing the backprojection operator . . . . .	60
5.4.2	Verifying the backprojection operator . . . . .	61
5.5	Optimization . . . . .	63
5.6	Structural velocities . . . . .	65
5.6.1	Constraining the optimization . . . . .	66
5.7	Summary . . . . .	67

<b>6</b>	<b>Field data results</b>	<b>69</b>
6.1	Description of the data . . . . .	69
6.2	Inversion results . . . . .	70
6.2.1	Residual moveout after inversion . . . . .	73
6.2.2	Imaging below the salt . . . . .	75
6.2.3	Structural model . . . . .	78
6.3	Conclusions . . . . .	79
<b>A</b>	<b>Derivatives of event parameters</b>	<b>81</b>
A.1	Relating reflector movement to changes in events . . . . .	81
A.2	Relating model perturbations to changes in events . . . . .	82
<b>B</b>	<b>MigVelAn: An interactive interface for migration-velocity analysis</b>	<b>85</b>
B.1	Picking migrated data . . . . .	85
	<b>Bibliography</b>	<b>91</b>



## List of Figures

1.1	Time-migrated image of Arco data set . . . . .	3
1.2	Common-midpoint and shot gather of Arco data set . . . . .	4
1.3	NMO velocity analysis of CMP gather in Figure 1.2a . . . . .	5
2.1	Near-offset section of Arco data set . . . . .	14
2.2	Far-offset section of Arco data set . . . . .	15
2.3	Migrated near-offset section of Arco data set . . . . .	17
2.4	Migrated far-offset section of Arco data set . . . . .	18
2.5	CRP gathers of Arco data set . . . . .	19
2.6	Detail of constant-offset section . . . . .	21
2.7	Picked reflectors in the migrated constant-offset sections . . . . .	22
3.1	Wedge model . . . . .	30
3.2	Rays traced through wedge model . . . . .	31
3.3	Finite-difference traveltimes for wedge model . . . . .	31
3.4	Comparison of finite-difference traveltimes with wavefield computed by acoustic wave-equation modeling . . . . .	32
4.1	Migration ellipse . . . . .	37
4.2	Schematic example of event modeling . . . . .	39
4.3	Constant-offset reflection events computed for the model in Figure 3.1. . . . .	40
4.4	Migration ellipses for reflection event off of a dipping reflector . . . . .	43
4.5	Detail of migrated constant-offset section (offset 1.75 km) and picked, steeply dipping reflectors. . . . .	46
4.6	Events modeled for the reflectors in Figure 4.5 . . . . .	47
4.7	Residually migrated reflectors . . . . .	48
4.8	Linear residual migration of a constant-offset reflection event from a dipping reflector with a “blob” model . . . . .	51

5.1	Dipping reflector migrated with wrong velocity model . . . . .	62
5.2	Pseudo-depth perturbations for the dipping reflector of Figure 5.1 . . . . .	63
5.3	Optimization algorithm. . . . .	64
6.1	Initial velocity model for Arco data set . . . . .	70
6.2	Inverted velocity models for Arco data set . . . . .	71
6.3	Inverted velocity profiles at a surface location of 4.5 km . . . . .	72
6.4	Reflectors in the migrated constant-offset sections before and after inversion	73
6.5	CRP gathers before and after inversion . . . . .	74
6.6	Initial depth image of region below the salt structure . . . . .	75
6.7	Final depth image after inversion . . . . .	76
6.8	Depth image after migration with structural velocity model . . . . .	77
6.9	Structural model . . . . .	78
B.1	Snapshot of MigVelAn . . . . .	87
B.2	Same as Figure B.1, but with zoomed-in section . . . . .	88
B.3	Residual-moveout curves in CRP gathers . . . . .	89