

"Forward and inverse modeling of controlled-source seismic data"

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Reference list

1. General papers

Braile and Smith 1975

Mooney 1983

Nowack and Braile 1993

Rawlinson and Sambridge 2003a

Zelt 1999

2. Experiments

BABEL Working Group 1993

Christeson *et al.* 1996

Fuis *et al.* 2001

Gorman *et al.* 2002

Henstock *et al.* 1997

Jarchow *et al.* 1994

Kaila and Krishna 1992

Kanasewich *et al.* 1985

Kohler and Fuis 1992

Lafond and Levander 1995

Levander *et al.* 1994

Mooney and Brocher 1987

Morgan *et al.* 2000

Morozova *et al.* 1999

Neves *et al.* 1996

Park *et al.* 2007

Peirce and Day 2002

Thybo and Perchuc 1997

Zelt *et al.* 2006b

3. Data processing

Christeson *et al.* 1999

Clayton and McMechan 1981

Gorman and Clowes 1999

Larkin and Levander 1996

Nakamura *et al.* 1987

Park *et al.* 2007

Purdy 1982

Spudich and Orcutt 1980

Toomey *et al.* 1994

Zelt 1999

Zelt and Forsyth 1994

Zelt *et al.* 2006a

4. 1D, 2D, 2.5D and 3D considerations

Aki and Richards 2002, pp. 413-29

Cerveny *et al.* 1977

Clayton and McMechan 1981

Fuchs and Mueller 1971

Hole *et al.* 2000a
 McMechan and Mooney 1980
 Mooney 1983
 Morgan *et al.* 2000
 Sain and Kaila 1996
 Smith *et al.* 1975
 Toomey *et al.* 1994
 Van Avendonk *et al.* 2004
 Wenzel and Sandmeier 1992
 Zelt and Barton 1998
 Zelt and White 1995
 Zelt and Zelt 1998
 Zelt *et al.* 1996
 Zelt *et al.* 2006b

5. Forward modeling

Cerveny *et al.* 1977
 Chapman and Drummond 1982
 Chiu *et al.* 1986
 Eaton 1993
 Hole and Zelt 1995
 Julian and Gubbins 1977
 McMechan and Mooney 1980
 Moser 1991
 Moser *et al.* 1992
 Nakanishi and Yamaguchi 1986
 Podvin and Lecomte 1991
 Popovici and Sethian 2002
 Rawlinson and Sambridge 2004
 Sethian and Popovici 1999

Spence *et al.* 1984
 Um and Thurber 1987
 Van Avendonk *et al.* 1998
 Van Avendonk *et al.* 2001
 van Trier and Symes 1991
 Vidale 1988; 1990
 White 1989 Rawlinson *et al.* 2001
 Zelt and Ellis 1988
 Zelt and Smith 1992
 Zhao *et al.* 1997

6. Traveltime inversion and tomography: theory and practical issues

Bevington 1969
 Boschetti *et al.* 1996
 Constable *et al.* 1987
 Hammer *et al.* 1994
 Menke 1989
 Nolet 1987
 Paige and Saunders 1982
 Park *et al.* 2007
 Press *et al.* 1992.
 Pullammanappallil and Louie 1994
 Rawlinson *et al.* 2001
 Scales *et al.* 1988
 Scales *et al.* 1990
 Sen and Stoffa 1995
 Shaw and Orcutt 1985
 Spence *et al.* 1985

Toomey *et al.* 1994

Van Avendonk *et al.* 1998

Zelt 1999

Zelt and Barton 1998

Zelt and Smith 1992

Zelt *et al.* 2006a

7. **Traveltime inversion and tomography: algorithms**

Aki and Lee 1976

Clowes *et al.* 1995

Crosson 1976

Firbas 1981

Hammer *et al.* 1994

Hobro *et al.* 2003

Hole 1992

Hole *et al.* 1992

Huang *et al.* 1986

Ilchenko 1985

Korenaga *et al.* 2000

Lailly and Sinoquet 1996

Lutter and Nowack 1990

Lutter *et al.* 1990

McCaughey and Singh 1997

Palmer 1981

Pavlenkova 1982

Rawlinson and Sambridge 2003b

Rawlinson *et al.* 2001

Spence *et al.* 1985

Toomey *et al.* 1994

Trinks *et al.* 2005

Van Avendonk *et al.* 1998

White 1989

Zelt 1994

Zelt and Barton 1998

Zelt and Smith 1992

Zelt *et al.* 1999

Zhang and Toksöz 1998

Zhang *et al.* 1998

8. **Amplitude modelling**

Braile and Smith 1975

Cerveny 1977

Cerveny *et al.* 1982

Chapman and Drummond 1982

Fuchs and Muller 1971

Gorman *et al.* 2006

Grad *et al.* 2006

Lendl *et al.* 1997

Levander 1988

Levander and Holliger 1992

Parsons *et al.* 1996

Robertsson *et al.* 1994

Weber 1988

Zelt and Forsyth 1994

Zelt and White 1995

Zelt *et al.* 1993

9. **Waveform inversion**

Brenders and Pratt 2006

Chironi *et al.* 2006

Gao *et al.* 2006

Gao *et al.* 2007

Hole *et al.* 2005

Jaiswal *et al.* 2008

Minshull *et al.* 1994

Operto *et al.* 2006

Pratt 1999

Pratt *et al.* 1996

Pratt *et al.* 1998

Ravaut *et al.* 2004

Shaw and Orcutt 1985

Shipp and Singh 2002

Sun and McMechan 1992

10. S-waves, density, attenuation and anisotropy

Barton 1986

Braile 1977

Brocher 2005

Carbonell *et al.* 1996

Caress *et al.* 1992

Christensen 1996

Christensen and Mooney 1995

Christeson *et al.* 2001

Darbyshire *et al.* 1998

Dunn and Toomey 2001

Fernandez Viejo *et al.* 2005

Godfrey *et al.* 2002

Gohl and Pedersen 1995

Hashizume 1979

Jones *et al.* 1999

Li *et al.* 2006

Stoerzel and Smithson 1998

White and Clowes 1994

Wilcock *et al.* 1995

Zelt and Ellis 1990

Zelt and White 1995

11. Wide-angle migration

Henstock *et al.* 1997

Holbrook *et al.* 1992

Holbrook *et al.* 1994

Lafond and Levander 1995

McMechan and Fuis 1987

Milkereit *et al.* 1990

Stoerzel and Smithson 1998

Van Avendonk 2004

Wissinger *et al.* 1997

Zelt and Forsyth 1994

Zelt and White 1995

Zelt *et al.* 1998

12. Fine-scale heterogeneities

Gorman *et al.* 2006

Lendl *et al.* 1997

Levander and Holliger 1992

Muller *et al.* 1992

Poppeliers and Levander 2004
 Pullammanappallil *et al.* 1997

13. Joint inversion

Benz *et al.* 1996
 Bosch *et al.* 2005
 Godfrey *et al.* 2002
 Hole *et al.* 2000b
 Jaiswal *et al.* 2006
 Jones *et al.* 1999
 Korenaga *et al.* 2001
 McCaughey & Singh 1997
 Nielsen and Jacobsen 2000
 Ramachandran *et al.* 2005
 Roy *et al.* 2005
 Symons and Crosson 1997
 Zelt 1999
 Zelt *et al.* 2003

14. Model assessment

Christeson *et al.* 1999
 Day *et al.* 2001
 Evangelidis *et al.* 2004
 Grad *et al.* 2006
 Holbrook *et al.* 2001
 Holbrook *et al.* 1994
 Korenaga *et al.* 2000

Levander *et al.* 2005
 Morgan *et al.* 2002
 Rawlinson and Sambridge 2003a
 Scales 1989
 Schlindwein *et al.* 2003
 Toomey *et al.* 1994
 White 1989
 White and Boland 1992
 Zelt 1999
 Zelt 1998
 Zelt and Barton 1998
 Zelt and Smith 1992
 Zelt and White 1995
 Zelt *et al.* 2006a
 Zelt *et al.* 1999
 Zelt *et al.* 2003
 Zhang and Toksöz 1998
 Zhang *et al.* 1998

15. Future directions

Aldridge *et al.* 2004
 Dahlen *et al.* 2000
 Komatitsch and Tromp 1999
 Komatitsch and Tromp 2005
 Pyun *et al.* 2005
 Spitzer and White 2005
 Watanabe *et al.* 1999

References

- Aki K, Lee W H K 1976 Determination of 3-dimensional velocity anomalies under a seismic array using 1st-P arrival times from local earthquakes .1. A homogeneous initial model. *J. Geophys. Res.*, **81**, 4381-99
- Aki K, Richards P G 2002 *Quantitative Seismology*, 2nd edn. University Science Books, Sausalito, CA
- Aldridge D F, Bartel L C, Symons N P 2004 Velocity-stress-pressure algorithm for 3D poroelastic wave propagation. In: *Soc. Explor. Geophy. Technical Program Extended Abstracts*, **23**, pp. 1917-20
- BABEL Working Group 1993 Deep seismic reflection/refraction interpretation of crustal structure along BABEL profiles A and B in the southern Baltic Sea. *Geophys. J. Int.*, **112**, 325-43
- Barton P J, 1986, The relationship between seismic velocity and density in the continental-crust - a useful constraint. *Geophys. J. R. Astr. Soc.*, **87**, 195-208
- Benz, H.M., Smith R.B., Mooney W.D., 1990, Crustal structure of the northwestern Basin and Range province from the 1985 Program for Array Seismic Studies of the Continental Lithosphere seismic Experiment, *J. Geophys. Res.*, **95**, 21823-21842.
- Benz H M, Chouet B A, Dawson P B, Lahr J C, Page R A, Hole J A 1996 Three-dimensional P and S wave velocity structure of Redoubt Volcano, Alaska. *J. Geophys. Res.*, **101**, 8111-28
- Bevington P R 1969 *Data reduction and error analysis for the physical sciences*. McGraw-Hill, New York
- Bosch M, Barton P, Singh S C, Trinks I 2005 Inversion of travelttime data under a statistical model for seismic velocities and layer interfaces. *Geophysics*, **70**, R33-43
- Boschetti F, Dentith M C, List R D 1996 Inversion of seismic refraction data using genetic algorithms. *Geophysics*, **61**, 1715-27
- Braile L W 1977 Interpretation of crustal velocity gradients and Q structure using amplitude-corrected seismic refraction profiles. In: Heacock J G (ed.) *The earth's crust*. American Geophysical Union, Geophysical Monograph Series, **20**, 427-39
- Braile L W, Smith R B 1975 Guide to the interpretation of crustal refraction profiles. *J. Geophys. Res.*, **40**, 145-76

- Brenders A J, Pratt R G 2007 Full waveform tomography for lithospheric imaging: results from a blind test in a realistic crustal model. *Geophys. J. Int.*, **168**, 133-151
- Brocher T M 2005 Empirical relations between elastic wavespeeds and density in the Earth's crust. *Bull. Seism. Soc. Am.*, **95**, 2081-92
- Carbonell R, Perez-Estaun P, Gallart J, Diaz J, Kashubin S, Mechie J, Stadlander R, Schulze, Knapp J H, Morozov A 1996 Crustal root beneath the Urals: Wide-angle seismic evidence. *Science*, **274**, 222-4
- Caress D W, Burnett M S, Orcutt J A 1992 Tomographic image of the axial low-velocity zone at 12-degrees-50'N on the East Pacific Rise. *J. Geophys. Res.*, **97**, 9243-63
- Cerveny V, Molotkov I, Psencik I 1977 *Ray Method in Seismology*. University of Karlova, Prague, Czechoslovakia
- Cerveny V, Popov M M, Psencik I 1982 Computation of wave fields in inhomogeneous-media—Gaussian-beam approach. *Geophys. J. Royal Astro. Soc.*, **70**, 109-28
- Chapman C H, Drummond R 1982 Body-wave seismograms in inhomogeneous-media using Maslov asymptotic theory. *Bull. Seism. Soc. Am.*, **72**, S277-317
- Chironi C, Morgan J V, Morgan M R 2006 Imaging of intrabasalt and subbasalt structure with full wavefield seismic tomography. *J. Geophys. Res.*, **111**, B05313, doi:10.1029/2004JB003595
- Chiu S K L, Kanasewich E R, Phadke S 1986 Three-dimensional determination of structure and velocity by seismic tomography. *Geophysics*, **51**, 1559-71
- Christensen N I 1996 Poisson's ratio and crustal seismology. *J. Geophys. Res.*, **101**, 3139-56
- Christensen N I, Mooney W D 1995 seismic velocity structure and composition of the continental-crust - a global view. *J. Geophys. Res.*, **100**, 9761-88
- Christeson G L, McIntosh K D, Shipley T H, Flueh E R, Goedde H 1999 Structure of the Costa Rica convergent margin, offshore Nicoya Peninsula. *J. Geophys. Res.*, **104**, 25443-68
- Christeson G L, Nakamura Y, Buffler R T, Morgan J, Warner M 2001 Deep crustal structure of the Chicxulub impact crater. *J. Geophys. Res.*, **106**, 21751-69
- Clayton R W, McMechan, G A 1981 Inversion of refraction data by wave field continuation. *Geophysics*, **46**, 860-8

- Clowes R M, Zelt C A, Amor J R, Ellis R M 1995 Lithospheric structure in the southern Canadian Cordillera from a network of seismic refraction lines. *Can. J. Earth Sci.*, **32**, 1485-1513
- Constable S C, Parker R L, Constable C G 1987 Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data. *Geophysics*, **52**, 289-300
- Crosson RS 1976 Crustal structure modeling of earthquake data .1. simultaneous least-squares estimation of hypocenter and velocity parameters. *J. Geophys. Res.*, **81**, 3036-46
- Dahlen F A, Hung S H, Nolet G 2000 Frechet kernels for finite-frequency traveltimes - I. Theory. *Geophys. J. Int.*, **141**, 157-74
- Darbyshire F A, Bjarnason I Th, White R S, Flóvenz O G 1998 Crustal structure above the Iceland mantle plume imaged by the ICEMELT refraction profile. *Geophys. J. Int.*, **135**, 1131-49
- Day AJ, Peirce C, Sinha M C 2001 Three-dimensional crustal structure and magma chamber geometry at the intermediate-spreading, back-arc Valu Fa Ridge, Lau Basin - results of a wide-angle seismic tomographic inversion. *Geophys. J. Int.*, **146**, 31-52
- Dunn R A, Toomey D R 2001 Crack-induced seismic anisotropy in the oceanic crust across the East Pacific Rise (9 degrees 30'N). *Earth Planet. Sci. Lett.*, **189**, 9-17
- Eaton D W S 1993 Finite difference travelttime calculation for anisotropic media. *Geophys. J. Int.*, **114**, 273-80
- Evangelidis C P, Minshull TA, Henstock T J 2004 Three-dimensional crustal structure of Ascension Island from active source seismic tomography. *Geophys. J. Int.*, **159**, 311-25
- Fernandez-Viejo G, Clowes R M, Welford K M 2005 Constraints on the composition of the crust and uppermost mantle in northwestern Canada: Vp/Vs variations along Lithoprobe's SNorCLE transect. *Can. J. Earth Sci.*, **42**, 1205-22
- Firbas P 1981 Inversion of travel-time data for laterally heterogeneous velocity structure - linearization approach. *Geophys. J. R. Astr. Soc.*, **67**, 189-98
- Fuchs K, Muller G 1971 Computation of synthetic seismograms with reflectivity method and comparison with observations. *Geophys. J. Royal Astr. Soc.*, **23**, 417-33
- Fuis G S, Ryberg T, Godfrey N J, Okaya D A, Murphy J M 2001 Crustal structure and tectonics from the Los Angeles basin to the Mojave Desert, southern California. *Geology*, **29**, 15-18
- Gao F, Levander A, Pratt R G, Zelt C A, Fradelizio G-L 2006 Waveform Tomography at a

- Ground Water Contamination Site: VSP-Surface Dataset, *Geophysics*, **71**, H1-H11
- Gao, F, Levander A, Pratt R G, Zelt C A Fradelizio G-L 2007 Waveform Tomography at a Ground Water Contamination Site: Surface reflection data, *Geophysics*, **72**, G45-G55
- Godfrey N J, Christensen N I, Okaya D A 2002 The effect of crustal anisotropy on reflector depth and velocity determination from wide-angle seismic data: a synthetic example based on South Island, New Zealand. *Tectonophysics*, **355**, 145-61
- Gohl K, Pedersen L B 1995 Collisional tectonics of the Baltic Shield in the northern Gulf of Bothnia from Seismic data of the BABEL project. *Geophys. J. Int.*, **120**, 209-26
- Gorman A R, Clowes R M 1999 Wave-field tau-*p* analysis for 2-D velocity models: Application to western North American lithosphere. *Geophys. Res. Lett.*, **26**, 2323-6
- Gorman A R, Clowes R M, Ellis R M, Henstock T J, Spence G D, Keller G R, Levander A, Snelson C M, Buriannyk M J A, Kanasewich E R, Asudeh I, Hajnal Z, Miller K C 2002 Deep probe: imaging the roots of western North America. *Can. J. Earth. Sci.*, **39**, 375-98
- Gorman A R, Nemeth B, Clowes R M, Hajnal Z 2006 An investigation of upper mantle heterogeneity beneath the Archaean and Proterozoic crust of western Canada from Lithoprobe controlled-source seismic experiments. *Tectonophysics*, **416**, 187-207
- Grad M, Guterch A, Keller G R, Janik T, Hegedus E, Vozar J, Slaczka A, Tiira T, Yliniemi J 2006 Lithospheric structure beneath trans-Carpathian transect from Precambrian platform to Pannonian basin: CELEBRATION 2000 seismic profile CEL05. *J. Geophys. Res.*, **111**, B03301, doi:10.1029/2005JB003647
- Hammer P T C, Dorman L M, Hildebrand J A, Cornuelle B D 1994 Jasper Seamount structure: seafloor seismic refraction tomography. *J. Geophys. Res.*, **99**, 6731-52
- Hashizume M 1979 *Q* of the crust beneath southwestern Honshu, Japan, derived from explosion seismic waves. *Phys. Earth Planet. Int.*, **20**, 25-32
- Henstock T J, Levander A, Hole J A 1997 Deformation in the lower crust of the San Andreas fault system in northern California. *Science*, **278**, 650-3
- Hobro J W D, Singh S C, Minshull T A 2003 Three-dimensional tomographic inversion of combined reflection and refraction seismic traveltimes data. *Geophys. J. Int.*, **152**, 79-93
- Holbrook W S, Reiter E C, Purdy G M, Toksoz M N 1992 Image of the Moho across the continent-ocean transition, United-States east-coast. *Geology*, **20**, 203-206

- Holbrook W S, Reiter E C, Purdy G M, Sawyer D S, Stoffa P L, Austin J A, Oh J, Makris J 1994 Deep structure of the U.S. Atlantic continental margin, offshore South Carolina, from coincident ocean bottom and multichannel seismic data. *J. Geophys. Res.*, **99**, 9155-78
- Holbrook W S, Larsen H C, Korenaga J, Dahl-Jensen T, Reid I D, Kelemen P B, Hopper J R, Kent G M, Lizarralde D, Bernstein S, Detrick R 2001 Mantle thermal structure and active upwelling during continental breakup in the North Atlantic. *Earth Planetary Sci. Lett.*, **190**, 251-62
- Holbrook, W.S., Páramo, P., Pearse, S., and Schmitt, R.W., 2003, Thermohaline fine structure in an oceanographic front from seismic reflection profiling, *Science*, **301**, 821-824, DOI: 10.1126/science.1085116.
- Hole J A 1992 Nonlinear high-resolution three-dimensional seismic travel time tomography. *J. Geophys. Res.*, **97**, 6553-62
- Hole J A, Beaudoin B C, Klemperer S L 2000a Vertical extent of the newborn San Andreas fault at the Mendocino triple junction, *Geology*, **28**, 1111-4
- Hole J A, Brocher T M, Klemperer S L, Parsons T, Benz H M, Furlong K P 2000b Three-dimensional seismic velocity structure of the San Francisco Bay area. *J. Geophys. Res.*, **105**, 13859-73
- Hole J A, Clowes R M, Ellis R M 1992 Interface inversion using broadside seismic refraction data and 3-dimensional travel time calculations. *J. Geophys. Res.*, **97**, 3417-29
- Hole J A, Ryberg T, Fuis G S, Bleibinhaus F, Sharma A K 2006 Structure of the San Andreas fault zone at SAFOD from a seismic refraction survey. *Geophys. Res. Lett.*, **33**, L07312
- Hole J A, Zelt B C 1995 Three-dimensional finite-difference reflection travel times. *Geophys. J. Int.*, **121**, 427-34
- Hole J A, Zelt CA, Pratt R G 2005 Advances in controlled-source seismic imaging. *EOS*, **86**, 177-181
- Holliger, K., and A.R. Levander, 1992, A stochastic view of the lower crust based on the Ivrea Zone, *Geophys. Res. Letters*, **19**, 11, 1153-1156.
- Huang H, Spencer C, Green A 1986 A method for the inversion of refraction and reflection travel times for laterally varying velocity structures. *Bull. Seism. Soc. Am.*, **76**, 837-46
- Hughes S, Barton P J, Harrison D 1998 Exploration in the Shetland-Faeroe Basin using densely spaced arrays of ocean-bottom seismometers. *Geophysics*, **63**, 490-501

- Ilchenko T V 1985 A technique for determining velocity structure from traveltimes along a system of DSS profiles. *Geophys. J.*, **7**, 59-66
- Jaiswal P, Zelt C A, Pecher I A 2006 Seismic characterization of a gas hydrate system in the Gulf of Mexico using wide-aperture data. *Geophys. J. Int.*, **165**, 108-20
- Jaiswal P, Zelt C A, Bally A W, Dasgupta R 2008 2-D travelttime and waveform inversion for improved seismic imaging: Naga Thrust and Fold Belt, India, *Geophys. J. Int.*, **173**, 642-58
- Jarchow, C M , Catchings, R D, Lutter, W J 1994 Large-explosive source, wide-recording aperture, seismic profiling on the Columbia Plateau, Washington. *Geophysics*, **59**, 259-271
- Jones K, Warner M, Brittan J 1999 Anisotropy in multi-offset deep-crustal seismic experiments. *Geophys. J. Int.*, **264**, 205-17
- Julian B R, Gubbins D 1977 Three-dimensional seismic ray tracing. *J. Geophys.*, **43**, 95-113
- Kaila K L, Krishna V G 1992 Deep seismic-sounding studies in India and major discoveries. *Current Sci.*, **62**, 117-54
- Kanasewich E R, Chiu S K L 1985 Least-squares inversion of spatial seismic refraction data. *Bull. Seism. Soc. Am.*, **75**, 865—80
- Kohler, W.M., and Fuis, G.S., 1992, Empirical dependence of seismic ground velocity on the weight of explosives, shotpoint site condition, and recording distance for seismic-refraction data, *Bull. Seism. Soc. Am.*, **82**, 2032-2044.
- Komatitsch D, Tromp J 1999 Introduction to the spectral element method for three-dimensional seismic wave propagation. *Geophys. J. Int.*, **139**, 806-22
- Komatitsch D, Tromp J 2005 The spectral element method in seismology, in A. Levander and G Nolet, editors, *Seismic Earth: Array Analysis of Broadband Seismograms*, Geophysical Monograph 157, American Geophysical Union, Washington DC, 205-228
- Korenaga J, Holbrook W S, Detrick R S, Kelemen P B 2001 Gravity anomalies and crustal structure at the southeast Greenland margin. *J. Geophys. Res.*, **106**, 8853-70
- Korenaga J, Holbrook W S, Kent G M, Kelemen P B, Detrick R S, Larsen H C, Hopper J R, Dahl-Jensen T 2000 Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography. *J. Geophys. Res.*, **105**, 21591-614
- Lafond C F, Levander A 1995 Migration of wide-aperture onshore-offshore seismic data, central California: Seismic images of late-stage subduction. *J. Geophys. Res.*, **100**, 22231–43

- Lailly P, Sinoquet D 1996 Smooth velocity models in reflection tomography for imaging complex geological structures. *Geophys. J. Int.*, **124**, 349-62
- Lanz E, Maurer H, Green A.G 1998 Refraction tomography over a buried waste disposal site. *Geophysics*, **63**, 1414-1433
- Larkin S P, Levander A 1996 Wave-equation datuming for improving deep crustal seismic images. *Tectonophysics*, **264**, 371-9
- Lendl C, Tréhu A M, Goff J A, Levander A R, Beaudoin B C 1997 Synthetic seismograms through synthetic Franciscan: Insights into factors affecting large-aperture seismic data. *Geophys. Res. Lett.*, **24**, 3317-20
- Levander A 1988 Fourth-order finite-difference *P-SV* seismograms. *Geophysics*, **53**, 1425-36
- Levander A R, Holliger K 1992 Small-scale heterogeneity and large-scale velocity structure of the continental crust. *J. Geophys. Res.*, **97**, 8797-804
- Levander A, Fuis GS, Wissinger E S, Lutter W J, Oldow J S, Moore T E 1994 Seismic images of the Brooks Range fold-and-thrust belt, arctic Alaska, from an integrated seismic-reflection refraction experiment. *Tectonophysics*, **232**, 13-30
- Levander A, Zelt C A, Magnani M B 2005 Crust and upper mantle velocity structure of the Southern Rocky Mountains from the Jemez Lineament to the Cheyenne belt. In: Karlstrom K E, Keller R G (eds.) *The Rocky Mountain Region: An Evolving Lithosphere*, Geophysical Monograph Series 154, American Geophysical Union, pp. 293-308
- Li Q, Wilcock W S D, Pratt T L, Snelson C M, Brocher T M 2006 Seismic attenuation structure of the Seattle basin, Washington State, from explosive-source refraction data. *Bull. Seism. Soc. Am.*, **96**, 553-571
- Lutter W J, Nowack R L 1990 Inversion for crustal structure using reflections from the PASSCAL Ouachita experiment. *J. Geophys. Res.*, **95**, 4633-46
- Lutter W J, Nowack R L, Braile L W 1990 Seismic imaging of upper crustal structure using travel times from the PASSCAL Ouachita experiment. *J. Geophys. Res.*, **95**, 4621-31
- McCaughey M, Singh S C 1997 Simultaneous velocity and interface tomography of normal-incidence and wide-aperture travelttime data. *Geophys. J. Int.*, **131**, 87-99
- McMechan GA, Fuis G S 1987 Ray equation migration of wide-angle reflections from southern Alaska. *J. Geophys. Res.*, **92**, 407-20

- McMechan G A, Mooney W D 1980 Asymptotic ray theory and synthetic seismograms for laterally varying structures: theory and application to the Imperial Valley, California. *Bull. seism. Soc. Am.*, **70**, 2021-35
- Menke W 1989 *Geophysical Data Analysis: Discrete Inverse Theory*, Academic Press, San Diego, CA
- Milkereit B, Epili D, Green A G, Mereu R F, Morel-à-l'Huissier P 1990 Migration of wide-angle seismic-reflection data from the Grenville Front in Lake Huron. *J. Geophys. Res.*, **95**, 10987-98
- Minshull T A, Singh S C, Westbrook G K 1994 Seismic velocity structure at a gas hydrate reflector, offshore western Colombia, from full-wave-form inversion. *J. Geophys. Res.*, **99**, 4715-34
- Mooney H M 1983 Synthetic seismograms for body waves: An overview. *First Break*, **1**, 9-20
- Mooney W D, Brocher T M 1987 Coincident seismic-reflection refraction studies of the continental lithosphere - a global review. *Rev. Geophys.*, **25**, 723-43
- Morgan J V, Christeson G L, Zelt C A 2002 Testing the resolution of a 3D velocity tomogram across the Chicxulub crater. *Tectonophysics*, **355**, 215-26
- Morgan J V, Warner M R, Collins G S, Melosh H J, Christeson G L 2000 Peak ring formation in large impact craters. *Earth Planet. Sci. Lett.*, **183**, 347-54
- Morozova E A, Morozov I B, Smithson S B, Solodilov L N 1999 Heterogeneity of the uppermost mantle beneath Russian Eurasia from the ultra-long-range profile QUARTZ. *J. Geophys. Res.*, **104**, 20329-48
- Moser T J 1991 Shortest path calculation of seismic rays. *Geophysics*, **56**, 59-67
- Moser T J, Nolet G, Snieder R 1992 Ray bending revisited. *Bull. Seism. Soc. Am.*, **82**, 259-88
- Muller G, Roth M, Korn M 1992 Seismic-wave travel-times in random-media. *Geophys. J. Int.*, **110**, 29-41
- Musacchio, G., Mooney, W.D., Luetgert, J.H., Christensen, N.I., 1997, Composition of the crust in the Grenville and Appalachian provinces of North America inferred from Vp/Vs ratios. *J. Geophys. Res.*, **102**, 15,225-15,241.
- Nakamura Y, Donoho P L, Roper P H, McPherson P M 1987 Large-offset seismic surveying using ocean-bottom seismographs and air guns - instrumentation and field technique. *Geophysics*, **52**, 1601-11

- Nakanishi I, Yamaguchi K 1986 A numerical experiment on nonlinear image reconstruction from first-arrival times for two-dimensional island arc structure. *J. Phys. Earth*, **34**, 195-201
- Neves F A, Singh S C, Priestley K F 1996 Velocity structure of upper-mantle transition zones beneath central Eurasia from seismic inversion using genetic algorithms. *Geophys. J. Int.*, **125**, 869-78
- Nielsen L, Jacobsen B H 2000 Integrated gravity and wide-angle seismic inversion for 2-D crustal modelling. *Geophys. J. Int.*, **140**, 222-32
- Nolet G 1987 Seismic wave propagation and seismic tomography. In: Nolet G (ed.) *Seismic Tomography*. Reidel, Dordrecht, pp. 1-24
- Nowack, R.L. & Braile, L.W., 1993. Refraction and wide-angle reflection tomography: theory and results, in *Seismic Tomography: Theory and Practice*, ed. Iyer, H.M. & Hirahara, K., pp. 733-765, Chapman & Hall, London.
- Operto S, Virieux J, Dessa J X, Pascal G 2006 Crustal seismic imaging from multifold ocean bottom seismometer data by frequency domain full waveform tomography: Application to the eastern Nankai trough. *J. Geophys. Res.*, **111**, B09306, doi:10.1029/2005JB003835
- Paige C C, Saunders M A 1982 LSQR: An algorithm for sparse linear equations and sparse least squares, *ACM Trans. Math. Software*, **8**, 43-71
- Palmer D 1981 An introduction to the generalized reciprocal method of seismic refraction interpretation. *Geophysics*, **46**, 1508-18
- Park J, Morgan J K, Zelt C A, Okubo P B, Peters L, Benesh N 2007 Comparative velocity structure of active Hawaiian volcanoes from 3-D onshore-offshore seismic tomography. *Earth Planet. Sci. Lett.*, **259**, 500-16
- Parsons T, Blakely R J, Brocher T M 2001 A simple algorithm for sequentially incorporating gravity observations in seismic travelttime tomography. *International Geol. Rev.*, **43**, 1073-86
- Parsons T, McCarthy J, Kohler W M, Ammon C J, Benz H M, Hole J A, Criley E E 1996 Crustal structure of the Colorado Plateau, Arizona: application of new long-offset seismic data analysis techniques *J. Geophys. Res.*, **101**, 11173-94
- Pavlenkova N I 1982 The intercept-time method - possibilities and limitations. *J. Geophys.*, **51**, 85-95
- Peirce C, Day A J 2002 Ocean-bottom seismograph tomographic experiments—a consideration

- of acquisition geometries vs. resources. *Geophys. J. Int.*, **151**, 543-65
- Podvin P, Lecomte I 1991 Finite difference computation of traveltimes in very contrasted velocity models: a massively parallel approach and its associated tools. *Geophys. J. Int.*, **105**, 271-84
- Popovici A M, Sethian J A 2002 3-D imaging using higher order fast marching traveltimes. *Geophysics*, **67**, 604-9
- Poppeliers, C., and A. Levander, 2004, Estimation of vertical stochastic scale parameters in the Earth's crystalline crust from seismic reflection data, *Geophys. Res. Lett.*, **31**, L13607
10.1029/2004GL019538.
- Pratt R G, Song Z-M, Williamson P, Warner M 1996 Two-dimensional velocity models from wide-angle seismic data by wavefield inversion. *Geophys. J. Int.*, **124**, 323-40
- Pratt, G.R., Shin and G.J. Hicks, 1998. Gauss-Newton and full Newton methods in frequency-space seismic waveform inversion, *Geophys. J. Int.*, 133, 341-362.
- Pratt, R. G., 1999, Seismic waveform inversion in the frequency domain, Part 1: Theory and verification in a physical scale model, *Geophysics*, **64**, 888-901.
- Press W H, Teukolsky S A, Vetterling W T, Flannery B P 1992 *Numerical Recipes in Fortran: The Art of Scientific Computing*, 2nd edn. Cambridge University Press, Cambridge, UK
- Pullammanappallil S K, Louie J N 1994 A generalized simulated-annealing optimization for inversion of first-arrival times. *Bull. seism. Soc. Am.*, **84**, 1397-1409
- Purdy G M 1982 The correction for the travel time effects of seafloor topography in the interpretation of marine seismic data. *J. Geophys. Res.*, **87**, 8389-96
- Pyun S, Shin C, Min D J, Ha T 2005 Refraction traveltime tomography using damped monochromatic wavefield. *Geophysics*, **70**, U1-7
- Ramachandran K, Dosso S E, Spence G D, Hyndman R D, Brocher T M 2005 Forearc structure beneath southwestern British Columbia: A three-dimensional tomographic velocity model. *J. Geophys. Res.*, **110**, B02303, doi:10.1029/2004JB003258
- Ravaut C, Operto S, Imbrota L, Virieux J, Herrero A, Dell'Aversana P 2004 Multiscale imaging of complex structures from multifold wide-aperture seismic data by frequency-domain full-waveform tomography: application to a thrust belt. *Geophys. J. Int.*, **159**, 1032-56
- Rawlinson N, Houseman G A, Sambridge M 2001 Inversion of seismic refraction and wide-angle reflection traveltimes for 3-D layered crustal structure. *Geophys. J. Int.*, **145**, 381-401

- Rawlinson N, Sambridge M 2003a Seismic traveltime tomography of the crust and lithosphere. *Adv. Geophys.*, **46**, 181-98
- Rawlinson N, Sambridge M 2003b Irregular interface parametrization in 3-D wide-angle seismic traveltime tomography. *Geophys. J. Int.*, **155**, 79-92
- Rawlinson N, Sambridge M 2004 Wave front evolution in strongly heterogeneous layered media using the fast marching method. *Geophys. J. Int.*, **156**, 631-47
- Robertsson J O A, Blanch J O, Symes W W 1994 Viscoelastic finite-difference modeling. *Geophysics*, **59**, 1444-56
- Roy L, Sen M K, McIntosh K, Stoffa P L, Nakamura Y 2005 Joint inversion of first arrival seismic travel-time and gravity data. *J. Geophys. Eng.*, **2**, 277-89
- Sain K, Kaila K L 1996 Ambiguity in the solution to the velocity inversion problem and a solution by joint inversion of seismic refraction and wide-angle reflection times. *Geophys. J. Int.*, **124**, 215-27
- Scales J A 1989 On the use of conjugate-gradient to calculate the eigenvalues and singular-values of large, sparse matrices. *Geophys. J.*, **97**, 179-83
- Scales J A, Docherty P, Gersztenkorn A 1990 Regularisation of nonlinear inverse problems: imaging the near-surface weathering layer. *Inverse Problems*, **6**, 115-31
- Scales J A, Gersztenkorn A, Treitel S 1988 Fast lp solution of large, sparse, linear-systems: Application to seismic travel time tomography. *J. Comp. Phys.*, **75**, 314-33
- Schlindwein V, Bonnemant C, Reichert C, Grevemeyer I, Flueh E 2003 Three-dimensional seismic refraction tomography of the crustal structure at the ION site on the Ninetyeast Ridge, Indian Ocean. *Geophys. J. Int.*, **152**, 171-84
- Sen M, Stoffa P L 1995 *Global optimization methods in geophysical inversion*. Elsevier, Amsterdam
- Sethian J A, Popovici A M 1999 3-D traveltime computation using the fast marching method. *Geophysics*, **64**, 516-23
- Shaw P R, Orcutt J A 1985 Waveform inversion of seismic refraction data and applications to young Pacific crust, *Geophys. J. R. Astr. Soc.*, **82**, 375-414
- Shipp R M, Singh S C 2002 Two-dimensional full wavefield inversion of wide-aperture marine seismic streamer data. *Geophys. J. Int.*, **151**, 325-44

- Smith R B, Braile L W, Keller G R 1975 Upper crustal low-velocity layers - possible effect of high-temperatures over a mantle upwarp at Basin Range Colorado Plateau transition. *Earth Planet. Sci. Lett.*, **28**, 197-204
- Spence G D, Clowes R M, Ellis R M 1985 Seismic structure across the active subduction zone of western Canada. *J. Geophys. Res.*, **90**, 6754-72
- Spence G D, Whittall K P, Clowes R M 1984 Practical synthetic seismograms for laterally varying media calculated by asymptotic ray theory. *Bull. seism. Soc. Am.*, **74**, 1209-23
- Spitzer R, White R S 2005 Advances in seismic imaging through basalts: A case study from the Faroe-Shetland Basin. *Petrol. Geosci.*, **11**, 147-56
- Spudich P, Orcutt J 1980 Petrology and porosity of an oceanic crustal site: results from wave form modeling of seismic refraction data. *J. Geophys. Res.*, **85**, 1409-33
- Sroda P 2006 Seismic anisotropy of the upper crust in southeastern Poland—effect of the compressional deformation at the EEC margin: Results of CELEBRATION 2000 seismic data inversion. *Geophys. Res. Lett.*, **33**, L22302, doi:10.1029/2006GL027701
- Stoerzel A, Smithson S B 1998 Two-dimensional travel time inversion for the crustal *P* and *S* wave velocity structure of the Ruby Mountains metamorphic core complex, NE Nevada. *J. Geophys. Res.*, **103**, 21121-43
- Sun R, McMechan GA 1992 2-D full-wave-field inversion for wide-aperture, elastic, seismic data. *Geophys. J. Int.*, **111**, 1-10
- Symons N P, Crosson R S 1997 Seismic velocity structure of the Puget Sound region from 3-D non-linear tomography. *Geophys. Res. Lett.*, **24**, 2593-6
- Thybo H, Perchuc E, 1997, The seismic 8° discontinuity and partial melting in the continental mantle, *Science*, **275**, 1626-1629.
- Toomey D R, Solomon S C, Purdy G M 1994 Tomographic imaging of the shallow crustal structure of the East Pacific Rise at 9°30'N. *J. Geophys. Res.*, **99**, 24,135-57
- Trinks I, Singh S C, Chapman C H, Barton P J, Bosch M, Cherrett A 2005 Adaptive travelttime tomography of densely sampled seismic data. *Geophys. J. Int.*, **160**, 925-38
- Um J, Thurber C 1987 A fast algorithm for two-point seismic ray tracing. *Bull. Seism. Soc. Am.*, **77**, 972-86
- Van Avendonk H J A 2004 Slowness-weighted diffraction stack for migrating wide-angle seismic data in laterally varying media. *Geophysics*, **69**, 1046-52

- Van Avendonk H J A, Harding A J, Orcutt J A, Holbrook W S 2001 Hybrid shortest path and ray bending method for traveltimes and raypath calculations. *Geophysics*, **66**, 648-53
- Van Avendonk H J A, Harding A J, Orcutt J A, McClain J S 1998 A two-dimensional tomographic study of the Clipperton transform, fault. *J. Geophys. Res.*, **103**, 17885-99
- Van Avendonk H J A, Shillington D J, Holbrook W S, Hornbach M J 2004 Inferring crustal structure in the Aleutian arc from a sparse wide-angle seismic data set. *Geochem. Geophys. Geosyst.*, **5**, doi:10.1029/2003GC000664
- Van Trier J, Symes W W 1991 Upwind finite-difference calculation of traveltimes. *Geophysics*, **56**, 812-21
- Vidale J E 1988 Finite-difference calculation of traveltimes. *Bull. Seism. Soc. Am.*, **78**, 2062-76
- Vidale J E 1990 Finite-difference calculation of traveltimes in three dimensions. *Geophysics*, **55**, 521-6
- Watanabe T, Matsuoka T, Ashida Y 1999 Seismic traveltimes tomography using Fresnel volume approach. In: *Soc. Explor. Geophys. Technical Program Extended Abstracts*, **18**, pp. 1402-5
- Weber M 1988 Computation of body-wave seismograms in absorbing 2-D media using the Gaussian-beam method: comparison with exact methods. *Geophys. J.*, **92**, 9-24
- Wenzel F, Sandmeier K J 1992 Geophysical evidence for fluids in the crust beneath the Black-Forest, SW Germany. *Earth-Science Rev.*, **32**, 61-75
- White D J 1989 Two-dimensional seismic refraction tomography. *Geophys. J. Int.*, **97**, 223-45
- White D J, Boland A V 1992 A comparison of forward modeling and inversion of seismic first arrivals over the Kapuskasing Uplift. *Bull. Seism. Soc. Am.*, **82**, 304-22
- White D J, Clowes R M 1994 Seismic attenuation structure beneath the Juan-de-Fuca Ridge from tomographic inversion of amplitudes. *J. Geophys. Res.*, **99**, 3043-56
- Wilcock W S D, Solomon S C, Purdy G M, Toomey D R 1995 Seismic attenuation structure of the East Pacific Rise near 9 degrees 30'N. *J. Geophys. Res.*, **100**, 24147-65
- Wissinger E S, Levander A, Christensen N I 1997 Seismic images of crustal duplexing and continental subduction in the Brooks Range. *J. Geophys. Res.*, **102**, 20847-71
- Zelt B C, Ellis R M, Clowes R M 1993 Crustal velocity structure in the eastern Insular and southernmost Coast belts, Canadian Cordillera. *Can. J. Earth Sci.*, **30**, 1014-27
- Zelt B C, Ellis R M, Clowes R M, Hole J A 1996 Inversion of three-dimensional wide-angle seismic data from the southwestern Canadian Cordillera. *J. Geophys. Res.*, **101**, 8503-29

- Zelt B C, Talwani M, Zelt, C A 1998 Prestack depth migration of dense wide-angle seismic data, *Tectonophysics*, **286**, 193-208
- Zelt C A 1994 3-D velocity structure from simultaneous travelttime inversion of in-line seismic data along intersecting profiles. *Geophys. J. Int.*, **118**, 795-801
- Zelt C A 1998 Lateral velocity resolution from three-dimensional seismic refraction data. *Geophys. J. Int.*, **135**, 1101-12
- Zelt C A 1999 Modeling strategies and model assessment for wide-angle seismic travelttime data. *Geophys. J. Int.*, **139**, 183-204
- Zelt C A, Azaria A, Levander A 2006a 3D seismic refraction travelttime tomography at a groundwater contamination site. *Geophysics*, **71**, H67-H78
- Zelt, C A, Barton P J 1998 Three-dimensional seismic refraction tomography: A comparison of two methods applied to data from the Faeroe Basin. *J. Geophys. Res.*, **103**, 7187-210
- Zelt C A, Ellis R M 1988 Practical and efficient ray tracing in two-dimensional media for rapid travelttime and amplitude forward modeling. *Can. J. Exp. Geophys.*, **24**, 16-31
- Zelt C A, Ellis R M 1990 Crust and upper mantle Q from seismic refraction data - Peace River region. *Can. J. Earth Sci.*, **27**, 1040-47
- Zelt C A, Ellis R M, Zelt B C 2006b 3-D structure across the Tintina strike-slip fault, northern Canadian Cordillera, from seismic refraction and reflection tomography. *Geophys. J. Int.*, **167**, 1292-1308
- Zelt C A, Forsyth D A 1994 Modeling wide-angle seismic data for crustal structure: southeastern Grenville province. *J. Geophys. Res.*, **99**, 11687-704
- Zelt C A, Hojka A M, Flueh E R, McIntosh K D 1999 3D simultaneous seismic refraction and reflection tomography of wide-angle data from the central Chilean margin. *Geophys. Res. Lett.*, **26**, 2577-80
- Zelt C A, Sain K, Naumenko J V, Sawyer D S 2003 Assessment of crustal velocity models using seismic refraction and reflection tomography. *Geophys. J. Int.*, **153**, 609-26
- Zelt C A, Smith R B 1992 Seismic travelttime inversion for 2-D crustal velocity structure. *Geophys. J. Int.*, **108**, 16-34
- Zelt C A, White D J 1995 Crustal structure and tectonics of the southeastern Canadian Cordillera *J. Geophys. Res.*, **100**, 24255-73

- Zelt C A, Zelt B C 1998 Study of out-of-plane effects in the inversion of refraction/wide-angle reflection traveltimes. *Tectonophysics*, **286**, 209-21
- Zhang J, ten Brink U S, Toksöz MN 1998 Nonlinear refraction and reflection traveltime tomography. *J. Geophys. Res.*, **103**, 29743-57
- Zhang J, Toksöz MN 1998 Nonlinear refraction traveltime tomography. *Geophysics*, **64**, 1726-37
- Zhao Z, Kubota R, Fumio S, Iizuka S 1997 Crustal Structure in the southern Kanto-Tokai region derived from tomographic method for seismic explosion survey. *J. Phys. Earth*, **45**, 433-53