Short Course Notes

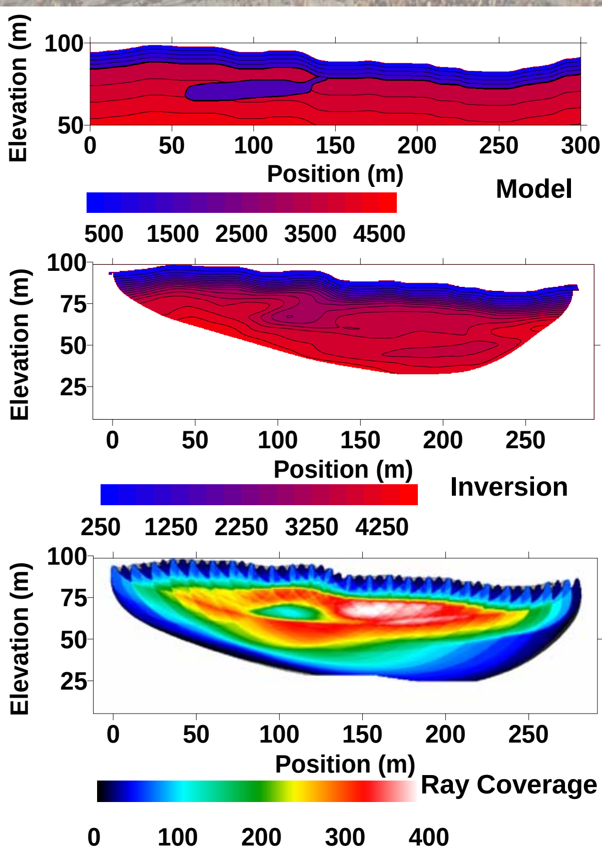
Processing of Seismic Refraction Tomography Data

Presented at

2010 Symposium on the Application of Geophysics to Engineering and Environmental Problems

Keystone, Colorado

April 10, 2010



Contributors

William Doll (Coordinator)
Battelle
Oak Ridge, TN

Jacob Sheehan
Battelle
Oak Ridge, TN

Siegfried Rohdewald
Intelligent Resources, Inc.
Vancouver, BC, Canada

Beth Burton
USGS
Denver, CO

Sponsored by Environmental and Engineering Geophysical Society

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1720 S. Bellaire Street, Suite 110
Denver, CO 80222-4303
Phone: 303.531.7517
Fax: 303.820.3844
E-mail: staff@eegs.org
Web Site: www.eegs.org

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Contact Information
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April 10, 2010

Siegfried Rohdewald
Intelligent Resources, Inc.
sales@rayfract.com
604-782-9845

Jacob Sheehan
Battelle – Oak Ridge
sheehanj@battelle.org
865-483-2538

Bethany Burton
USGS – Denver
blburton@usgs.gov
303-236-1327

Course Presenter Biosketches

Siegfried Rohdewald received a M.S. equivalent degree in Computer Science at ETH Zurich (Swiss Federal Institute of Technology) in 1988, with Geophysics as a minor field of studies. As his Thesis (with Prof. Stephan Mueller) he developed and documented an Apple Macintosh based software application for computer aided processing of geodynamic data, at the ETH Institute of Geophysics in Hoenggerberg near Zurich. During a period of practical training, he was employed by Logitech, Inc. in Redwood City, California. After obtaining his degree he worked and consulted for two Swiss geophysical/geological companies including GeoExpert ag in Schwerzenbach, until 1991. From 1991 to 2000 he was employed by and consulted for various Swiss software companies (bank accounting, database application development, communications software for message exchange), including former DEC Digital Equipment Corporation located in Duebendorf. Since 1993 he has been developing, marketing and supporting seismic refraction software, first as Swiss company Intelligent Resources and then as Canadian company Intelligent Resources Inc. located in Vancouver. He is a member of EAGE and EEGS and an Associate member of SEG.

Jacob R. Sheehan received a B.S. in Physics and Mathematics and a M.S. in Geophysics from Ohio University in 2000 and 2002, respectively. After receiving his M.S. he worked as a post-masters researcher at Oak Ridge National Laboratory for 3 years. During that time, his primary emphasis was on evaluation and application of commercial seismic refraction tomography codes, with support from the Department of Energy and Army Environmental Command. He is currently employed with Battelle in Oak Ridge, TN. His main area of research is airborne magnetic and electromagnetic methods for UXO detection. He is a member of SEG, GSA and EEGS.

Bethany L. Burton is a geophysicist with the U.S. Geological Survey in Denver, Colorado. Beth received a B.S. in Geophysical Engineering from the Colorado School of Mines (CSM) in 1999. After working for Phillips Petroleum Co. for one year in Bartlesville, Oklahoma processing 2D seismic data, she returned to CSM and completed her M.Sc. in Geophysics in 2004. Her thesis involved evaluating GPR frequency-dependent signal loss mechanisms. Beth began her career with the USGS in 2002, and since graduation, has focused on the application of several methods including resistivity, seismic refraction and reflection, frequency domain electromagnetics, magnetics, and GPR in solving various near surface problems such as Superfund site characterizations, determination of leakage potential along irrigation canals, and several dam and levee investigations. She is a member of AGU and EEGS.

SAGEEP and JEEG Papers on Seismic Refraction Tomography

The following papers are included in full as pdf files on the CD-ROM that accompanies this volume.

SAGEEP Papers

Year	Title	Authors
1989	Application of Refraction Tomography to Map the Extent of Blast-Induced Fracturing	Cumerlato, C. L., Stachura, V. J., and Tweeton, D. R.
1995	Time-Term Method with Tomographic Determination of Refractor Velocities	Yamauchi, M., and Saito, H.,
1996	Conventional Processing Techniques and Nonlinear Refraction Traveltime Tomography for Imaging Bedrock at an Eastern Massachusetts Coastal Site	Kutrubes, D., Zhang, J., and Hager, J.
1996	High-Resolution Shallow Seismic Structure Imaging Using Grid-Based Nonlinear Refraction Traveltime Tomography	Zhang, J., Kutrubes, D. L., and Toksoz, N.
1997	Refraction Traveltime Tomography of Bala Kimberlite in Riley County, Kansas	Zhang, J., and Macy,
1998	Composite Landfill Characterization: an Integrated Geophysical Study	Lanz, E., Maurer, H., Boerner, D. E., Horstmeyer, H., and Green, A. G.,
2000	Mapping Poisson's Ratio of Unconsolidated Materials from a Joint Analysis of Surface-Wave and Refraction Events	Ivanov, J., Park, C. B., Miller, R. D., and Xia, J.
2000	Viscoelastic Finite-Difference Modeling with Application to Shallow Seismic Refraction Data	Hayashi, K.
2001	Evaluation Of New Geophysical Tools For Investigation Of A Landfill, Camp Roberts, California	W.E. Doll and T.J. Gamey, J.E. Nyquist, W. Mandell, D. Groom, S. Rohdewald
2002	Geophysical Profiling In Support Of A Nitrate And Uranium Groundwater Remediation Study	William E. Doll, T. Jeffrey Gamey, David B. Watson, and Philip M. Jardine
2002	Seismic And Resistivity Tomography Characterization Of A Till-Shale Bedrock Interface	Gilein J. Steensma, Paul D. Bauman, Ian Dyck, Matthew Brassard
2003	Accuracy Of Seismic Refraction Tomography Codes At Karst Sites	Philip J. Carpenter, I. Camilo Higuera-Diaz, Michael D. Thompson, Shashank Atre, Wayne Mandell
2003	3D Refraction Tomography For Near-Surface Geological Studies	Jie Zhang, Hye Sun Kim
2003	On-Site Instant Automated Refraction Tomography	Jie Zhang, Zhikun Sun, Craig Lippus

SAGEEP Papers (continued)

2004	Seismic Tomographic Imaging Of Buried Karst Features	Philip J. Carpenter, Eduard Breuer, I. Camilo Higuera-Diaz, Michael Thompson, Jacob Sheehan, William E. Doll, Wayne Mandell
2004	Comparison Of Masw And Refraction Tomography	Jacob R. Sheehan, William E. Doll, Wayne Mandell
2004	P- And S-Wave Refraction Studies In The Yangsan Fault Zone Of Korea	K. Y. Kim, D. H. Kim, and S. Y. Lee
2004	Waste Volume Estimation Using Geophysical Methods In A Complex Geologic Setting	Mike Thompson, Drew Clemens, Steve Miller, John Tesner, Wayne Mandell , Phil Durgin, Bill Davies, and Jim McKenna
2005	Detecting Cavities with Seismic Refraction Tomography: Can it be done?	Jacob Sheehan, William Doll, Wayne Mandell, David Watson
2005	The Application of Time-Lapse Ground Penetrating Radar, Electrical Tomography and Seismic Refraction Tomography in Subsurface Water Content Studies	Giovanni Leucci
2005	Geophysical Exploration at the Giza Plateau, Egypt – A Ten Year Odyssey	Thomas Dobecki
2005	Integrated Geophysical Methods for LNG Site Characterization in a Jungle Environment	Finn Michelsen, Martin Miele
2006	Refraction Seismic Tomography - Aid in Groundwater Flow Modelling	David Abbott , Shane Dunn, Nichole Gassien
2006	A New Joint Inversion Approach applied to the Combined Tomography of DC Resistivity and Seismic Refraction Data	Thomas Günther , Carsten Rücker
2006	Advancements in Subsurface Modeling using Seismic Refraction Data	Phil Sirles , Alan Rock, Khamis Haramy
2006	A Narrow Spaced Seismic Refraction Survey for a Loosened Rock-Mass in Landslide Area	Toshiyuki Kurahashi , Yuuichi Yamawaki, Kazunori Ito
2006	Integrating Amplitudes and Traveltimes with High Resolution Refraction Methods	Derecke Palmer
2006	Seismic Refraction Response On An Asphalt Covered Surface	John Patskan and R. Michael Quesada,
2006	An Overview of Seismic Landstreamer Projects at Montana Tech	Curtis Link , Marvin Speece, Seth Betterly
2007	Geophysical Investigation of the Success Dam Foundation: An Overview	Lewis Hunter, Theodore Asch, Michael Powers, Beth Burton, Seth Haines

SAGEEP Papers (continued)

2007	Combining Seismic and Ground Penetrating Radar Techniques to Analyze Geologic Controls of Riparian Meadow Complexes in the Central Great Basin, Nevada USA	Kristin Sturtevant, Gregory Baker, Mark Lord, Jerry Miller, Dave Jewitt, Dru Germanowski, Jeanne Chambers
2007	Compressional and shear wave seismic refraction tomography at Success Dam, Porterville, California	Michael Powers, Bethany Burton, Seth Haines
2007	Interrogating Levees in Southern Texas, New Mexico, and New Orleans using Seismic Methods	Julian Ivanov, Richard Miller, Joseph Dunbar, John Lane, Steve Smullen
2007	Time Cross-Sections Generated From Shallow Seismic Refraction Data: Preliminary Results	Patrizio Torrese, Patrizio Signanini,
2007	Integrated Geophysical Investigation of Preferential Flowpaths at the Former Tyson Valley Powder Farm near Eureka, Missouri	Bethany Burton, Lyndsay Ball, Gregory Stanton
2007	Test For Detecting An Impermeable Water Barrier In An Earth-Fill Dam In Austria Using MASW Method	Silke Hock, Julian Ivanov, Richard D. Miller,
2008	Seismic Refraction Tomography in an Urban Environment using a Vibrator Source	Michael Powers, Bethany Burton
2008	Geotechnical site characterization of a flood plain by refraction microtremor and seismic refraction methods	Javier Olona-Allué, Javier A. Pulgar, Gabriela Fernández-Viejo, Juan M. González-Cortina
2008	Engineering Geophysics in Australia: Urban Case Studies from Downunder	Bob Whiteley, Simon Stewart
2008	Geophysical Investigations Of Earthen Dams: An Overview	Lewis E. Hunter, Michael H. Powers,
2008	Integrated Approach Using Body Waves, Surface Waves And Gravimetric Prospections For Solving An Urban Geology Problem: The Abbadia San Salvatore Case (Siena, Italy)	Patrizio Torrese, Mario Luigi Rainone, Patrizio Signanini
2009	Time-Lapse Seismic Measurements On A Small Earthen embankment During An Internal Erosion Experiment	Craig J. Hickey, Alexander Ekimov, Gregory J. Hanson, James M. Sabatier,
2009	Angle-Dependent Tomostatics	Lindsay M. Mayer, Richard D. Miller, Julian Ivanov, Tom Weis, Bob Anderson,
2009	Seismic Measurements For Detecting Underground High contrast Voids	Craig J. Hickey, Douglas R. Schmitt, James M. Sabatier, Grey Riddle

JEEG Paper

2005	An Evaluation of Methods and Available Software for Seismic Refraction Tomography Analysis	Jacob R. Sheehan, William E. Doll, and Wayne A. Mandell

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EEGS Short Course

Processing of Seismic Refraction Tomography Data

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Instructors

Siegfried Rohdewald Intelligent Resources, Inc. sales@rayfract.com 604-782-9845
Jacob Sheehan Battelle – Oak Ridge sheehanj@battelle.org 865-483-2538
Beth Burton USGS – Denver blburton@usgs.gov 303-236-1327

Schedule

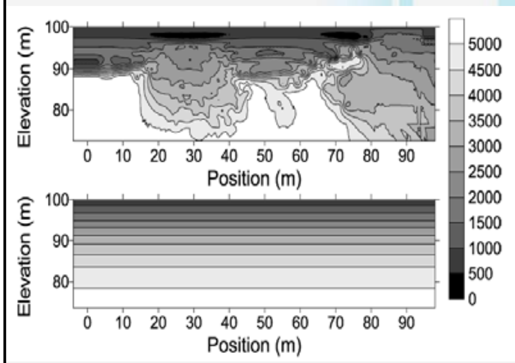
13:00 – 13:10	Overview and introductions
13:10 – 13:40	Introduction to refraction method & Rayfract®
13:40 – 14:40	Rayfract® tutorial dataset #1: Val de Travers
14:40 – 14:55	Break
14:55 – 15:45	Rayfract® tutorial dataset #2: Success Dam
15:45 – 17:00	Work on individual datasets

Refraction Analysis Comparison

ORIGINAL METHODS	REFRACTION TOMOGRAPHY
EXAMPLES	
•Generalized reciprocal method (GRM) •Delay-time method •Slope-Intercept method •Plus-minus method	•Raytracing algorithms •Numerical eikonal solvers •Wavepath eikonal traveltime (WET) •Generalized simulated annealing
VELOCITY MODELS	
•Layers defined by interfaces –Can be dipping	•Not interface-based
•All layers have constant velocities –May define lateral velocity variations by dividing layer into finite “blocks”	•Smoothly varying lateral & vertical vels. –Can be difficult to image distinct, or abrupt, interfaces
•Limited number of layers	•Unlimited “layers”
•Layers only increase in velocity with depth	•Imaging of discontinuous velocity inversions possible
•Typically requires more subjective input –Assignment of traces to refractors	•Typically requires less user input

Smooth Inversion = 1D gradient initial model + 2D WET Wavepath Eikonal Traveltime tomography

Get minimum-structure
1D gradient initial model :



Top : pseudo-2D Delta-t-V display

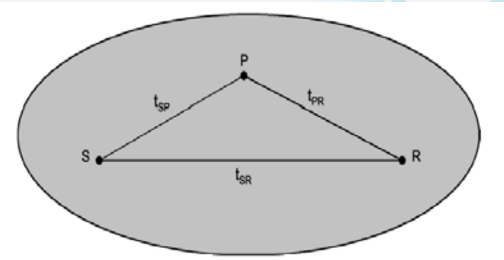
- 1D Delta-t-V velocity-depth profile below each station
- 1D Newton search for each layer
- velocity too low below anticlines
- velocity too high below synclines
- based on synthetic times for Broad Epikarst model (Sheehan, 2005a, Fig. 1).

Bottom : 1D-gradient initial model

- generated from top by lateral averaging of velocities
- minimum-structure initial model
- Delta-t-V artefacts are completely removed

2D WET Wavepath Eikonal Traveltime inversion

Fresnel volume or
wave path approach :



- rays that arrive within half period of fastest ray : $t_{SP} + t_{PR} - t_{SR} <= 1 / 2f$ (Sheehan, 2005a, Fig. 2)
- nonlinear 2D optimization with steepest descent, to determine model update for one wavepath
- SIRT-like back-projection step, along wave paths instead of rays
- natural WET smoothing with wave paths (Schuster 1993, Watanabe 1999)
- partial modeling of finite frequency wave propagation
- partial modeling of diffraction, around low-velocity areas
- WET parameters sometimes need to be adjusted, to avoid artefacts
- see RAYFRACT.HLP help file

Supported Recording Geometries

Compressional (P-) wave & shear (S-) wave interpretation

- Surface refraction, see appended tutorials
- Crosshole tomography, see IGTA13.PDF
- Multi-offset VSP, see WALKAWAY.PDF
- Zero-offset downhole VSP, see VSP.PDF
- Combine downhole shots with crosshole shots, if all receivers in same borehole, for all shots
- POISSON.PDF: determine dynamic Poisson's Ratio from P & S wave

Supported Recording Geometries (cont.)

Constrain surface refraction interpretation with uphole shots

- See COFFEY04.PDF. Use 1D-gradient initial model or constant-velocity
- Anisotropy: velocity may be dependent on predominant direction of ray and wave path propagation. This becomes visible directly adjacent to borehole. Imaged structure/layering is blurred out.
- Velocity inversions / low-velocity layers may become visible
- Walkaway VSP shots recorded with one or more boreholes may be converted to uphole shots by resorting traces by common receiver. Then import these exported uphole shots into one surface refraction profile.
- Use two or more boreholes for improved resolution and reliability

Survey Design Requirements and Suggestions

- **Survey requirements**
  - 24 or more channels/receivers per shot recommended
  - WET works with shots recorded only in one direction
  - more reliable with shots recorded in both directions and reciprocal shots. This enables correction of picking errors.
  - at least 1 shot every 3 receivers, ideally every 2 receivers

- **Survey design suggestions**
  - overlapping receiver spreads, so internal far offset shots can be used for WET tomography.
  - receiver spreads should overlap by 30% to 50%.
  - see OVERLAP.PDF and RAYFRACT.PDF chapter Overlapping receiver spreads, on your CD

Station Numbering Concept

- ***Single*** station spacing defined for each profile
  - Typically equivalent to receiver spacing

- All receivers at integer station numbers
  - Shot locations can be fractional station numbers

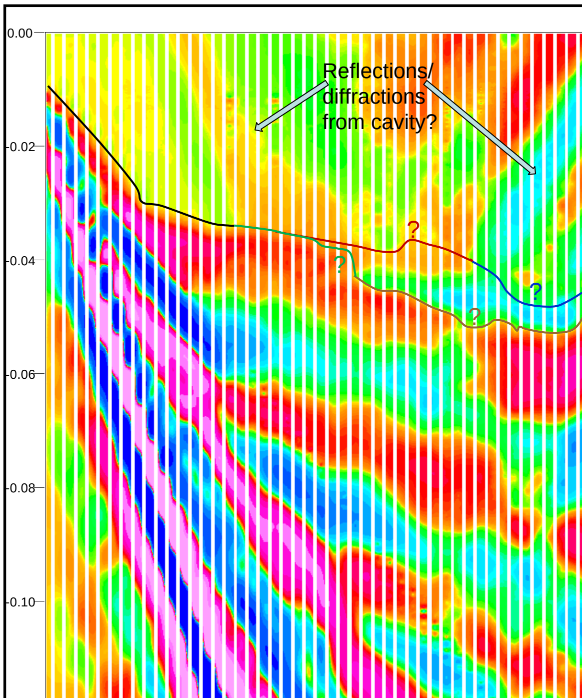
- Station spacing = greatest common divisor of all receiver spacings across profile

  - Example: Rx position (ft/m) = 0, 5, 15, 25, 45, 50, 60,...
    → Station spacing = 5 (ft/m)
    → Rx position (station numbers) = 0, 1, 3, 5, 9, 10, 12,...

- See *Defining your own layout types* in Rayfract® Help|Contents

Irregular Receiver Spread Types Supported

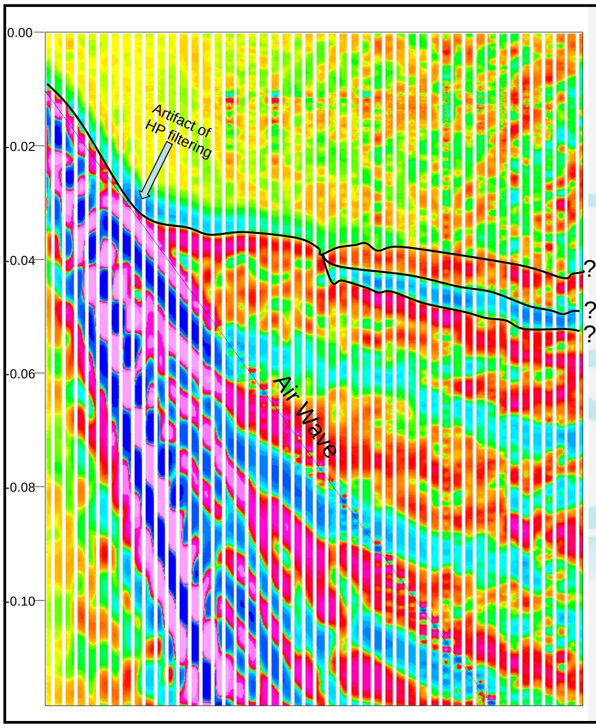
- Several standard receiver spread types already defined in Rayfract®
- For input file formats *SEG-2* and *ASCII column format*, you always need to define an irregular receiver spread type, even in case of missing channels e.g. at road crossing.
- For all other input file formats e.g. *Interpex Gremix*™, *Geometrics SeisImager*™ and *OPTIM LLC SeisOpt®* , you don't need to define your own spread type if the spread layout used is regular, with constant channel separation (receiver spacing), and some channels missing e.g. due to road crossing.
  - The default spread layout type "10: 360 channels" will work fine in this case. The number of active channels used is recognized automatically by our import routine.
- See *Receiver spread types* in Rayfract® Help|Contents



First Break Picks

Where to pick first breaks?

- Real dataset over cavity
- Raw data – no filtering

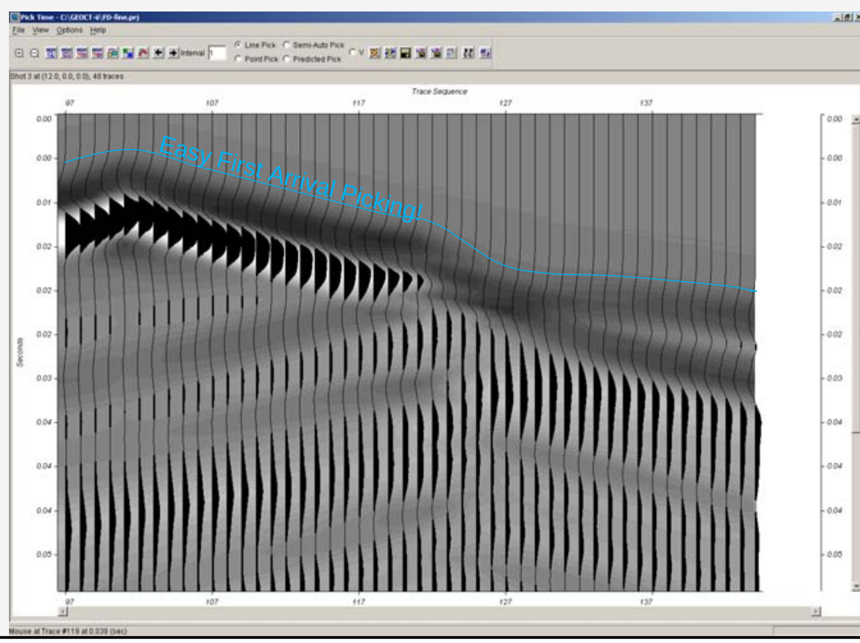


First Break Picks

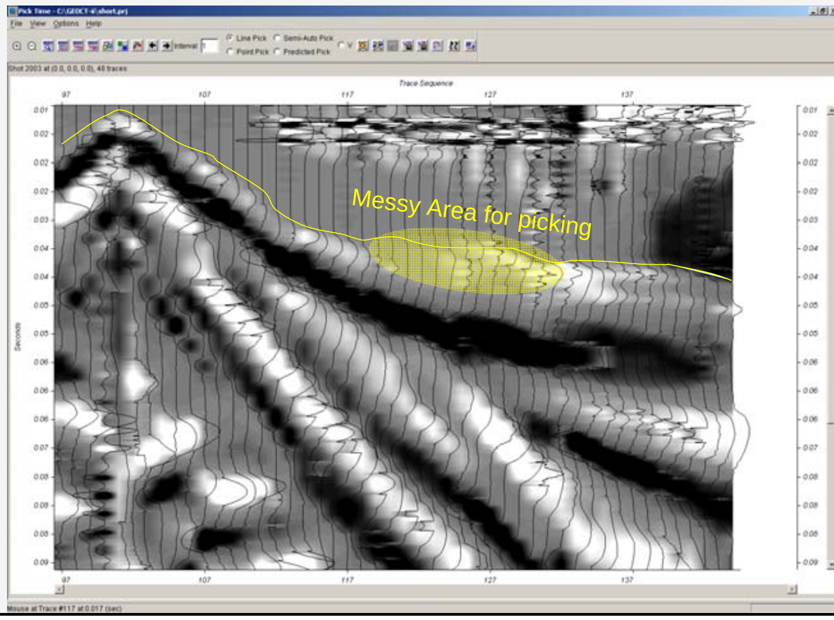
Where to pick first breaks?

- Same real dataset over cavity
- High-pass filter applied
  - Caution: Wavelet precursor results

First Break Picks - Synthetic Cavity Data



First Break Picks - Messy Real Cavity Data



Generalized Rayfract® Flow Chart

Create new profile database

Define header information
(minimum: Line ID, Job ID, instrument, station spacing (m))

Import data
(ASCII first break picks or shot records)

Update geometry information
(shot & receiver positional information)

Run inversion
Smooth invert|WET with 1D-gradient initial model
(results output in Golden Software's Surfer)

Edit WET & 1D-gradient parameters & settings

Smooth Inversion, DeltatV and WET Parameters

- always start with default parameters: run Smooth inversion without changing any setting or parameter
- next adapt parameters and option settings if required, e.g. to remove artefacts or increase resolution
- more smoothing and wider WET wavepath width in general results in less artefacts
- increasing the WET iteration count generally improves resolution
- don't over-interpret data if uncertain picks : use more smoothing and/or wider wavepaths.
- explain traveltimes with minimum-structure model
- tuning of parameters and settings may introduce or remove artefacts. Be ready to go one step backwards.
- use Wavefront refraction method (Ali Ak, 1990) for independent velocity estimate.

WET tomography main dialog: see help menu

Number of WET tomography iterations	Default value is 20 iterations. Increase to 50 or 100 for better resolution and usually less artefacts. WET can improve with increasing iterations, even if RMS error does not decrease.
Central Ricker wavelet frequency	Ricker wavelet used to modulate/weight the wavepath misfit gradient, during model update. Leave at default of 50Hz.
Degree of differentiation of Ricker wavelet	0 for original Ricker wavelet, 1 for once derived wavelet. Default value is 0. Value 1 may give artefacts : wavepaths may become "engraved" in the tomogram.
Wavepath width	In percent of one period of Ricker wavelet. Increase width for smoother tomograms. Decreasing width too much generates artefacts and decreases robustness of WET inversion.
Envelope wavepath width	Width of wavepaths used to construct envelope at bottom of tomogram. Default is 0.0. Increase for deeper imaging.
Maximum valid velocity	Limit the maximum WET velocity modeled. Default is 6,000 m/s. Decrease to prevent high-velocity artefacts in tomogram.
Full smoothing	Default smoothing filter size, applied after each WET iteration
Minimal smoothing	Select this for more details, but also more artefacts. May decrease robustness and reliability of WET inversion.

WET tomography options in Settings submenu

Scale wavepath width	➢scale WET wavepath width with picked time, for each trace ➢better weathering resolution, more smoothing at depth ➢disable for wide shot spacing & short profiles (72 or less receivers) to avoid artefacts ➢also disable if noisy trace data and uncertain or bad picks
Scale WET filter height	➢scale height of smoothing filter with depth of grid row, below topography ➢may decrease weathering velocity and pull up basement ➢disable for short profiles, wide shot spacing and steep topography, and if uncertain picks
Interpolate missing coverage after last iteration	➢interpolate missing coverage at tomogram bottom, after last iteration ➢will always interpolate for earlier iterations ➢use if receiver spreads don't overlap enough
Disable wavepath scaling for short profiles	➢automatically disable wavepath width scaling and scaling of smoothing filter height, for short profiles with 72 or less receivers ➢this option is enabled per default, to avoid over-interpretation of small data sets, in case of bad picks

Smooth inversion options in Settings submenu to vary the 1D-gradient initial model

Lower velocity of 1D-gradient layers	➢set gradient-layer bottom velocity to (top velocity + bottom velocity) / 2 ➢enable to lower the velocity of the overburden layers, and pull up the imaged basement ➢disabled per default
Interpolate velocity for 1D-gradient initial model	➢linearly interpolate averaged velocity vs. depth profile, to determine 1D-gradient initial model ➢disable to model constant-velocity initial layers with the layer-top velocity assumed for the whole layer except the bottom-most 0.1m ➢disable for sharper velocity increase at bottom of overburden. This may pull up basement as imaged with WET. ➢enabled per default, since WET tomography works most reliably with smooth minimum-structure initial model, in both horizontal and vertical direction

Delta-t-V Options in Settings submenu to vary the 1D-gradient initial model

Enforce Monotonically increasing layer bottom velocity	➢disable to enhance low velocity anomaly imaging capability ➢disabled per default
Suppress velocity artefacts	➢enforce continuous velocity vs. depth function ➢use for medium to high coverage profiles only, to filter out bad picks and reflection events ➢disabled per default, use for high-coverage profiles only
Process every CMP offset	➢do Delta-t-V inversion at every offset recorded ➢get better vertical resolution, possibly more artefacts ➢disabled per default
Smooth CMP traveltime curves	➢use for high-coverage profiles only ➢disable to get better vertical resolution ➢disabled per default
Max. velocity exported	➢*Interactive Delta-t-V|Export Options* setting ➢set to 5,000 m/s per default ➢decrease to e.g. 2,000 or 3,000 m/s and redo Smooth inversion, to vary WET output at bottom of tomogram

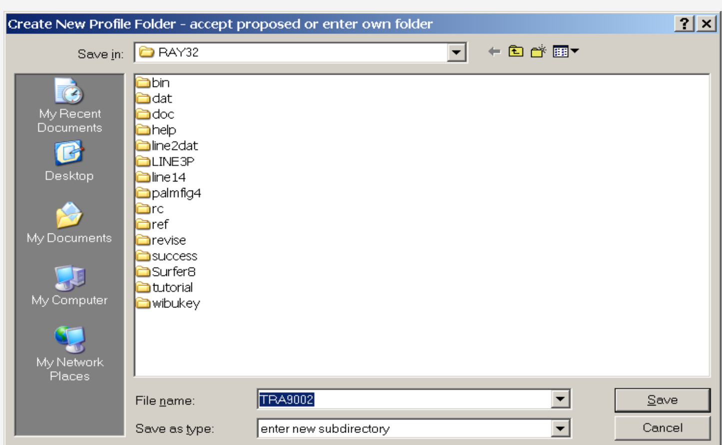
Tutorial #1

Val de Travers, Switzerland, GeoExpert ag
P-wave surface profile

29 shots, 48 traces per shot, roll-along recording with overlapping receiver spreads
Receiver spacing = 5m

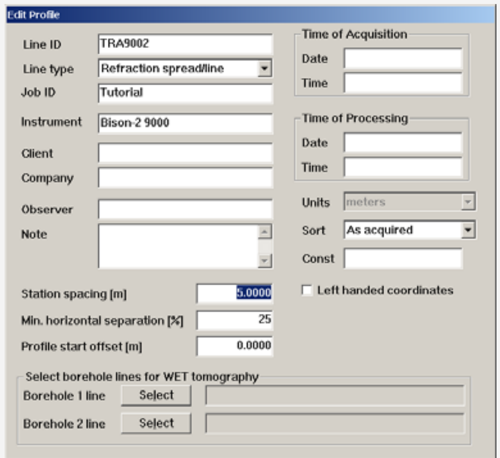
Planning of a highway tunnel in an area prone to rockfalls, in Jura Mountains north of Geneva and near French border

Create new profile



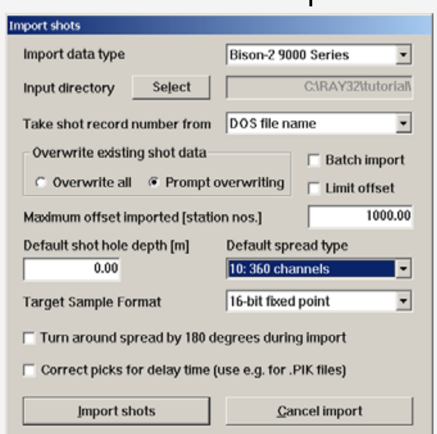
1 Start up Rayfract® software with *desktop icon* or *Start menu*
2 Select *File|New Profile…*
3 Set *File name* to TRA9002 and click *Save*

Fill in profile header



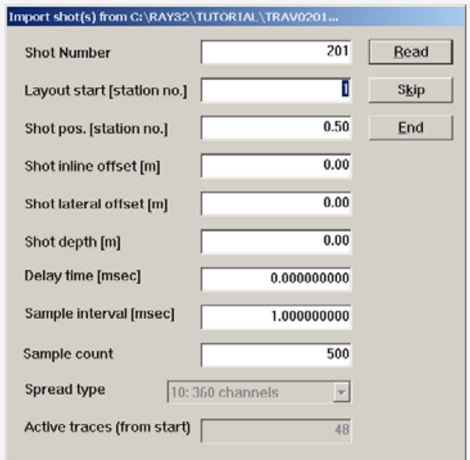
1 Select *Header|Profile…* Use *function key F1* for help on fields.
2 Set *Line ID* to TRA9002 and *Job ID* to Tutorial
3 Set *Instrument* to Bison-2 9000 and *Station spacing* to 5m
4 Hit ENTER, and confirm the prompt

Seismic data import



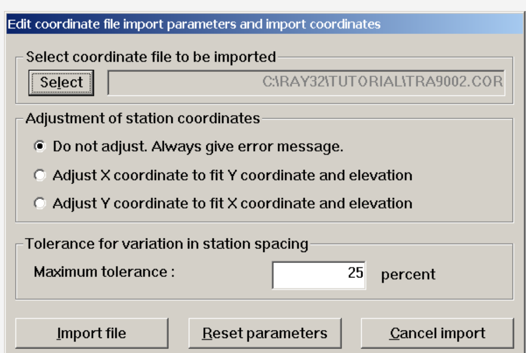
1 Download and unzip http://rayfract.com/tutorials/TRA9002.ZIP to directory C:\RAY32\TUTORIAL
2 Select *File|Import Data…* for *Import shots dialog*, see above
3 Set *Import data type* to Bison-2 9000 Series
4 Click *Select button*, select file TRAV0201 in directory C:\RAY32\TUTORIAL
5 Click on *Open*, *Import shots*, and confirm the prompt

Import each shot



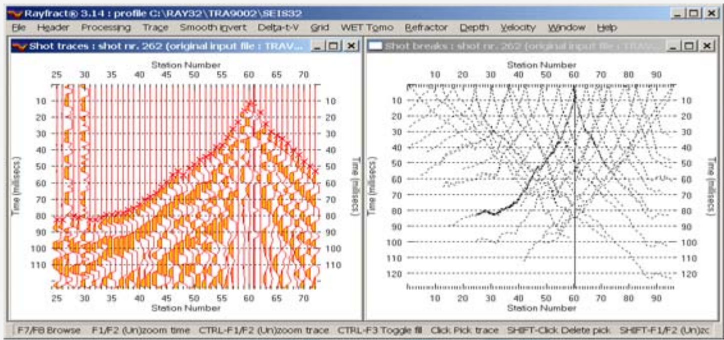
Click on *Read* for all shots shown in *Import Shot dialog*, see above.
Don't change *Layout start* and *Shot pos*., these are correct already

Update geometry and first breaks



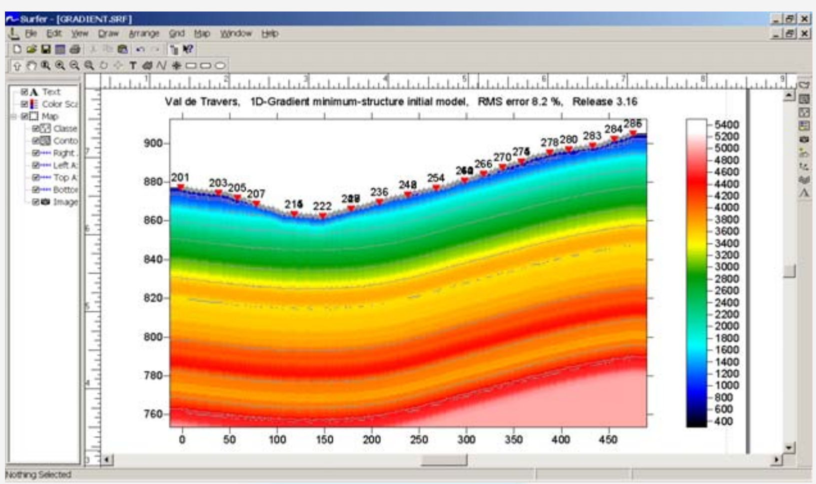
1 Select *File|Update header data|Update Station Coordinates…*
2 Click on *Select* and C:\RAY32\TUTORIAL\TRA9002.COR
3 Click on *Open*, *Import File* and confirm the prompt
4 Select *File|Update header data|Update First Breaks* and C:\RAY32\TUTORIAL\TRA9002.LST and click *Open*

View and repick traces, display traveltime curves



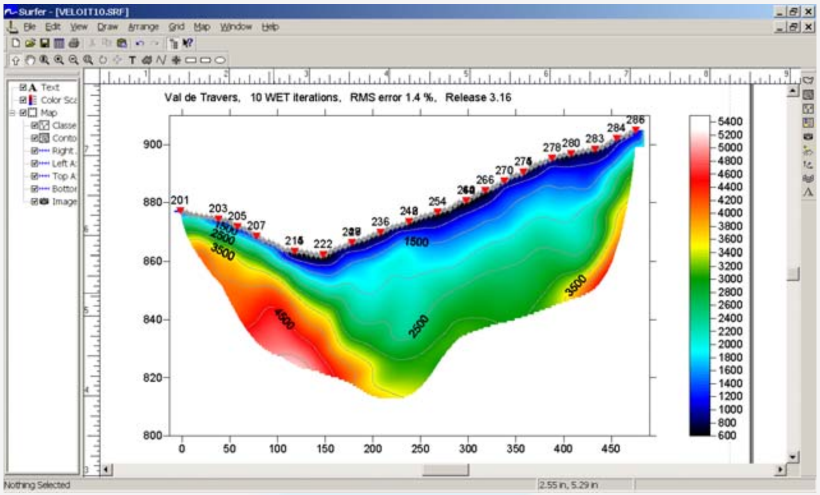
1 Select *Trace|Shot gather* and *Window|Tile.* Browse shots with F7/F8
2 Click on *Shot breaks window* and press ALT-P
3 Set *Maximum time* to 130 msecs. and hit ENTER
4 Click on *Shot traces window* and press F1 twice to zoom time
5 CTRL-F1 twice to zoom amplitude, CTRL-F3 twice to toggle trace fill mode
6 Select *Processing|Color traces* and *Processing|Color trace outline*
7 Use up/down/left/right arrow keys to navigate along and between traces
8 Zoom spread with SHIFT-F1. Pan zoomed sections with SHIFT-PgDn/PgUp
9 Optionally repick trace with left mouse key or space bar, delete first break with ALT-DEL or SHIFT-left mouse key. Press ALT-Y to redisplay traveltime curves

Smooth inversion of first breaks : 1D-gradient initial model



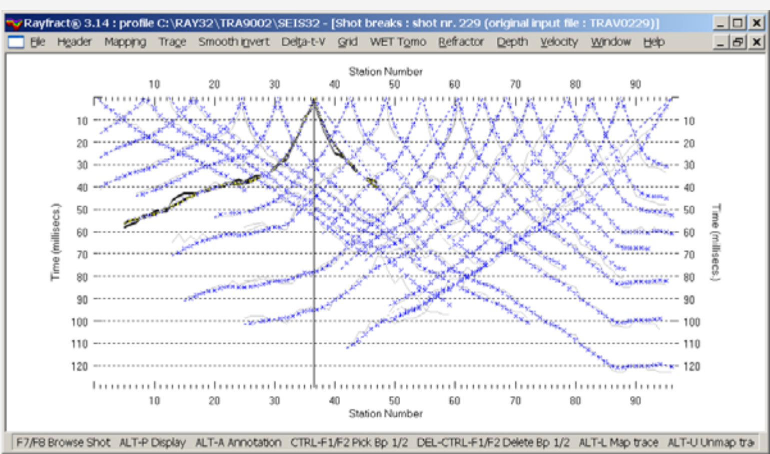
1 Select *Smooth invert|WET with 1D-gradient initial model*
2 Once the 1D-gradient model is shown in Surfer™, click on *Rayfract® icon* at bottom of screen, to continue. Confirm following prompts.

Smooth inversion of first breaks : 2D WET tomography



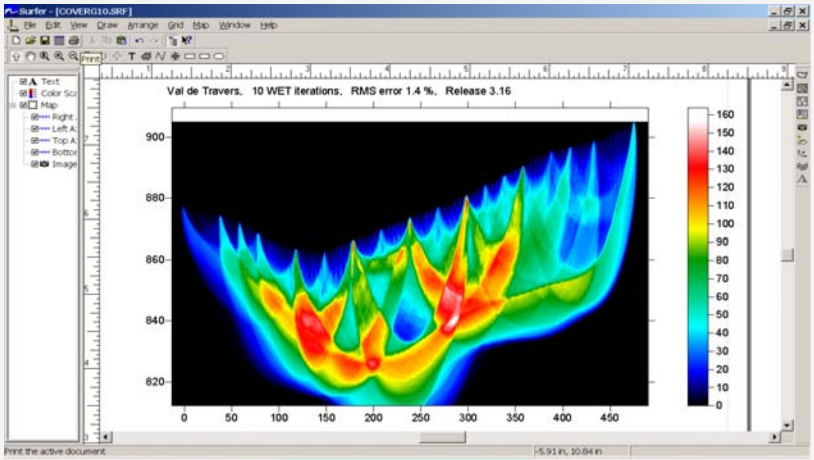
1 Click on *Surfer icon* shown at bottom of screen
2 Select *View|Object Manager* to show outline at left, if not yet shown
3 Click on *Image* in outline, right-select *Properties.*
4 Click on *Colors* spectrum, adjust *Minimum* and/or *Maximum* fields.

Display modeled picks and traveltime curves



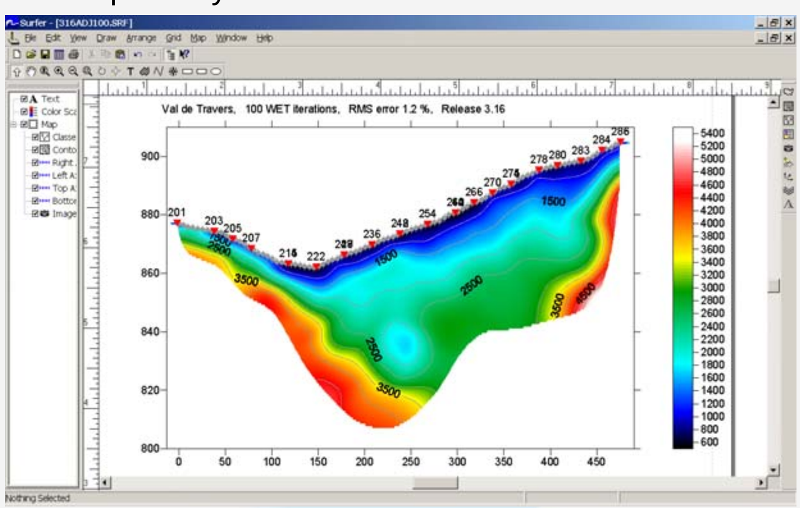
1 Click on *Rayfract® icon* at bottom of screen
2 Select *Refractor|Shot breaks* to view picked and modeled (blue) times
3 Press F7/F8 keys to browse through shot-sorted traveltime curve
4 Use *Mapping|Gray picked traveltime curves* to toggle curve pen style

Display WET wavepath coverage



1. Click on *Surfer icon* at bottom of screen
2. Use CTRL-TAB to cycle between WET tomogram, wavepath coverage plot and 1D-gradient initial model

Optionally increase number of WET iterations



1. Click on *Rayfract® icon* at bottom of screen
2. Select *WET Tomo|Interactive WET tomography…*
3. Change *Number of WET tomography iterations* to 100
4. Click *button Start tomography processing*, confirm prompts as above

Tutorial #2

Success Dam, Porterville, CA, USGS
P-wave surface profile

48 shots into 48 fixed geophones
station spacing = 15ft

Determine depth to bedrock, likelihood of liquefiable zones, define lateral continuity of geologic units, and identify faults/fracture zones

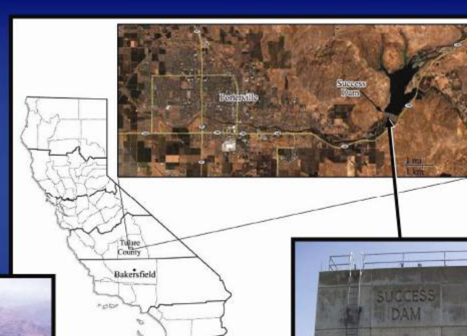
South Pacific Division

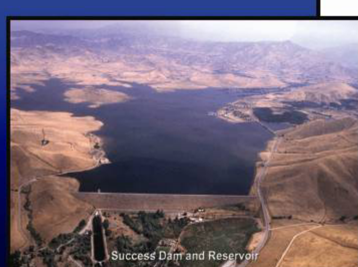
USGS

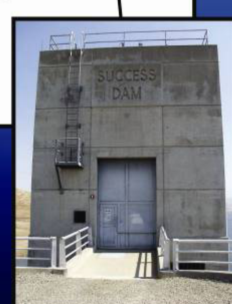
BACKGROUND

Success Dam

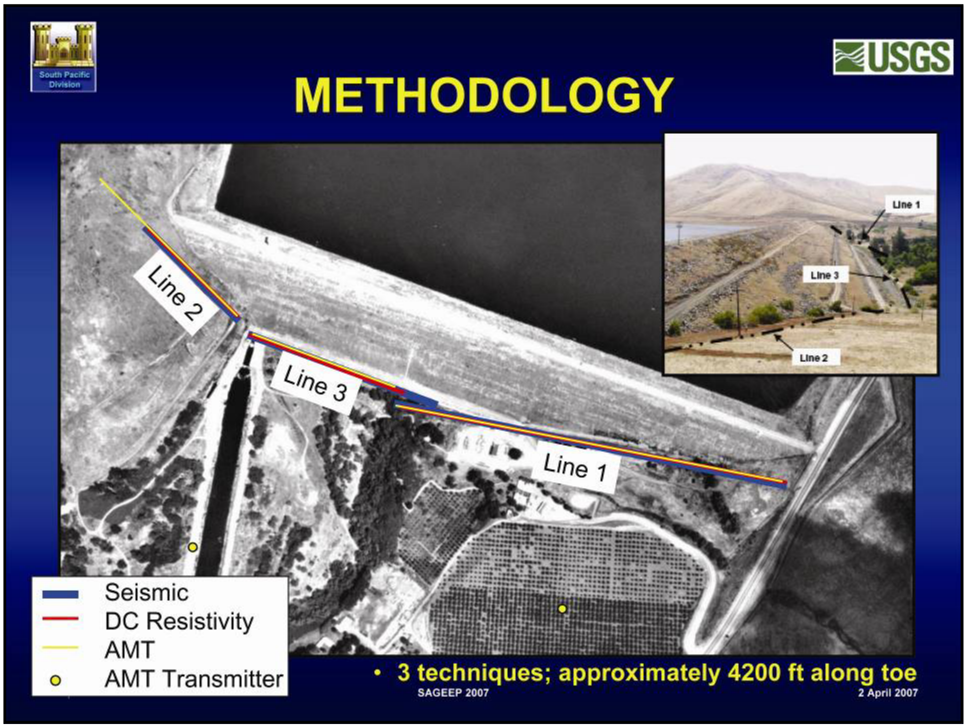
- Located on Tule River
- 6-mi east of Porterville, CA
- 60-mi north of Bakersfield, CA



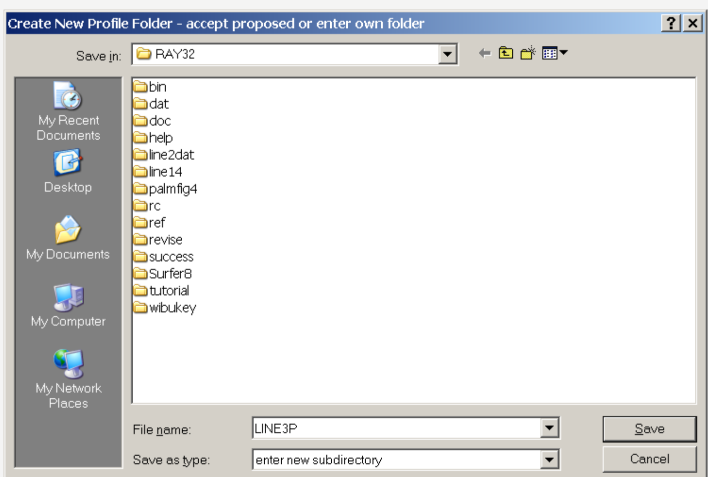

Success Dam and Reservoir



Denver, CO

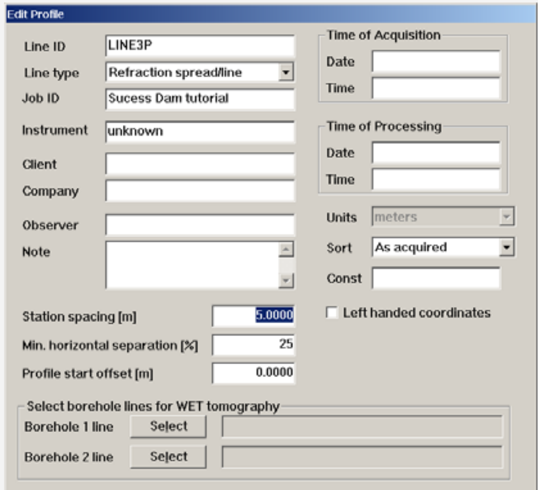


Create new profile



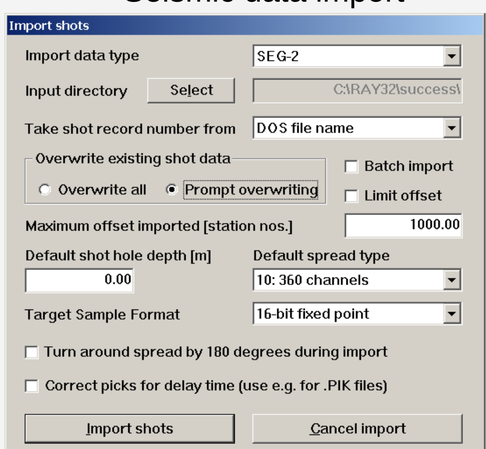
1 Start up Rayfract® software with *desktop icon* or *Start menu*
2 Select *File|New Profile…*
3 Set *File name* to LINE3P and click *Save*

Fill in profile header



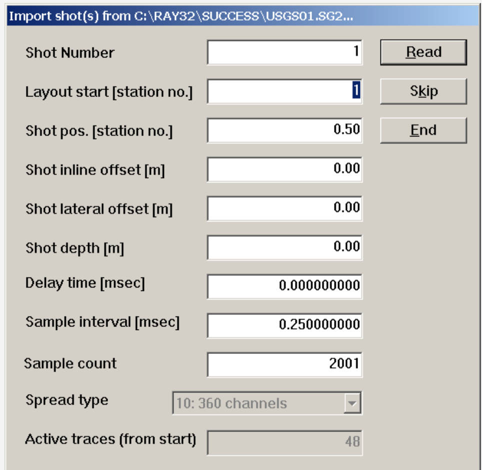
1 Select *Header|Profile…* Use *function key F1* for help on fields.
2 Set *Line ID* to LINE3P and *Job ID* to Success Dam Tutorial
3 Set *Instrument* to unknown and *Station spacing* to 5m
4 Hit ENTER, and confirm the prompt

Seismic data import



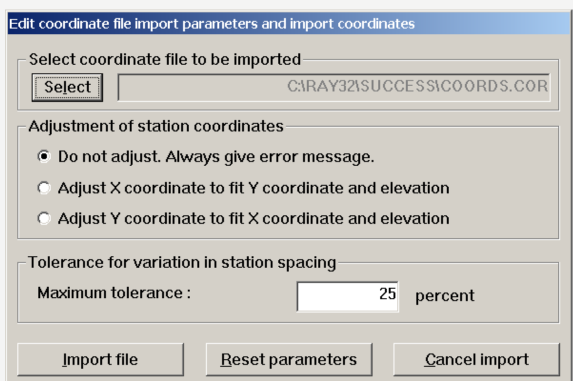
1 Unzip http://rayfract.com/tutorials/LINE3P.ZIP to C:\RAY32\SUCCESS
2 Select *File|Import Data…* for *Import shots dialog*, see above
3 Set *Import data type* to SEG-2
4 Click *Select button*, set *Files of type* to ABEM files (*.SG2)
5 Select file USGS01.SG2 in directory C:\RAY32\SUCCESS
6 Click on *Open*, *Import shots*, and confirm the prompt

Import each shot



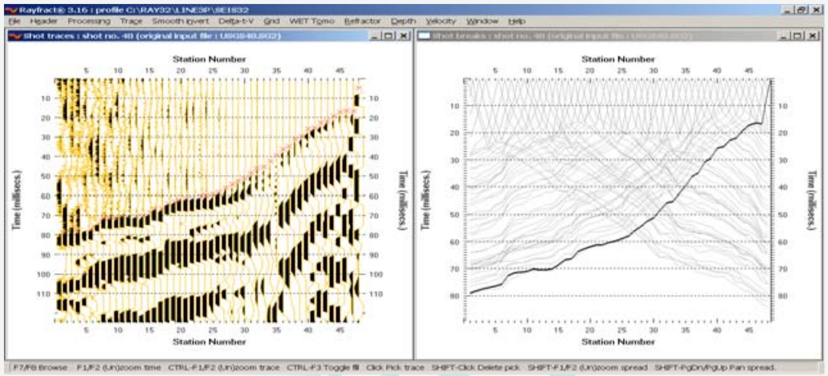
Click on *Read* for all shots shown in *Import Shot dialog*, see above.
Don't change *Layout start* and *Shot pos*., these are correct already

Update geometry and first breaks



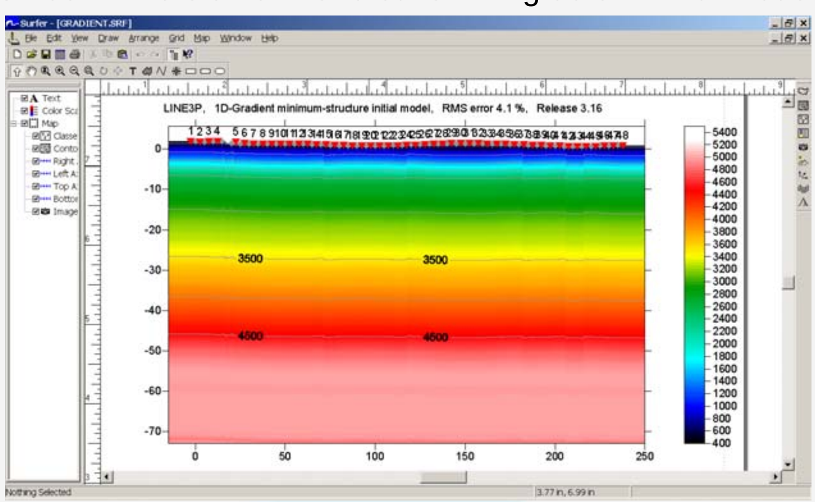
1 Select *File|Update header data|Update Station Coordinates…*
2 Click on *Select* and C:\RAY32\SUCCESS\COORDS.COR
3 Click on *Open*, *Import File* and confirm the prompt
4 Select *File|Update header data|Update Shotpoint coordinates…*
5 Select C:\RAY32\SUCCESS\SHOTPTS.SHO, click *Open*, confirm prompt
6 Select *File|Update header data|Update First Breaks* and C:\RAY32\SUCCESS\BREAKS.LST and click *Open*

View and zoom traces, display traveltime curves



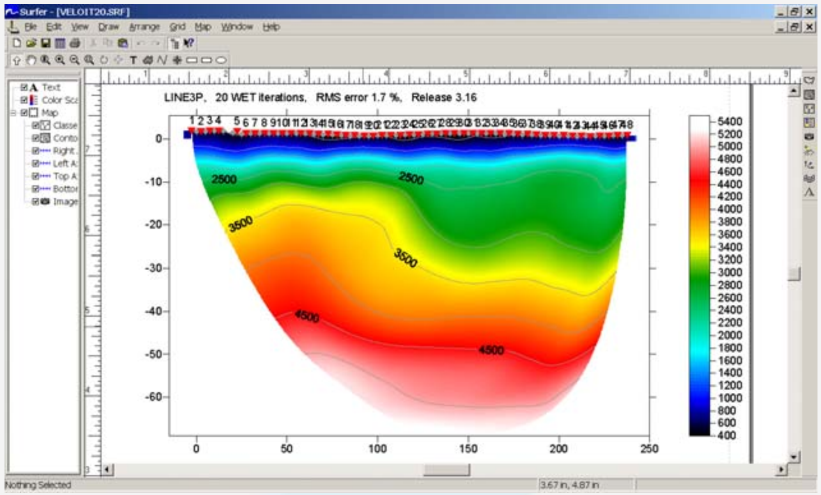
1 Select *Trace|Shot gather* and *Window|Tile.* Browse shots with F7/F8
2 Click on *Shot breaks window* and select *Mapping|Gray picked traveltime curves*
3 Press ALT-P, set *Maximum time* to 90 msecs. and hit ENTER
4 Click on *Shot traces window* and press F1 twice to zoom time
5 CTRL-F1 four times to zoom amplitude, CTRL-F3 twice to toggle trace fill mode
6 Select *Processing|Color traces* and *Processing|Color trace outline*
7 Use up/down/left/right arrow keys to navigate along and between traces
8 Zoom spread with SHIFT-F1. Pan zoomed sections with SHIFT-PgDn/PgUp

Smooth inversion of first breaks : 1D-gradient initial model



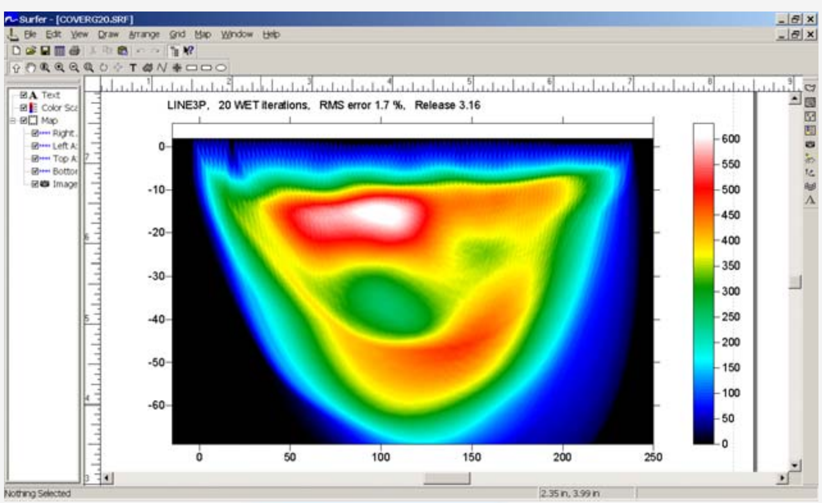
1 Select *Smooth invert|WET with 1D-gradient initial model*
2 Once the 1D-gradient model is shown in Surfer™, click on *Rayfract® icon* at bottom of screen, to continue. Confirm following prompts.

Smooth inversion of first breaks : 2D WET tomography



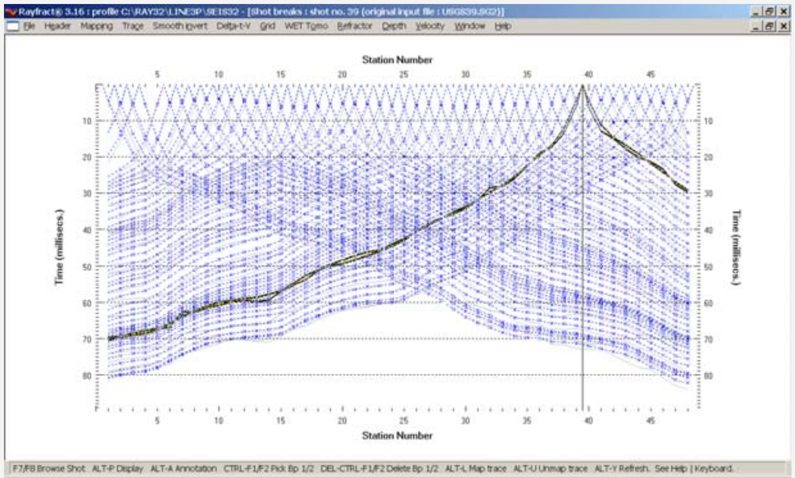
1 Click on *Surfer® icon* shown at bottom of screen
2 Select *View|Object Manager* to show outline at left, if not yet shown
3 Click on *Image* in outline, right-select *Properties.*
4 Click on *Colors* spectrum, adjust *Minimum* and/or *Maximum* fields.

Display WET wavepath coverage



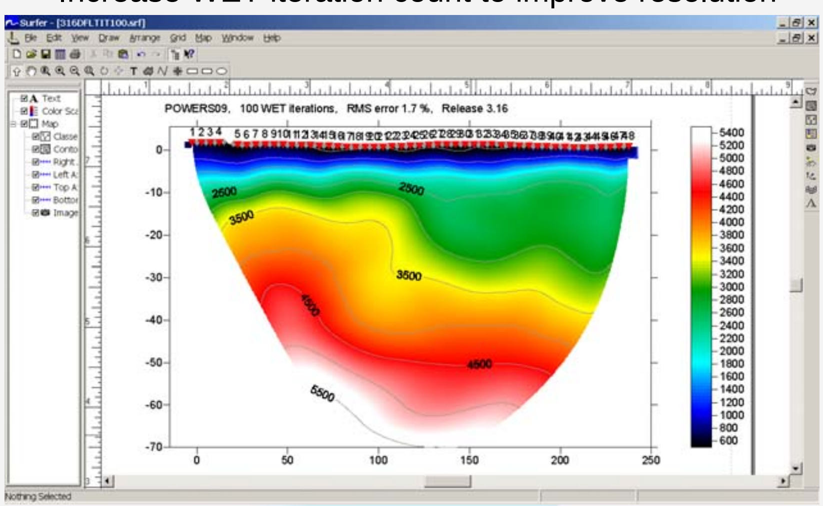
1 Click on *Surfer® icon* at bottom of screen
2 Use CTRL-TAB to cycle between WET tomogram, wavepath coverage plot and 1D-gradient initial model

Display modeled picks and traveltime curves



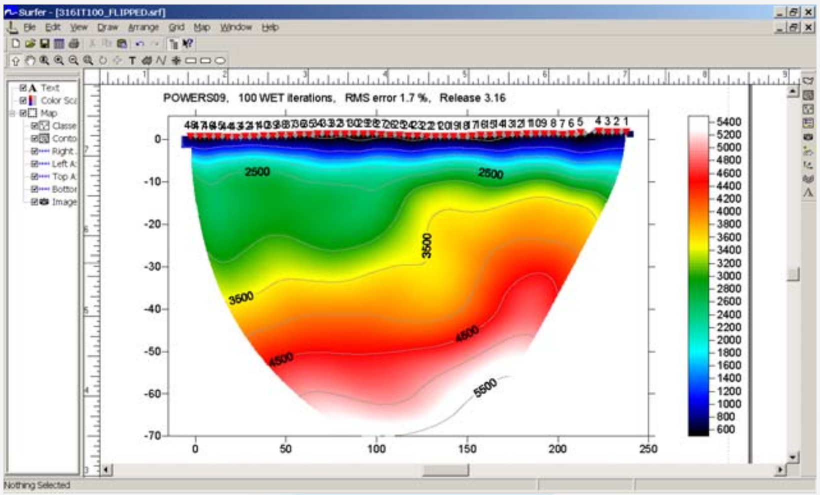
1 Click on *Rayfract® icon* at bottom of screen
2 Select *Refractor|Shot breaks* to view picked and modeled (blue) times
3 Press F7/F8 keys to browse through shot-sorted traveltime curve
4 Use *Mapping|Gray picked traveltime curves* to toggle curve pen style

Increase WET iteration count to improve resolution

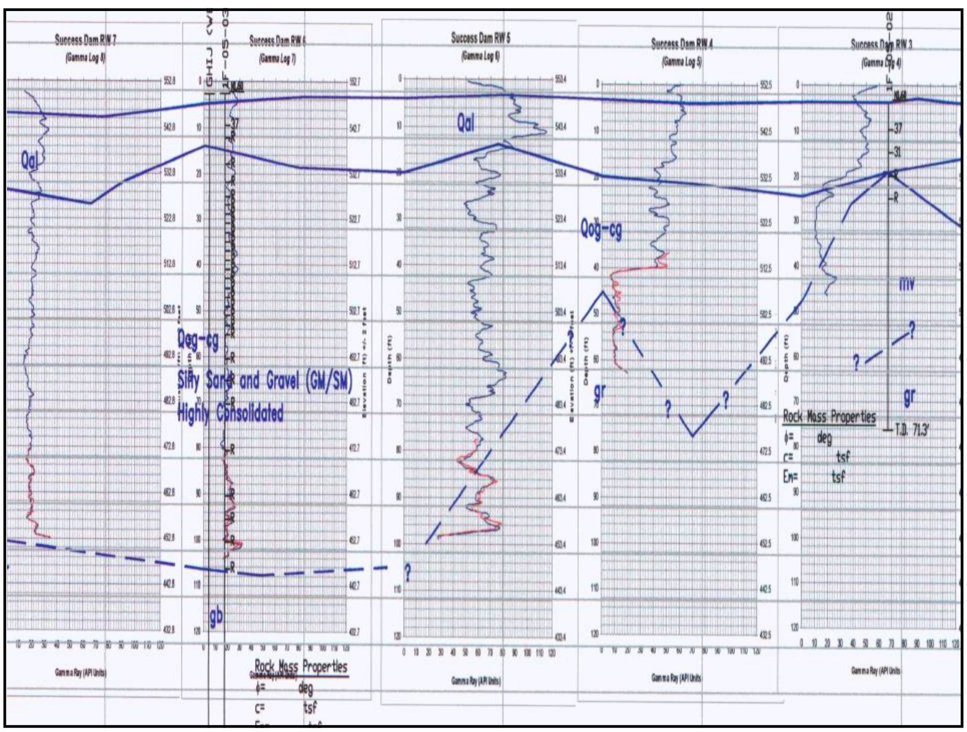


1 Select *WET Tomo|Interactive WET tomography…*
2 Click *button Reset* to reset WET parameters to default settings
3 Change *Number of WET tomography iterations* to 100
4 Click *button Start tomography processing*, confirm prompts as above
5 Note improved imaging of fault : velocity step in center of tomogram

Flip over tomogram

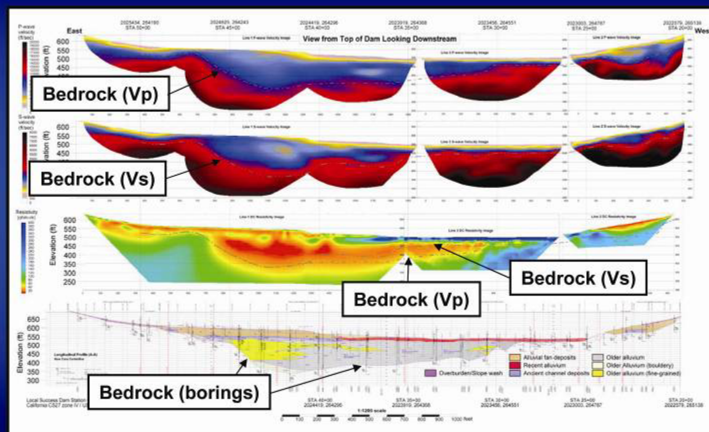


1. Select *Grid|Turn around grid file by 180 degrees…*
2. Select file C:\RAY32\GRADTOMO\VELOIT100.GRD, click *Open*
3. Select *Grid|Image and contour velocity and coverage grids…*
4. Select file C:\RAY32\GRADTOMO\VELOIT100.GRD, click *Open*
5. Click on *Surfer icon* at bottom of screen, use CTRL-TAB to cycle



UTILIZATION

Depth to bedrock

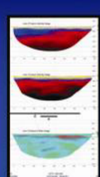


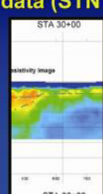
Different bedrock surface identified between Vp & Vs
- Compaction, lithification, weathering

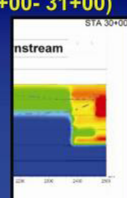
UTILIZATION

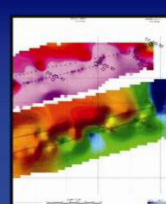
Fault analysis

Geophysical data (STN 29+00- 31+00)









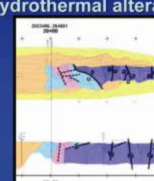
Step in bedrock surface (S-wave data) Poisson's ratio anomaly (elev. 400 ft)

Sharp boundary (STN 30+00 – 31+00)

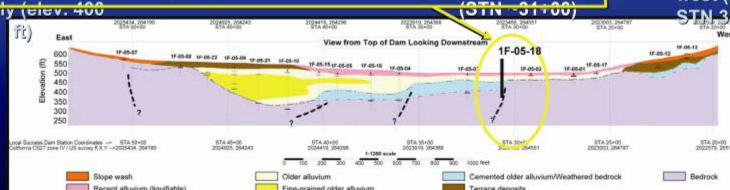
Sharp discontinuity (STN ~31+00)

Outer boundary of sheet flow anomaly (STN ~31+00)

Supporting information 1F-05-18 (STN 31+00)
- Elev. 429.9 - 439.9
- Fault gouge
- Slickensides
- Hydrothermal alteration

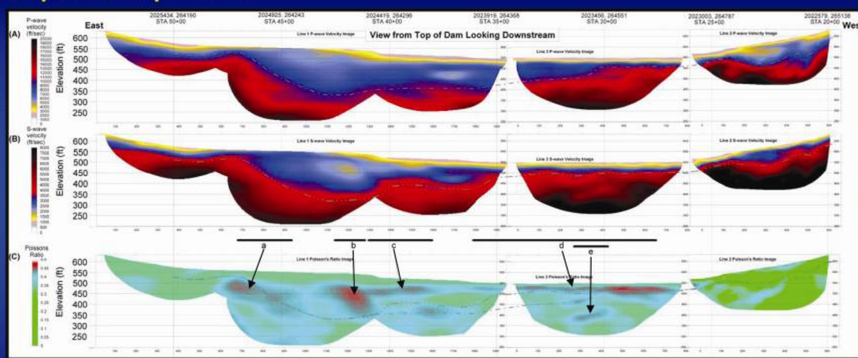


1948 Core Trench
Faults exposed west (right) of STN 31+00



UTILIZATION

Liquifaction potential



Liquifiable:

- Vs < 600 fps: highly liquifiable
- Vs 600 – 1200 fps: potentially liquifiable

Evaluation:

- Used Poisson's Ratio to look for units where Vs disproportionately low relative to Vp
  - Red zones in plot C (Poisson's Ratio)
  - 5 zones identified
  - 4 eliminated because conditions known
  - 1 (e) will be drilled

Supplemental Success Dam Information

Additional Rayfract® Tutorials

Smooth inversion, Plus-Minus, Wavefront layer refraction of 7 shots into 24 receivers :

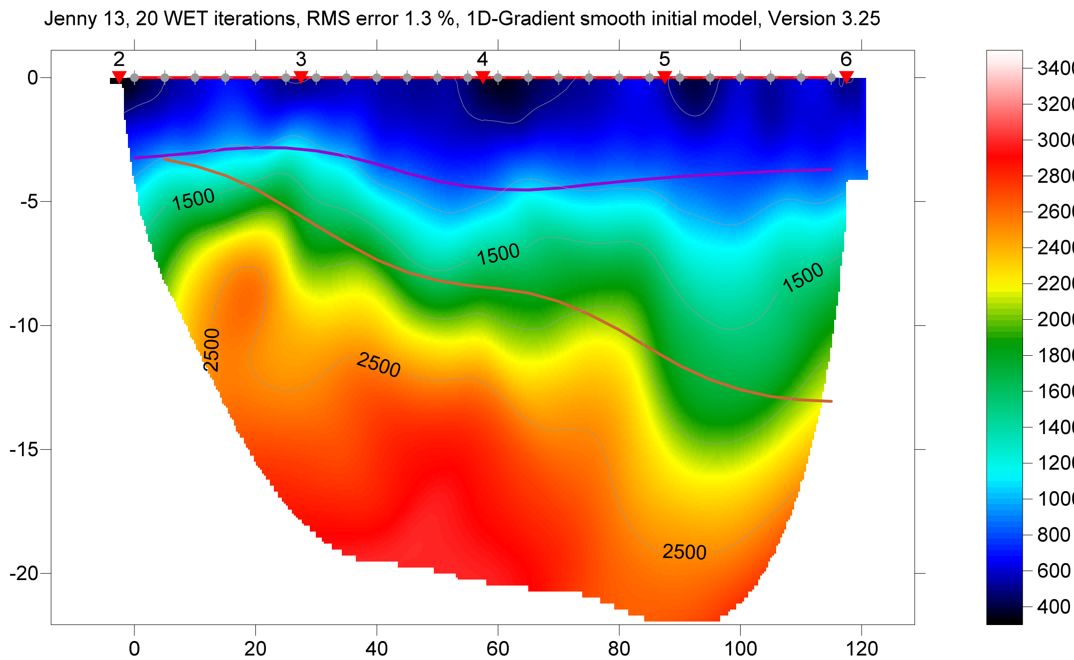


Fig. 1 : Velocity tomogram obtained with Smooth inversion with default settings and 20 WET iterations.
Layer-based Plus-Minus refractors are plotted in magenta and brown, see Fig. 3 below.

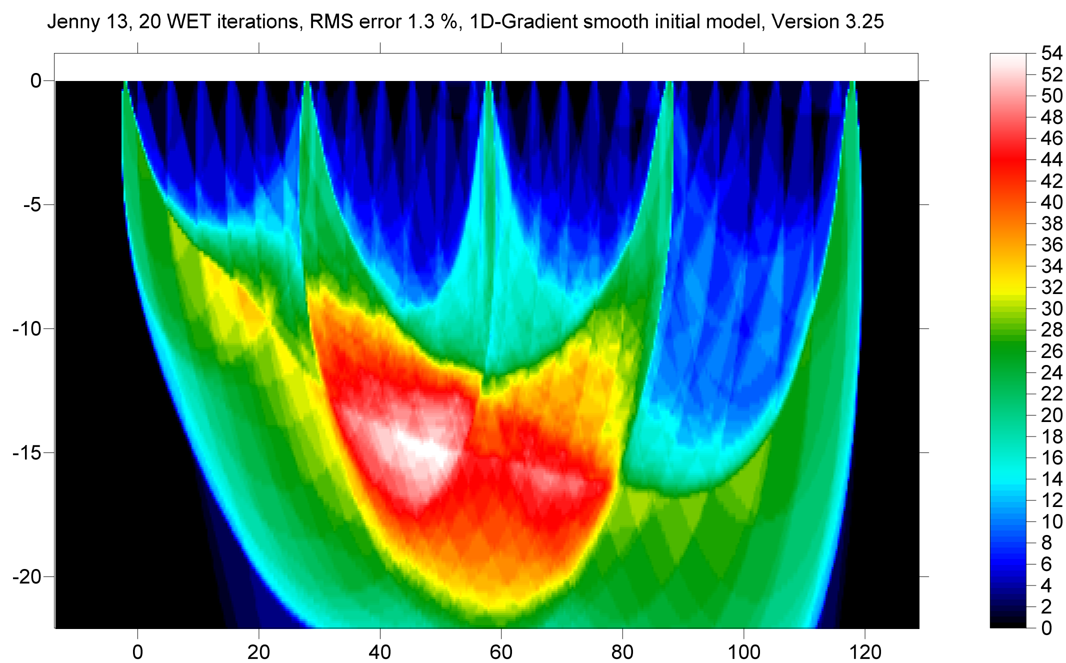


Fig. 2 : WET wavepath coverage plot obtained with tomogram shown in Fig. 1

We recommend shooting at every 3rd receiver, not just every 6th receiver. Import the data into a Rayfract® profile and run our *Smooth inversion* and *Plus-Minus* methods, with our free trial :

- create a new profile with *File|New Profile…*, set *File name* to JENNY13 and click *Save button*
- unzip jenny13.zip in \RAY32\JENNY13\INPUT directory
- specify a *Station spacing* of 5m in *Header|Shot*, before importing the data.

- check *File|Import Data Settings|Keep same Layout start for consecutive shot files*
- check *File|Import Data Settings|Default layout start is 1.0*
- select *File|Import Data…* and specify *Import data type* SEG-2
- click upper *Select button*, navigate into \RAY32\JENNY13\INPUT and select 2001.DAT
- set *Default spread type* to 01: 24 channels
- click *Open button* and *Import shots button*
- leave *Layout start* at 1 for all shots
- specify *Shot pos. [station no.]* -5.5, 0.5, 6.5, 12.5, 18.5, 24.5, 30.5, click *Read* for shots 1 to 7
- select *File|Update header data|Update First Breaks…*
- navigate into \RAY32\JENNY13\INPUT directory and select file BREAKS.LST, click *Open*
- select *Smooth invert|WET with 1D-gradient initial model…*
- confirm prompts for 1D starting model, WET tomogram and wavepath coverage (Fig. 1, Fig. 2)

Iteratively vary mapping of traces to refractors in *Refractors|Shot breaks*, select *Depth|Plus-Minus* and *Velocity|Plus-Minus* until *Plus-Minus interpretation* (Fig. 3) matches *Smooth inversion* tomogram (Fig. 1).

In *Depth|Plus-Minus*, press ALT+M keyboard shortcut and decrease *Base filter width [station nos.]* to 5, from default value 10. Hit ENTER key to recompute and redisplay *Plus-Minus* depth and velocity sections.

See our release notes for latest version 3.25 and *Grid menu options* (Fig. 6) for plotting of refractors on WET tomograms. To redisplay the WET tomogram with Plus-Minus refractors :

- select *Depth|Plus-Minus* and *File|Export header data|Export ASCII Model of depth section...*
- click *Save button* to export Plus-Minus refractors and layer velocities to file PLUSMODL.CSV
- select *Grid|Select ASCII .CSV layer model for refractor plotting...* and above PLUSMODL.CSV
- check *Grid menu options* for refractor plotting as shown in Fig. 6
- select *Grid|Image and contour velocity and coverage grids…*
- select tomogram grid file \RAY32\JENNY13\GRADTOMO\VELOIT20.GRD to obtain Fig. 1

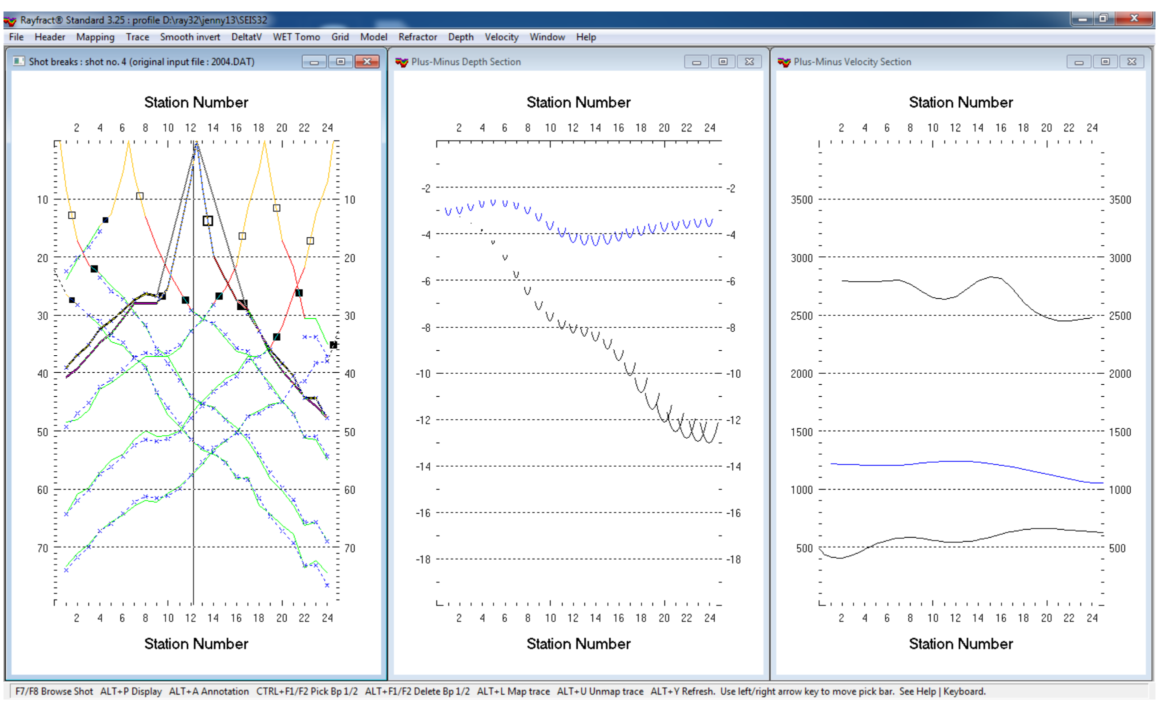


Fig. 3 : Layer-based Plus-Minus refraction interpretation, 3 layers. Left : interactively map traces to refractors. Center : Depth section obtained with Plus-Minus method. Right : Plus-Minus Velocity section.

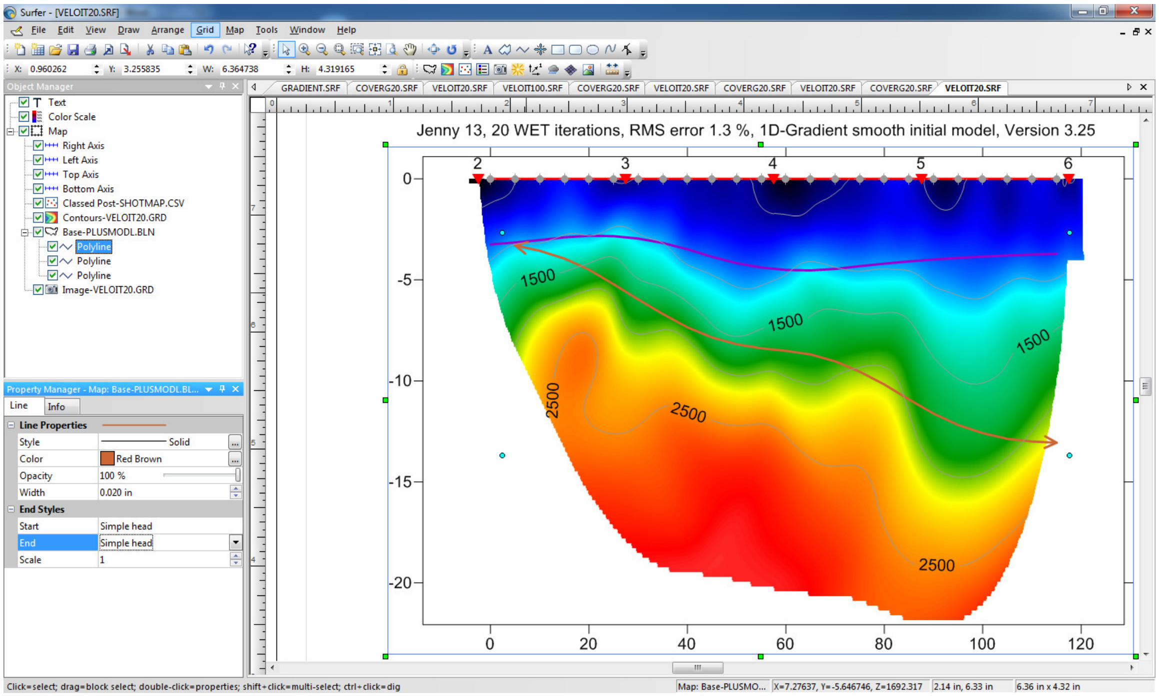


Fig. 4 : Edit Base map and refractor polyline properties in Surfer's Object Manager.

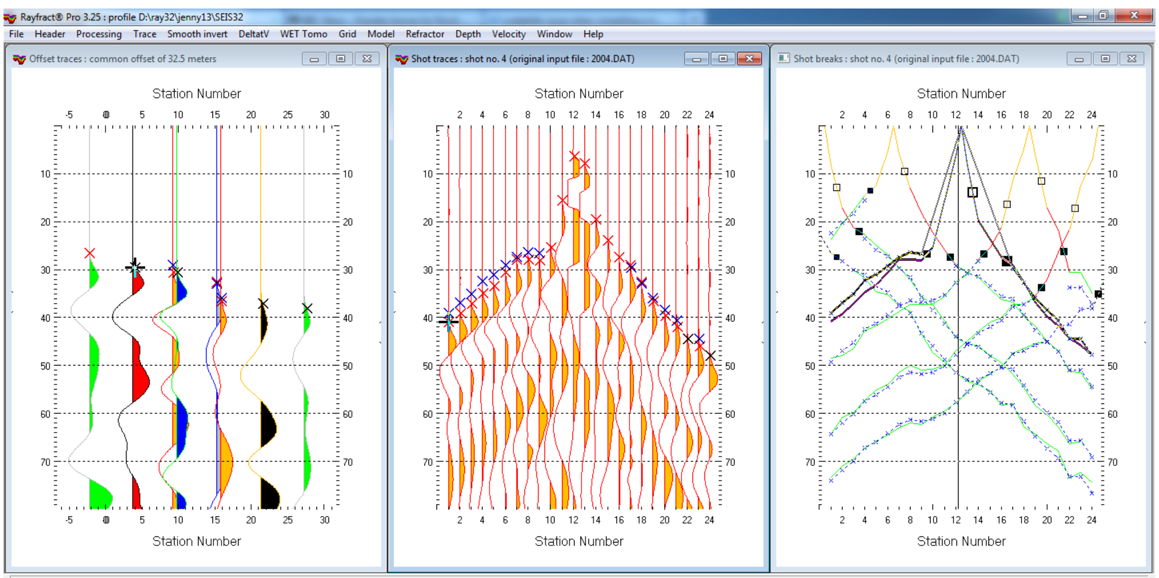


Fig. 5 : *Trace|Offset gather* (left), *Trace|Shot gather* (center), *Refractor|Shot breaks* (right). Browse offset gathers with F7/F8 in *Trace|Offset gather*, to quality-check for reciprocal traveltime errors. Note asymmetry of first breaks for shot no. 4 (center), relative to shot point (station no. 12.5). This indicates a dipping basement refractor, as indicated in *Trace|Offset gather* (left) and *Refractor|Shot breaks* (right).

Quality-check your first break picks for reciprocal traveltime errors in *Trace|Offset gather*, see Fig. 5. and riveral8 tutorial. Browse common-offset sorted trace gathers with F7/F8 function keys.

Edit refractor polyline properties line style, color, width and end styles as in Fig. 4, in Golden Software Surfer's Object Manager.

Our layer-based Plus-Minus refraction (Fig. 3), Wavefront refraction and CMP Intercept-time refraction methods can use **far-offset shots** no. 1 and no. 7 positioned at station nos. -5.5 and 30.5.

Offset shots no. 1 and no. 7 cannot be used for 2D WET inversion, since there are no receivers near these shot points, at station no. -5.5 and 30.5 . Use overlapping receiver spreads, for our WET inversion to be able to use profile-internal offset shots.

Also see our .pdf reference topics Mapping traces to refractors, Time-to-depth conversion and Overlapping receiver spreads.

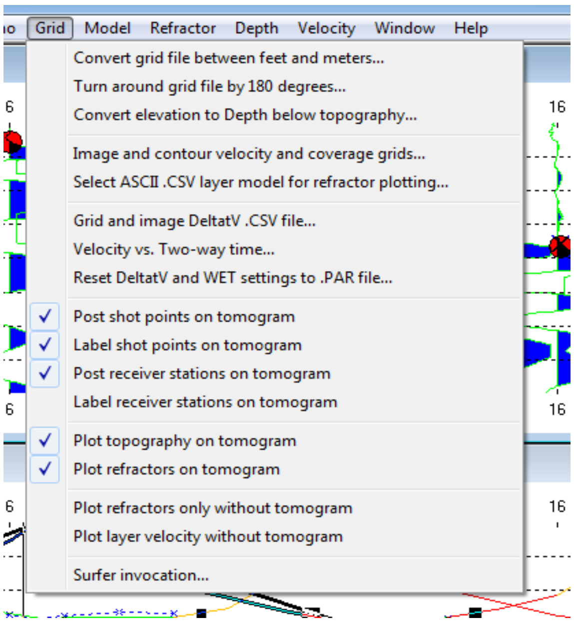


Fig. 6 : Grid menu options, for Rayfract® version 3.25

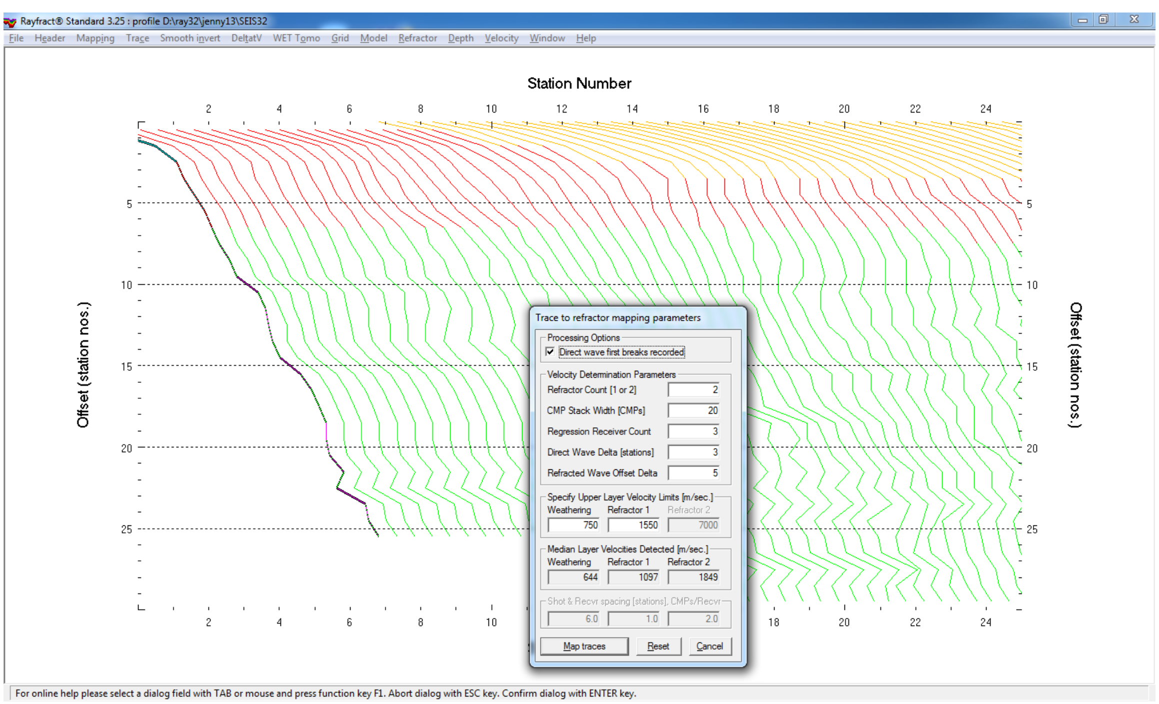


Fig. 7 : *Refractor|Midpoint breaks*, mapping traces to refractors with ALT+M and 1D velocity model

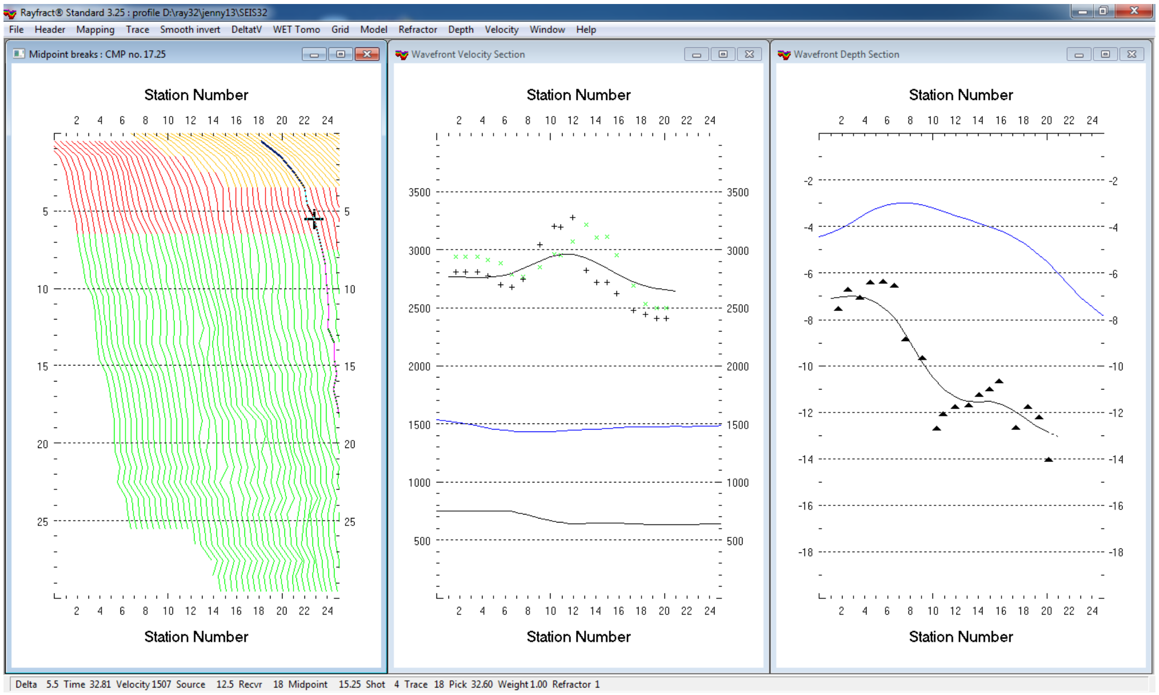


Fig. 8 : left : *Refractor|Midpoint breaks*, center : *Velocity|Wavefront*, right : *Depth|Wavefront*

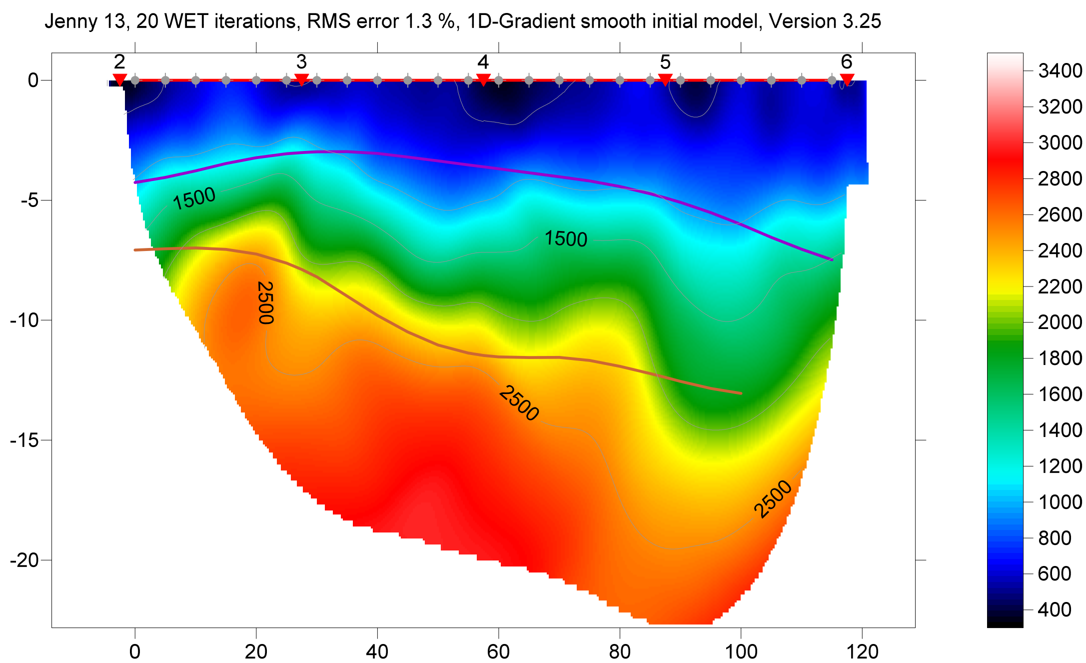


Fig. 9 : Velocity tomogram obtained with Smooth inversion with default settings and 20 WET iterations. Layer-based Wavefront method refractors are plotted in magenta and brown. Compare Fig. 8.

To obtain Fig. 9 overlaying Wavefront method refractors on WET tomogram :

- select *Refractor|Midpoint breaks*, press ALT+M. Edit *mapping parameters* as in Fig. 7
- set *Refracted Wave Offset Delta* to 5, *Weathering* to 750 m/s and *Refractor 1* to 1550 m/s
- hit ENTER key to map traces to refractors.
- press ALT+G for *Crossover distance processing dialog*, edit as in Fig. 10
- leave *Basement filter [station nos.]* at 10, click *Accept button* to smooth crossover distance
- press CTRL+F1 to zoom dip of CMP curves in Fig. 7
- select *Depth|Wavefront*, press ALT+M, edit model parameters as in Fig. 11

- set both *Overburden filter* and *Base filter width* to 6 station number intervals
- hit ENTER key to recompute Wavefront depth section using above parameters
- press ALT+M again, hit ENTER key to redo Wavefront method 2nd time
- select *Velocity|Wavefront* and *Window|Tile* to obtain Fig. 8
- select *Depth|Wavefront* and *File|Export header data|Export ASCII Model of depth section...*
- click *Save button* to export Wavefront refractors and layer velocities to file WAVEMODL.CSV
- select *Grid|Select ASCII .CSV layer model for refractor plotting...* and above WAVEMODL.CSV
- check *Grid menu options* for refractor plotting as shown in Fig. 6
- select *Grid|Image and contour velocity and coverage grids…*
- select tomogram grid file \RAY32\JENNY13\GRADTOMO\VELOIT20.GRD to obtain Fig. 9

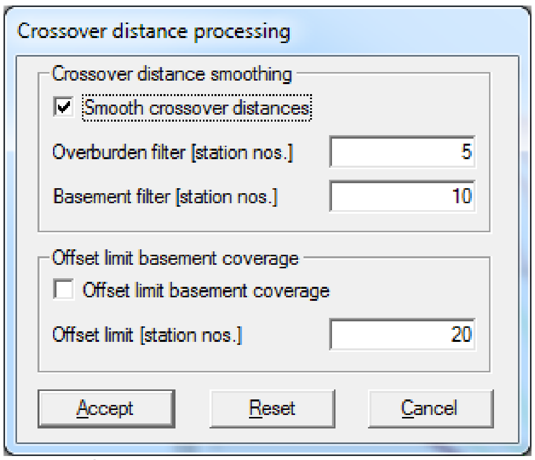


Fig. 10 : Crossover distance processing

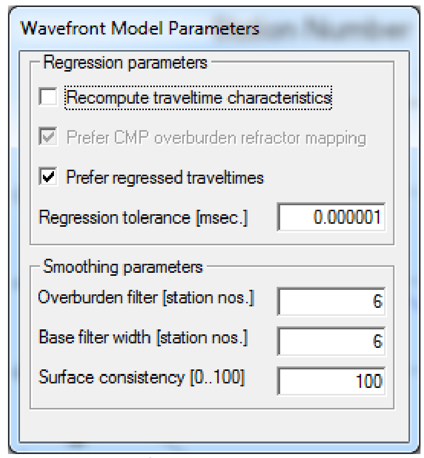


Fig. 11 : Wavefront model parameters

For an explanation of *Refractor|Midpoint breaks* display of CMP sorted traveltime curves (Fig. 7) see our DeltatV paper, Fig. 2. The steeper the local dip of a CMP sorted traveltime curve, the higher the local apparent velocity.

See jenny10.pdf for our interpretation of a synthetic layer-based data set.

We thank our reseller Jacques Jenny at **Geo2X** in Oulens-sous-Echallens, Switzerland for making available these data sets.

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Palmer 2010 Syncline Model construction and forward modeling, with Rayfract® 3.25 and Golden Software Surfer® 11

We show how to define the recording geometry by importing dummy shots into a Rayfract® profile database, without first break picks. Next we create a syncline model grid with Surfer, as in Palmer 2010 Fig. 5. Then we generate synthetic shots with our Eikonal Solver, by forward modeling wave propagation through this model grid. Finally we run our *2D Smooth inversion* and *1.5D layer-based Wavefront refraction* methods on these synthetic data. See also http://rayfract.com/tutorials/fig9inv.pdf .

Create a new Rayfract® profile database, import dummy shots

Download archive PALMFIG9.ZIP containing file ONESHOT.ASC from our web site :

http://rayfract.com/tutorials/palmfig9.zip .

Now create new profile database named PALMFIG9, as described in our manual available at http://rayfract.com/help/manual.pdf . Specify *station spacing* of 5m, in *Header|Profile*. Copy above file ONESHOT.ASC into directory \RAY32\PALMFIG9\INPUT. ONESHOT.ASC specifies 49 channels, with first breaks set to -1. You may edit such a dummy .ASC shot with any text editor e.g. Windows WordPad.

Now import file ONESHOT.ASC repeatedly, once for each shot position which we want to model, as in above manual.pdf . Specify *Import data type* ASCII column format. Leave *Default spread type* at default setting 10: 360 channels. Specify *Shot pos. [station no.]* 0, 6, 12, 18, 24, 30, 36, 42, 48 as in Palmer 2010 Fig. 8. Specify *Shot Number* 1 to 9 for these shots, during import. Leave *Layout start* at 0.0 .Once done with import, set topography elevation “z” to 0.0 in *Header|Station* for one station. Hit ENTER and confirm prompt, to extrapolate elevation 0.0 to all stations.

Build model grid file with Surfer 8

Start up Surfer 8. Select *File|New* and choose *Plot Document*, then click OK. Now select *Grid|Function...* and specify the parameters for generation of our overburden grid as in Fig. 1 :

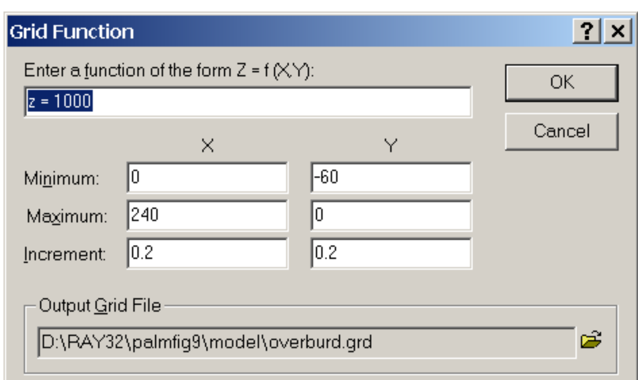

Fig. 1 : Generate overburden grid in Surfer

Click on OK to generate our constant-velocity overburden grid file. Select *Grid|Function...* again and set the “function” text field to “z = 2820”. Specify \RAY32\PALMFIG9\MODEL\BASEMENT.GRD for *Output Grid File*. Click on OK to generate the constant-velocity basement grid file.

Next we edit a *blanking file,* with any text editor. Select *Start|Run...,* enter the program name NOTEPAD.EXE and hit RETURN. Then enter content as in Fig. 2 :

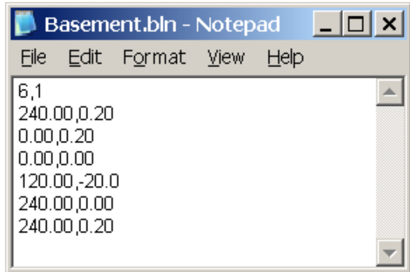

Fig. 2 : Edit basement blanking file in Notepad

Be sure to hit ENTER at end of last line 240.00, 0.20, to force an end-of-line character in the disk file. Select *File|Save As...* . Set *Save as type* to *All Files*. Set *File name* to BASEMENT.BLN. Click on *Save button*. This file is a *Golden Software Blanking File*; see your Surfer 8 manual Appendix C. Our blanking file describes the "syncline" triangular polygon which we want to cut out of above basement grid file. The lower side of the polygon is the "top of basement" topography i.e. relief.

Go back into Surfer, select *Grid|Blank...* and then the BASEMENT.GRD file as generated above. Then select our BASEMENT.BLN file. Specify \RAY32\PALMFIG9\MODEL\SYNCLINE.GRD as output file name and click on Save to generate our "basement with syncline" grid file.

Now we add our constant-velocity overburden to the syncline model. Select *Grid|Mosaic...* and then above OVERBURD.GRD file. Click on Add... and select above SYNCLINE.GRD file. Set *Overlap method* to *Maximum*. Click on the folder icon to the right of field *Output Grid File* and enter file name PALMFIG9.GRD. Our *Grid Mosaic dialog* should now look as in Fig. 3 :

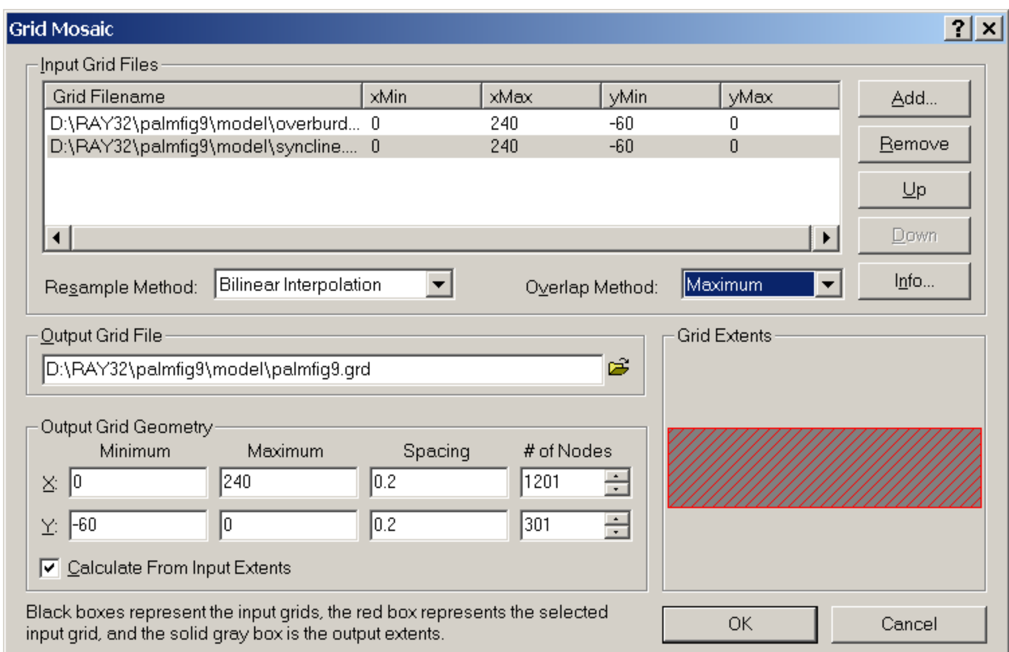

Fig. 3 : Combine overburden grid with blanked basement grid in Surfer

Click on OK to generate the final syncline model. Select *Map|Image Map*... and our PALMFIG9.GRD file. Double-click the resulting plot with left mouse key. Click on *Colors bar* in *General tab*, and load *Color scale* \RAY32\RAINBOW2.CLR. In frame *Data to Color Mapping*, set *Minimum* to 500, and *Maximum* to 5000. Adapt *Limits and Scale tabs* to obtain Fig. 4 :

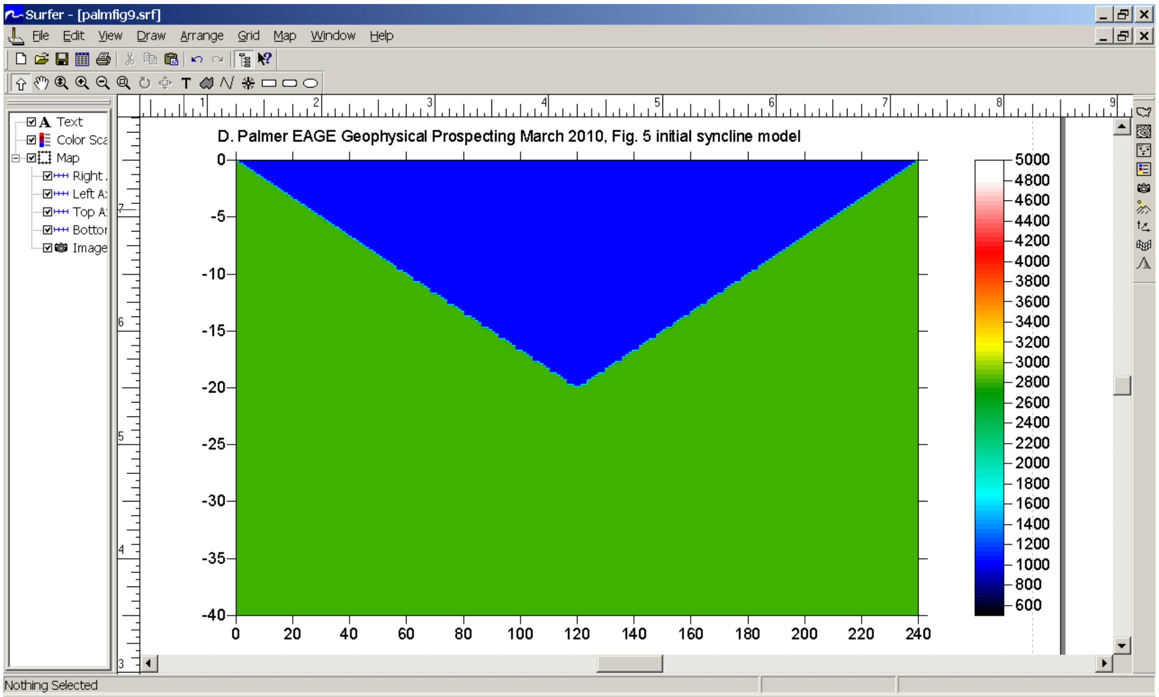

Fig. 4 : Image syncline model in Surfer

Forward model seismic body wave propagation through syncline model

Open profile database \RAY32\PALMFIG9 as created above, with Rayfract® *File|Open Profile…* Select *Model|Model synthetic shots…* and \RAY32\PALMFIG9\MODEL\PALMFIG9.GRD . Select *File|Export header data|Export First Breaks as ASCII…* . Save to file PALMFIG9.ASC. Select *Refractor|Shot breaks*. Now press ALT+P, set *Maximum time [msecs.]* to 90 and hit ENTER. Compare the traveltimes as shown in our Fig. 5 to Palmer 2010 Fig. 8; these data are identical.

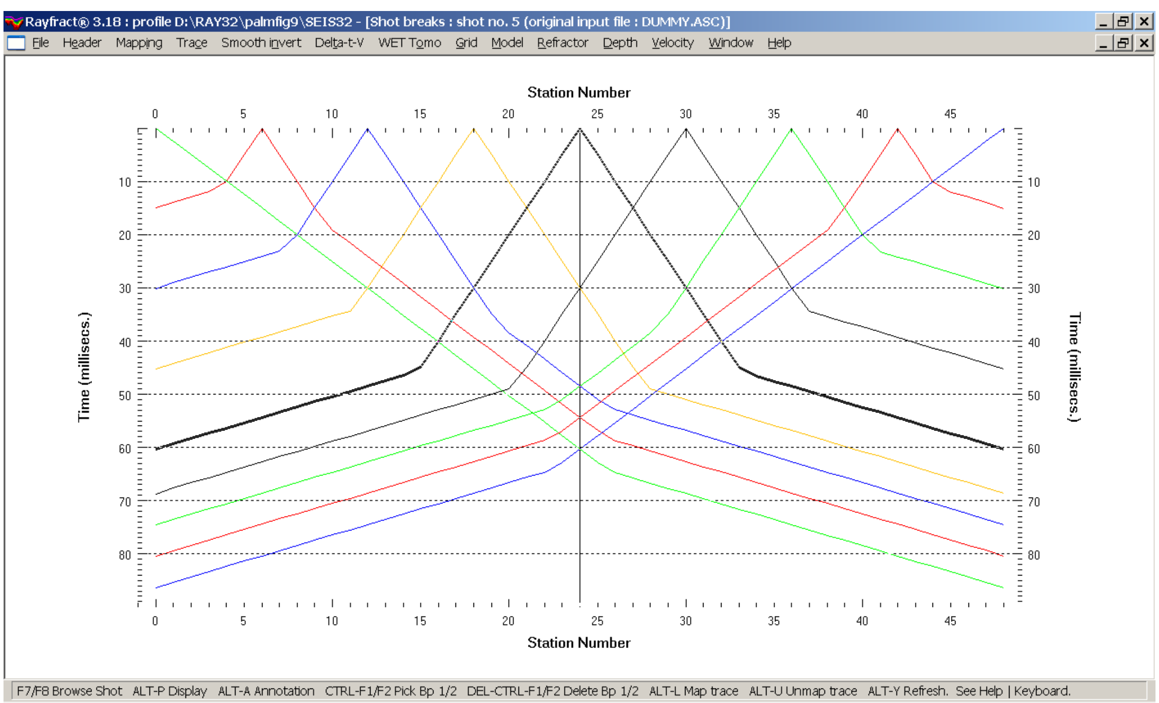

Fig. 5 : *Refractor|Shot breaks*, showing shot-sorted traveltime curves

Next we show *Smooth inversion* of above synthetic first break data, shown in Fig. 5 :

- uncheck *WET Tomo|WET tomography Settings|Scale wavepath width*
- uncheck *WET Tomo|WET tomography Settings|Scale filter height*
- select *Smooth invert|WET with 1D-gradient initial model*, confirm prompts to obtain Fig. 6
- when you see the prompt "Continue with WET tomography ?" click *No button*
- select *WET Tomo|Interactive WET tomography…*
- click *Select button* and select \RAY32\PALMFIG9\GRADTOMO\GRADIENT.GRD
- click *button Accept parameters*
- set *Number of WET tomography iterations* to 100, and set *Wavepath width* to 10%
- set *Maximum valid velocity* to 3,000 m/s, and uncheck *or RMS error does not improve for n =*
- click *button Edit grid file generation*. Set *Store each nth iteration only : n =* to 20
- click buttons *Accept parameters* and *Start tomography processing* for Fig. 7 and 8

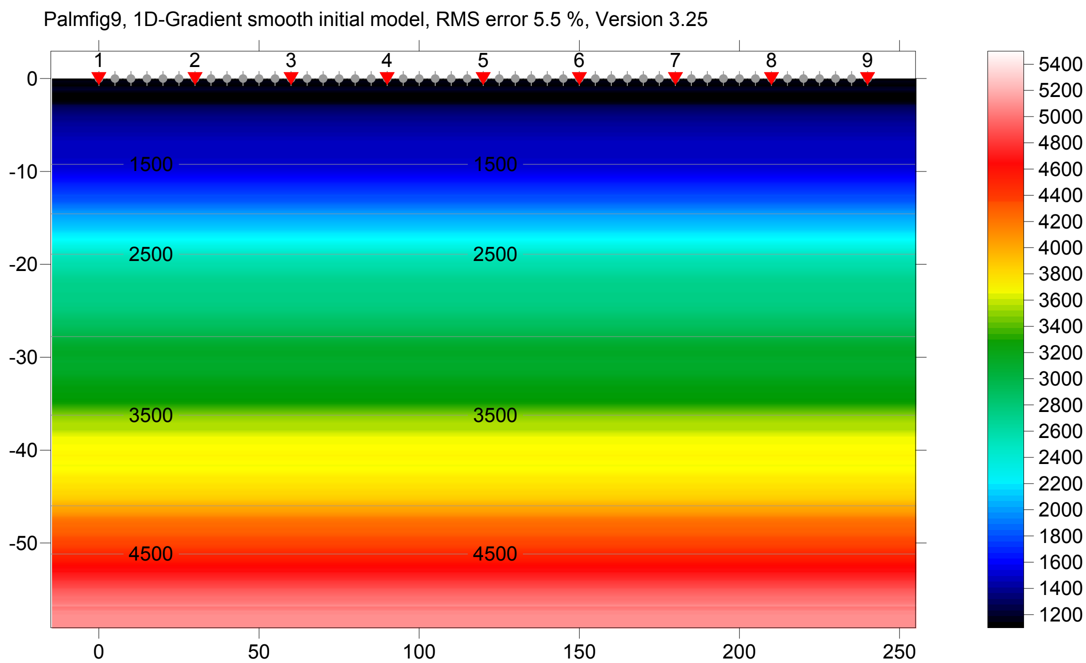

Fig. 6 : 1D starting model obtained with Smooth inversion

To obtain layer-based interpretation with our *Wavefront refraction* method :

- select *Refractor|Midpoint breaks,* press CTRL+F1 to zoom dip of *CMP traveltime curves*
- press ALT+M, edit fields as in Fig. 10, hit ENTER to map traces to refractors
- press ALT+G, hit ENTER to smooth *crossover distances*
- select *Depth|Wavefront*, press ALT+M, set *Base filter width* to 5 (Fig. 11), hit ENTER
- select *Velocity|Wavefront* and *Window|Tile* to obtain Fig. 9

To plot the basement refractor obtained in Fig. 9 on the 2D WET tomogram shown in Fig. 7 :

- click on *Window Wavefront Depth Section* (center) in Fig. 9
- select *File|Export header data|Export ASCII model of depth section…*
- click *Save button* to generate file WAVEMODL.CSV with refractor depths and velocities
- check *Grid|Plot refractors on tomogram*
- select *Grid|Select ASCII .CSV layer model for refractor plotting…* and your WAVEMODL.CSV
- select *Grid|Image and contour velocity and coverage grids...*
- select tomogram grid \RAY32\STEP\GRADTOMO\VELOIT100.GRD for Fig. 7

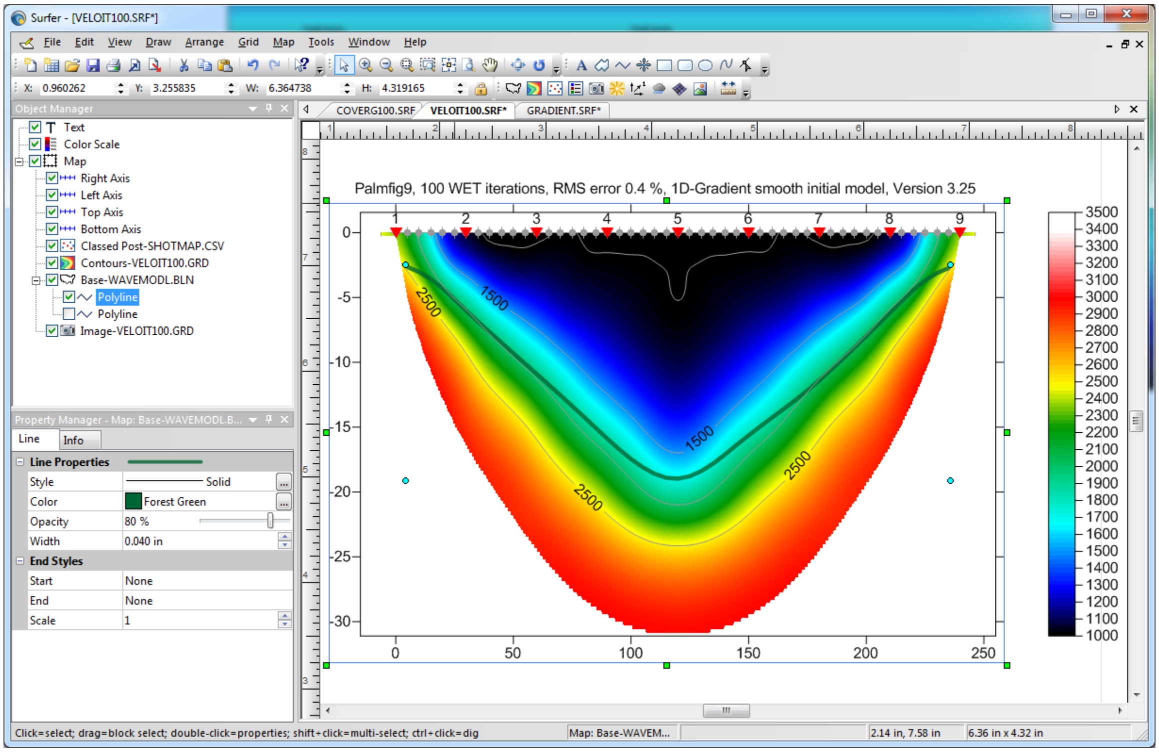

Fig. 7 : 2D WET tomogram obtained with Smooth inversion, 100 WET iterations, wavepath width 10%, maximum WET velocity limited to 3,000 m/s. No scaling of WET wavepath width and filter height. Basement refractor obtained with Wavefront refraction method (Fig. 9) is plotted as green line.

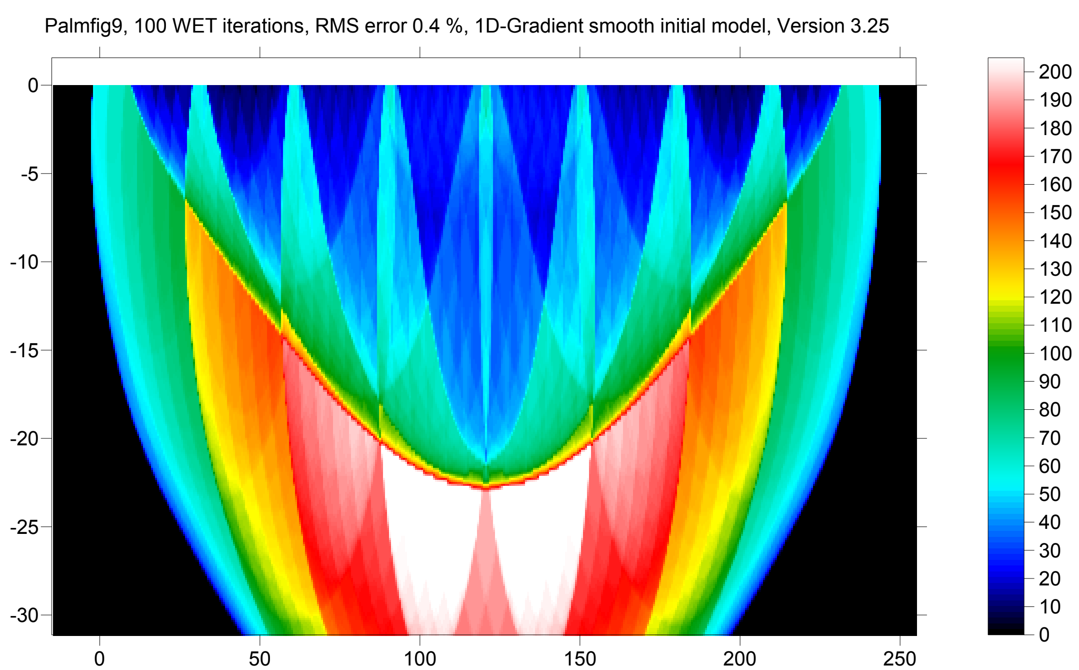

Fig. 8 : Wavepath coverage plot obtained with Fig. 7

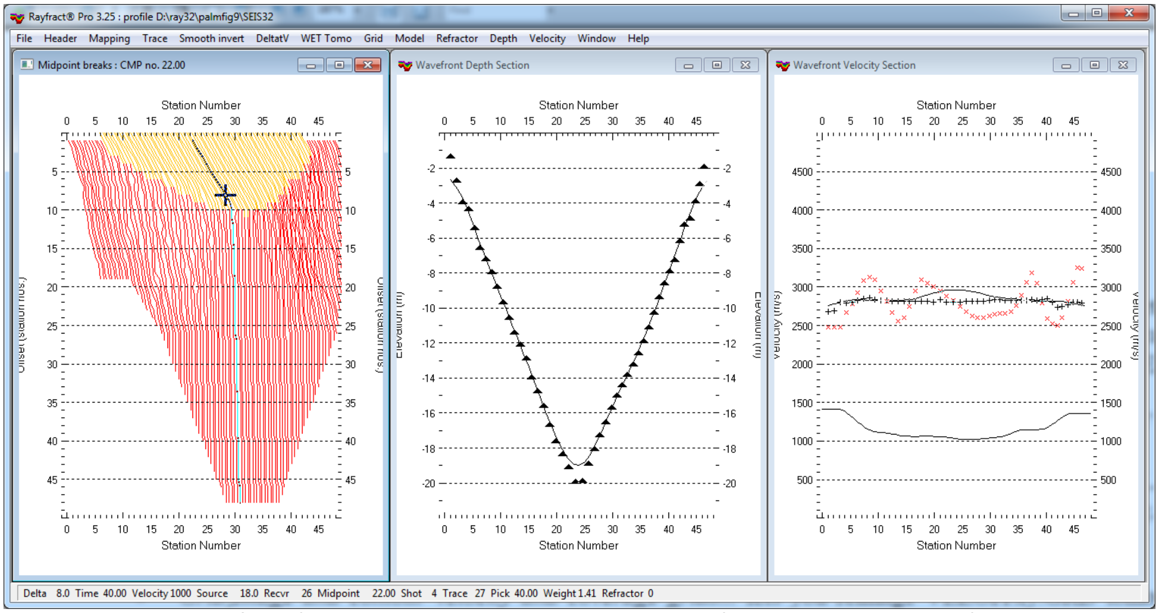

Fig. 9 : left : *Refractor|Midpoint breaks*, center : *Depth|Wavefront*, right : *Velocity|Wavefront*

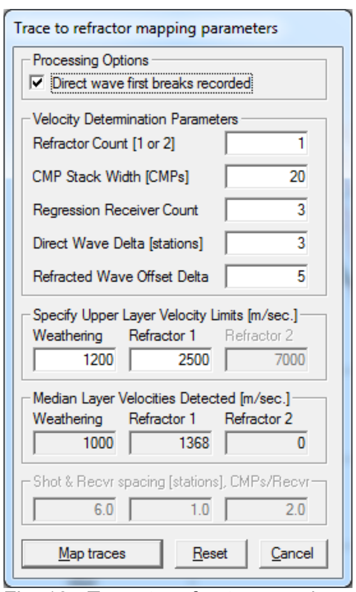

Fig. 10 : Trace to refractor mapping

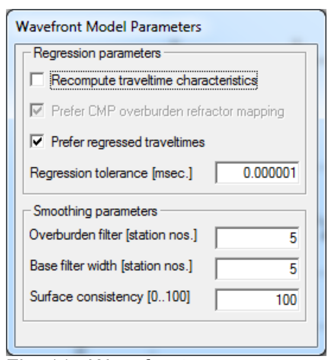

Fig. 11 : Wavefront parameters

For an explanation of *Refractor|Midpoint breaks* display of CMP sorted traveltime curves (Fig. 9 left) see our DeltatV paper, Fig. 2. The steeper the local dip of a CMP sorted traveltime curve, the higher the local apparent velocity.

Obviously the layer-based *Wavefront refraction* method interpretation (Fig. 9) works better in this simple case. But as shown by Sheehan et al. in 2005, *Smooth inversion* including 2D WET inversion (Fig. 7) often works better than layer-based interpretation, in case of strong lateral velocity variation, gradual increase of velocity with depth, laterally discontinuous layers, pinch outs, outcrops, fault zones, low-velocity layers etc. Also, WET inversion does not depend on your always **subjective and non-unique mapping of traces to refractors**.

Also see our earlier tutorial showing the effect of limiting the maximum velocity for synthetic syncline traveltime data, when determining the starting model with DeltatV inversion.

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Basement Step Model construction and forward modeling, with Rayfract® 3.25 and Golden Software Surfer® 11

We show how to define the recording geometry by importing dummy shots into a Rayfract® profile database, without first break picks. Next we create a basement step model grid with Surfer. Then we generate synthetic shots with our Eikonal Solver, by forward modeling wave propagation through this model grid. Finally we invert these synthetic traveltime data with our *2D Smooth inversion* and *1.5D layer-based Wavefront refraction* methods.

We use the model described by M.S. Mendes and T. Teixidó in 2008, in their Fig. 1. Instead of only 5 shots into 48 receivers we model 9 shots, with shot spacing of 6 (six) receiver *station spacings*. Mendes et al. run only 5 WET iterations for their Fig. 2, not the default 20 iterations shown in our Fig. 5.

Create a new Rayfract® profile database, import dummy shots

Download archive STEP.ZIP containing file ONESHOT.ASC from our web site.

Now create a new profile database named STEP, as described in our manual available at http://rayfract.com/help/manual.pdf . Specify *station spacing* of 2m, in *Header|Profile*. Copy above file ONESHOT.ASC into directory \RAY32\STEP\INPUT. ONESHOT.ASC specifies 49 channels, with first breaks set to -1. You may edit such a dummy .ASC shot with any text editor e.g. Windows WordPad.

Now import file ONESHOT.ASC repeatedly, once for each shot position which we want to model, as in above manual.pdf . Specify *Import data type* ASCII column format. Leave *Default spread type* at default setting 10: 360 channels. Specify *Shot pos. [station no.]* 0, 6, 12, 18, 24, 30, 36, 42, 48. Specify *Shot Number* 1 to 9 for these shots, during import. Leave *Layout start* at 0.0 .Once done with import, set topography elevation "z" to 0.0 in *Header|Station* for one station. Hit ENTER and confirm prompt, to extrapolate elevation 0.0 to all stations.

Build model grid file with Surfer 11

Start up Surfer 11. Select *File|New* and choose *Plot Document*, then click OK. Now select *Grid|Function...* and specify the parameters for generation of our overburden grid as in Fig. 1 :

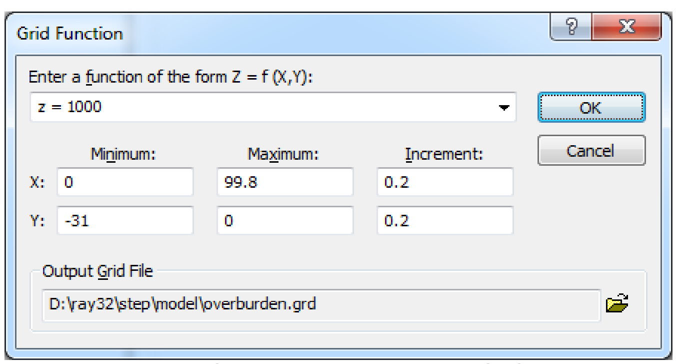

Fig. 1 : Generate overburden grid in Surfer

Click on OK to generate our constant-velocity overburden grid file. Select *Grid|Function...* again and set the "function" text field to "z = 3000". Specify \RAY32\STEP\MODEL\BASEMENT.GRD for *Output Grid File*. Click on OK to generate the constant-velocity basement grid file.

Next we edit a *blanking file,* with any text editor. Select *Start|Run...,* enter the program name NOTEPAD.EXE and hit RETURN. Then enter content as in Fig. 2 :

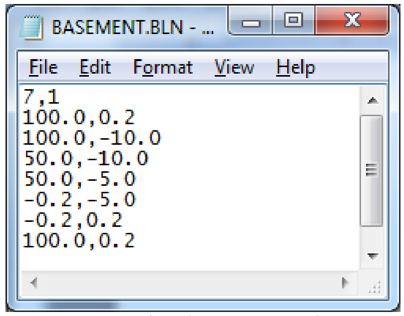

Fig. 2 : Edit blanking file, for blanking of basement grid

Be sure to hit ENTER at end of last line 100.0, 0.20, to force an end-of-line character in the disk file. Select *File|Save As...* . Set *Save as type* to *All Files*. Set *File name* to BASEMENT.BLN. Click on *Save button*. This file is a *Golden Software Blanking File*; see your Surfer 11 manual Appendix C. Our blanking file describes the "step" polygon which we want to cut out of above basement grid file. The lower side of the polygon is the "top of basement" topography i.e. relief.

Go back into Surfer, select *Grid|Blank...* and then the BASEMENT.GRD file as generated above. Then select our BASEMENT.BLN file. Specify \RAY32\STEP\MODEL\FAULT.GRD as output file name and click on *Save button* to generate our "basement with monocline" grid file.

Now we add our constant-velocity overburden to the step model. Select *Grid|Mosaic...* and then above OVERBURDEN.GRD file. Click on *Add... button* and select above FAULT.GRD file. Set *Overlap method* to *Maximum*. Click on the *folder icon* to the right of field *Output Grid File* and enter file name STEP.GRD. Our *Grid Mosaic dialog* should now look as follows :

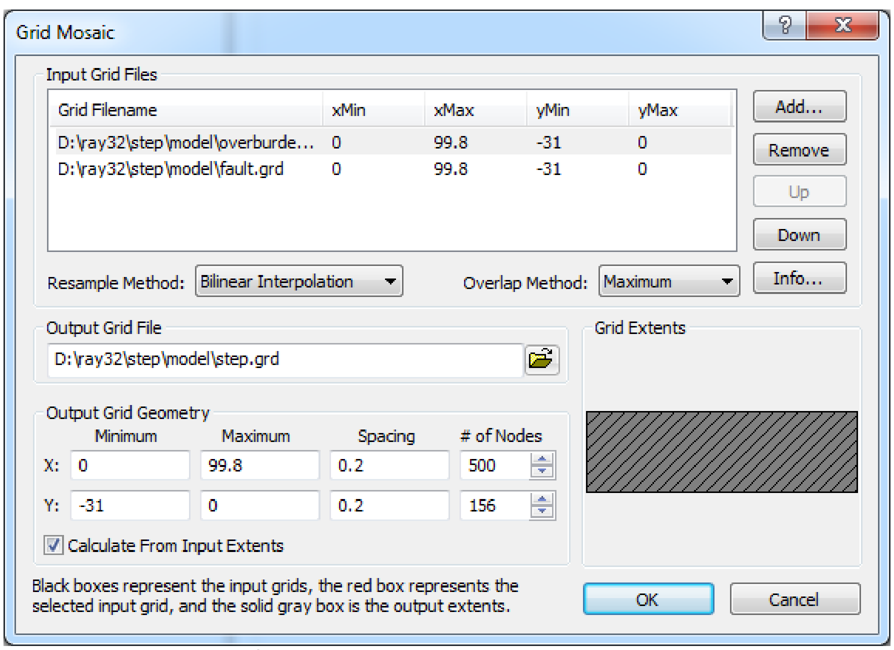

Fig. 3 : Combine overburden with blanked basement grid

Click on *OK button* to generate the final step model. Select *Map|New|Image Map...* and our STEP.GRD file. Click the resulting plot with left mouse key. Select *View|Manangers|Object Manager*. Left-click *Image-step.grd*. Click on *Colors bar* in *Property Manager|General tab*, and load *Color scale* BlueRed1. Check *Interpolate pixels* and *Show color scale*. Left-click *Map icon* in *Object Manager*. Click *Scale tab* in *Property Manager*, uncheck *Proportional XY*, set *X Scale|Length* to 6.0 in and *Y Scale|Length* to 4.0 in to obtain Fig. 4 :

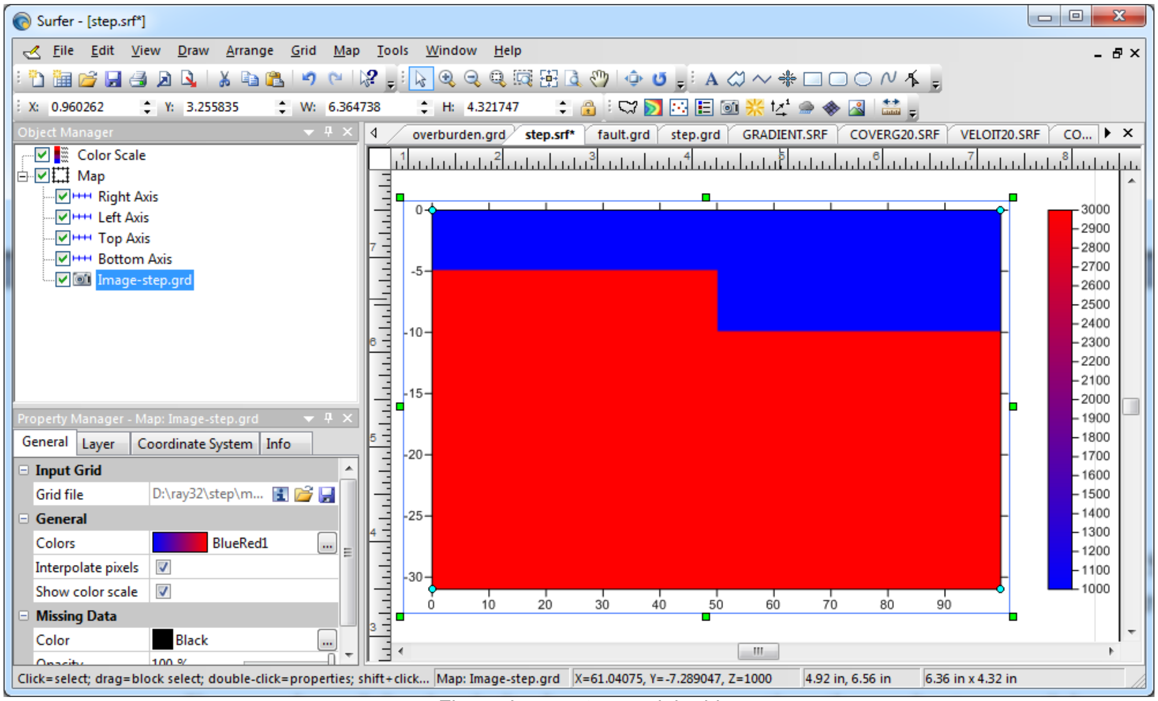

Fig. 4 : Image step model grid

You may need to repeat above grid generation steps with Golden Software Surfer once or twice, and shut down/restart Surfer in between. Otherwise Surfer may not update/read old versions of disk files.

Forward model seismic body wave propagation through step model

Open profile database \RAY32\STEP as created above, with Rayfract® *File|Open Profile…* Select *Model|Model synthetic shots…* and \RAY32\STEP\MODEL\STEP.GRD . Select *File|Export header data|Export First Breaks as ASCII…* . Save to file STEP.ASC. Select *Refractor|Shot breaks*. Now press ALT+P, set *Maximum time [msecs.]* to 50 and hit ENTER, to obtain Fig. 5 :

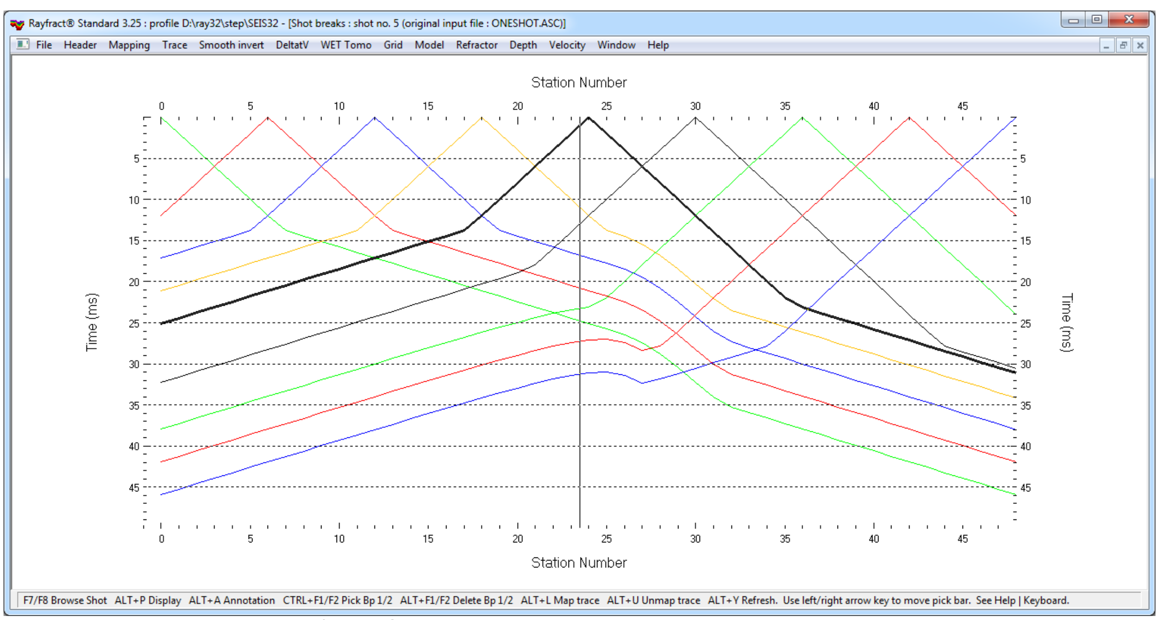

Fig. 5 : *Refractor|Shot breaks display*, showing shot-sorted traveltime curves

Next we show Smooth inversion of these synthetic traveltime data as shown in Fig. 5 :

- select *Smooth invert|WET with 1D-gradient initial model*
- confirm prompts to obtain 1D starting model as in Fig. 6
- confirm prompts to obtain 2D WET tomogram after 20 iterations as in Fig. 7
- select *WET Tomo|Interactive WET tomography…*
- set *Number of WET tomography iterations* to 100
- uncheck *or RMS error does not improve for n =*
- click *button Edit grid file generation*. Set *Store each nth iteration only : n =* to 20
- click buttons *Accept parameters* and *Start tomography processing* for Fig. 8 and 9

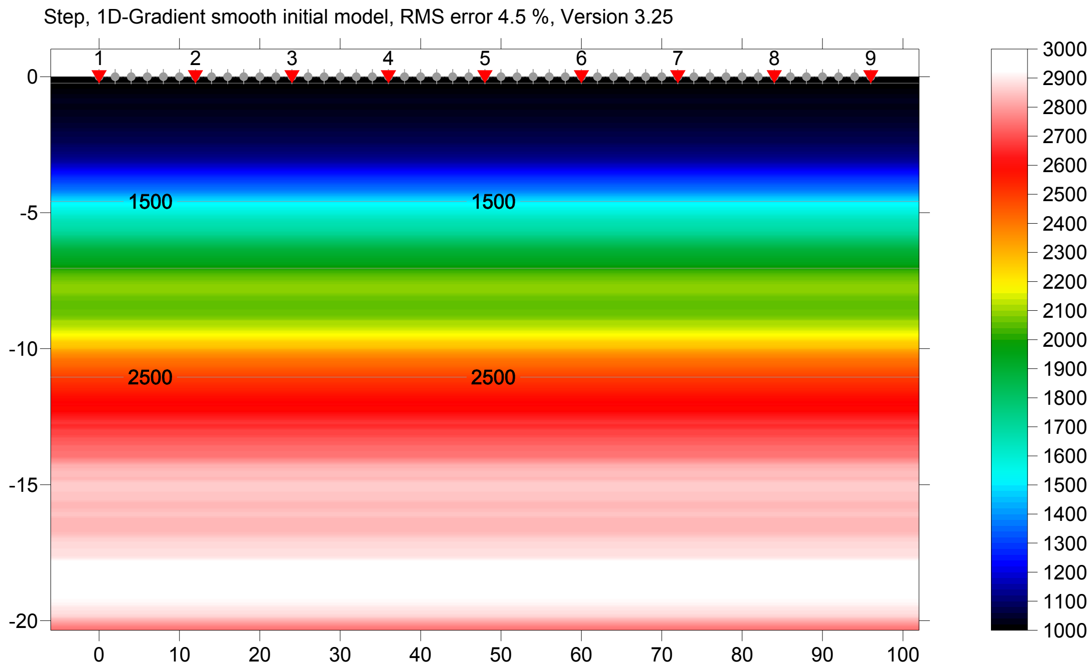

Fig. 6 : 1D-gradient starting model, obtained with *Smooth invert|WET with 1D-gradient initial model* and default settings

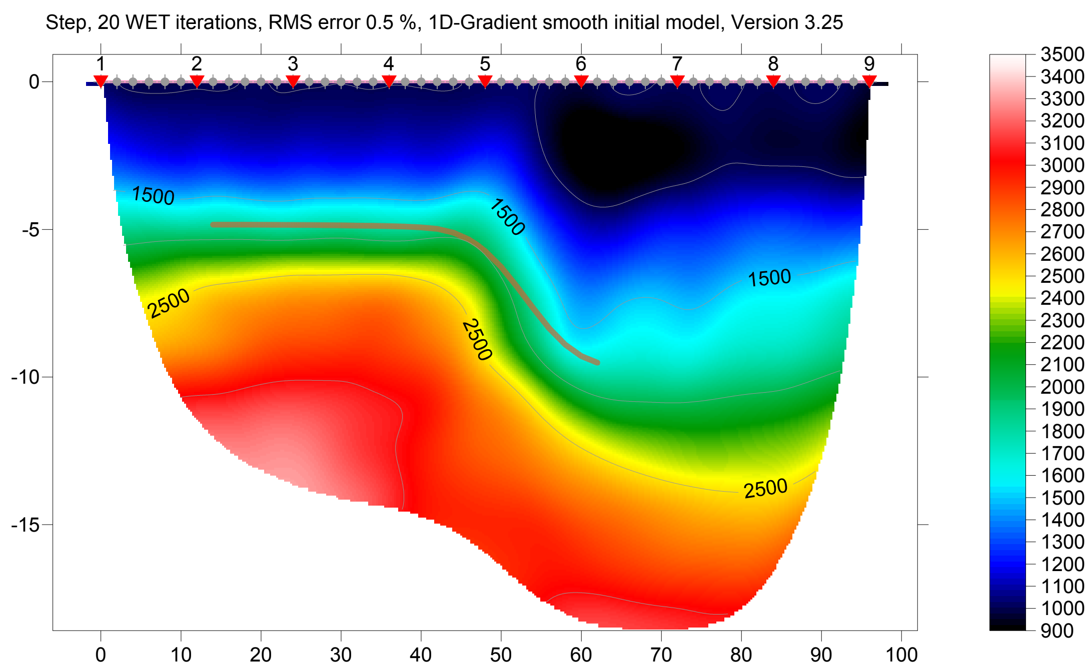

Fig. 7 : Smooth inversion, 20 WET iterations, default settings. . Basement refractor obtained with Wavefront refraction method is plotted as brown line. See jenny13 tutorial for instructions.

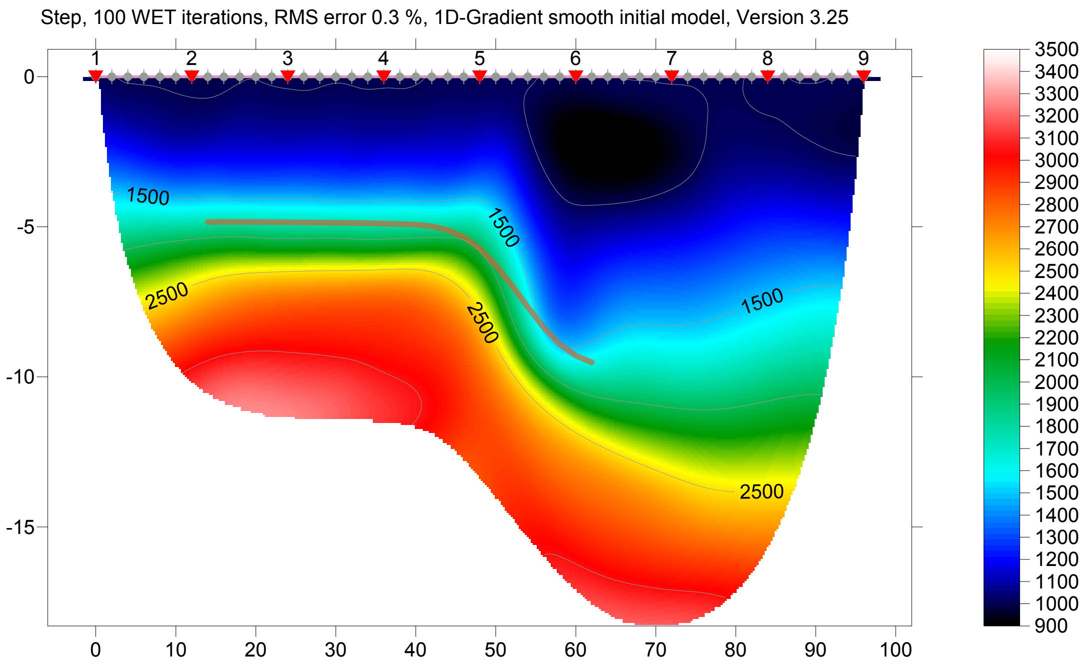

Fig. 8 : Smooth inversion, 100 WET iterations. Basement refractor obtained with Wavefront method plotted as brown line.

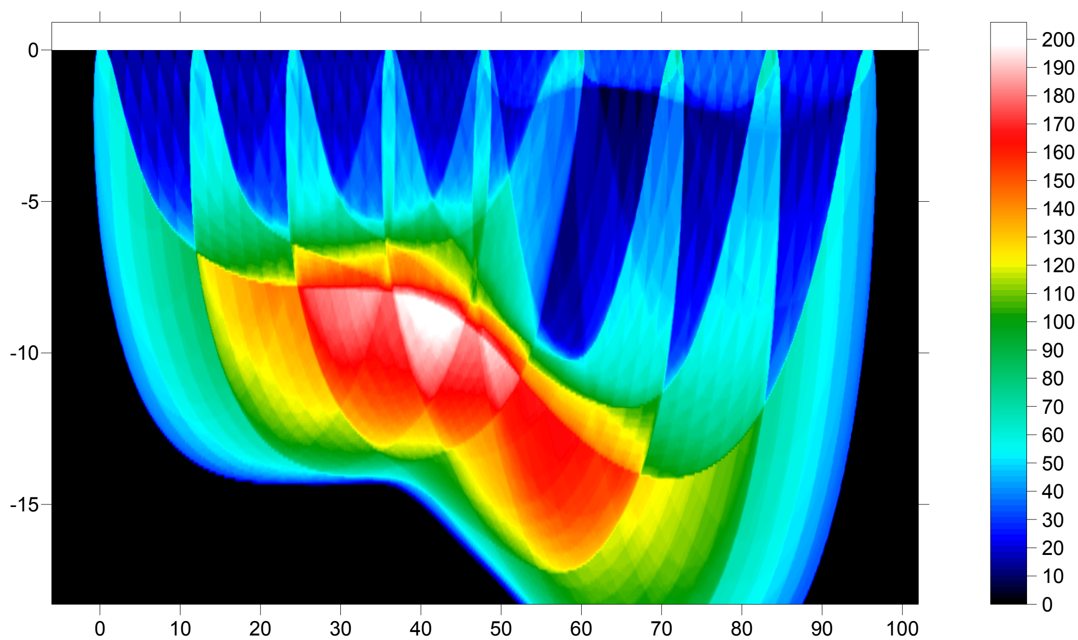

Fig. 9 : WET wavepath coverage plot, obtained with Fig. 8

Obviously Fig. 8 is a better approximation than Fig. 7, of the true step model (Fig. 4) . This shows that increasing the WET iteration count from 20 to 100 makes sense, at least in this case and most of the time.

Obtain a layer-based interpretation with our Wavefront refraction method :

- select branch point no. 1 with CTRL+F1 for traveltime curves in *Refractor|Shot breaks*, Fig. 10
- press ALT+L to map traces to refractors, based on your branchpoint locations
- select *Depth|Wavefront*, press ALT+M, set *Base filter width* to 5, press ENTER for Fig. 11
- select *Velocity|Wavefront*, press ALT+P, set *Maximum velocity* to 5000, press ENTER

Plot the basement refractor shown in Fig. 11 (center) on WET tomograms (Fig. 7, Fig. 8) :

- click on *Window Wavefront Depth Section* (center) in Fig. 11

- ➢ select *File|Export header data|Export ASCII model of depth section…*
- ➢ click *Save button* to generate file WAVEMODL.CSV with refractor depths and velocities
- ➢ check *Grid|Plot refractors on tomogram*
- ➢ select *Grid|Select ASCII .CSV layer model for refractor plotting…* and your WAVEMODL.CSV
- ➢ select *Grid|Image and contour velocity and coverage grids…*
- ➢ select tomogram grid \RAY32\STEP\GRADTOMO\VELOIT100.GRD for Fig. 8

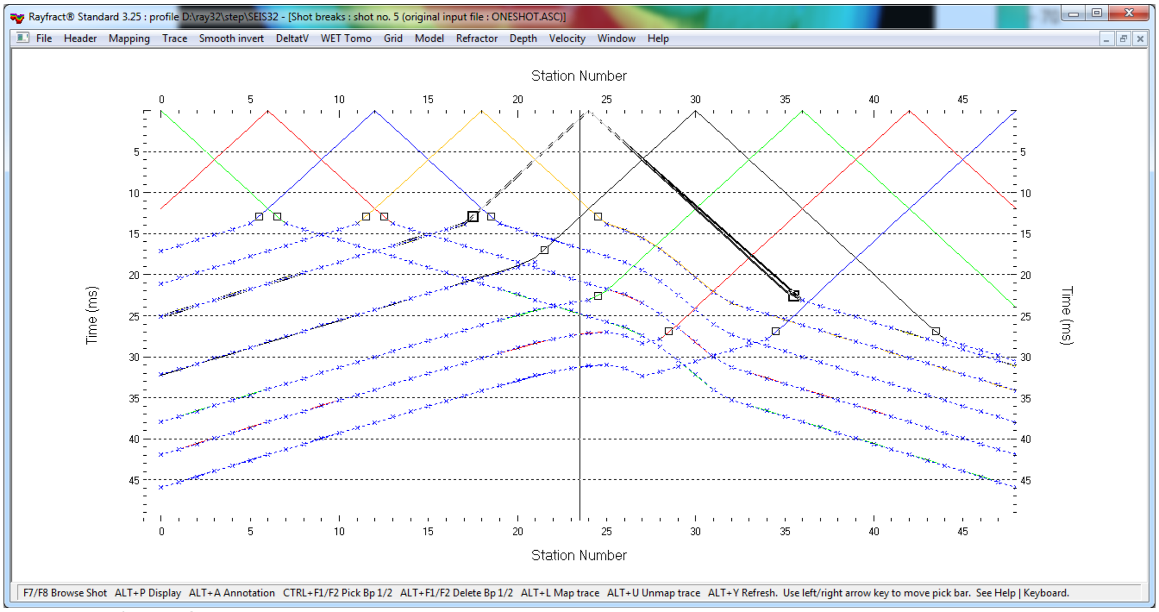

Fig. 10 : *Refractor|Shot breaks* with branch points selected (outlined squares). Dashed blue curves and blue crosses are modeled first breaks for basement refractor, obtained with *Depth|Wavefront*.

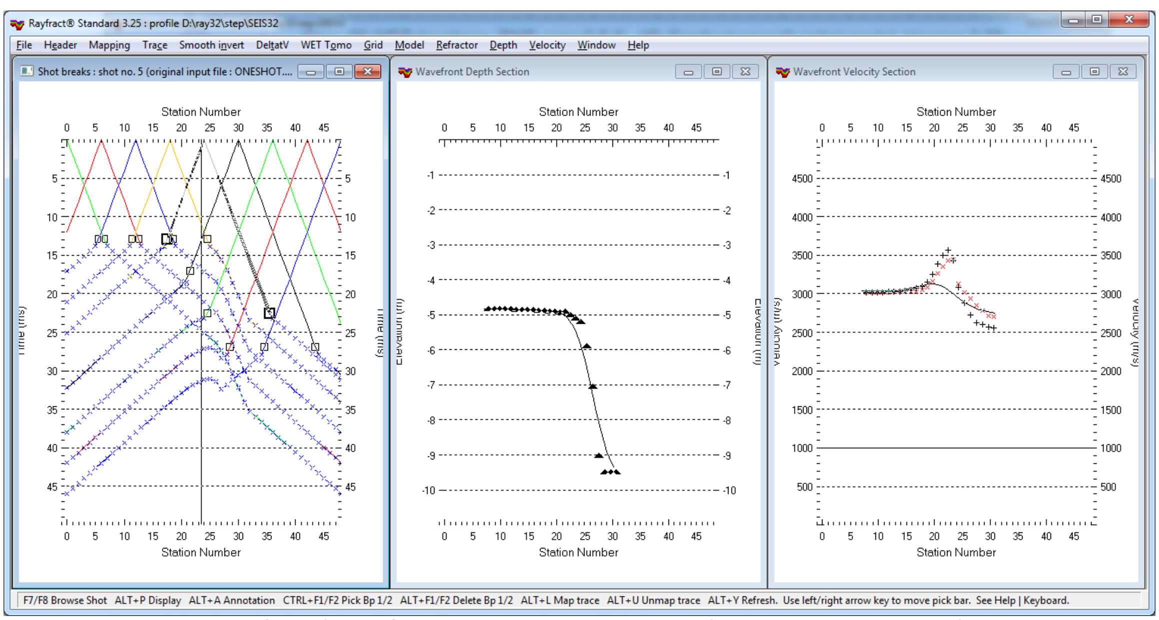

Fig. 11 : left : *Refractor|Shot breaks*, center : *Depth|Wavefront*, right : *Velocity|Wavefront*

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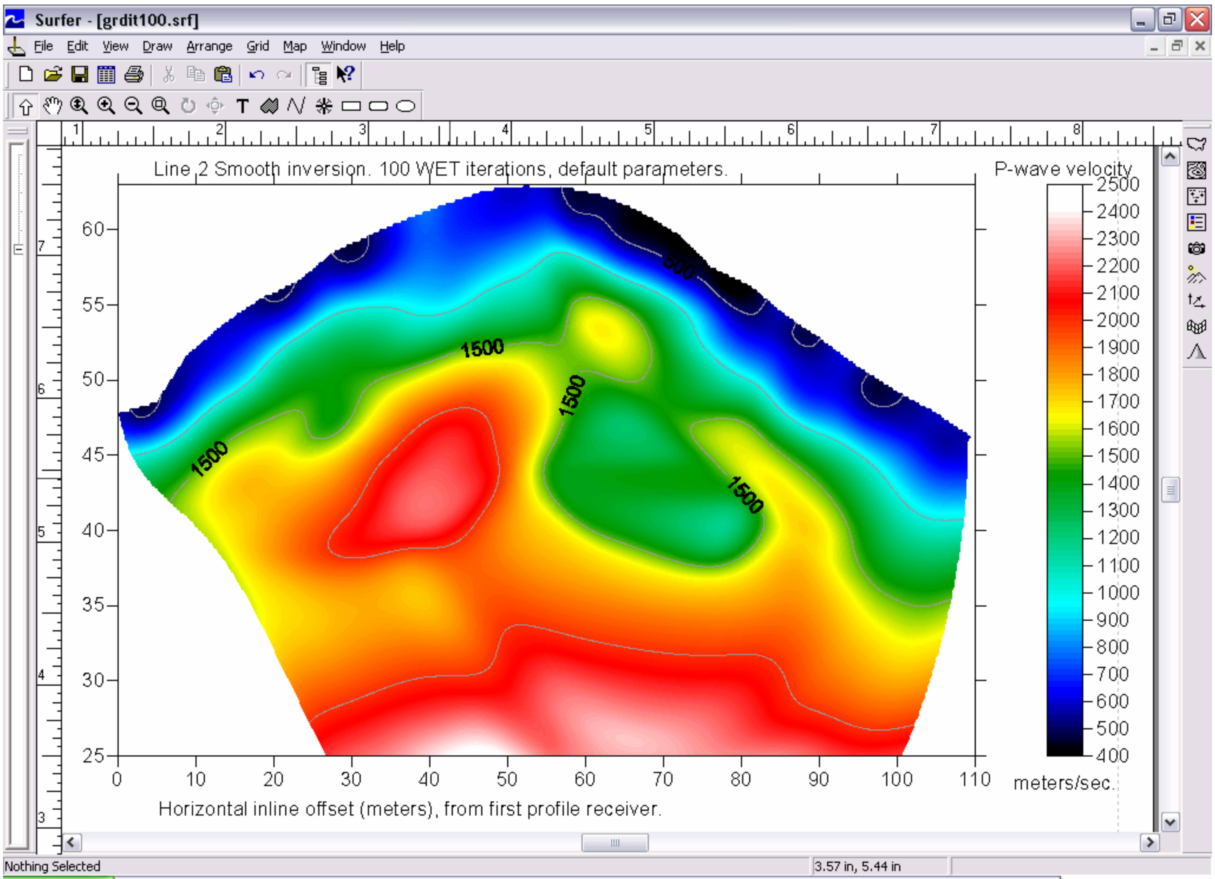
Smooth inversion and conventional Wavefront inversion of LINE2 as sent by Subsurface Engineering in October 2004 :

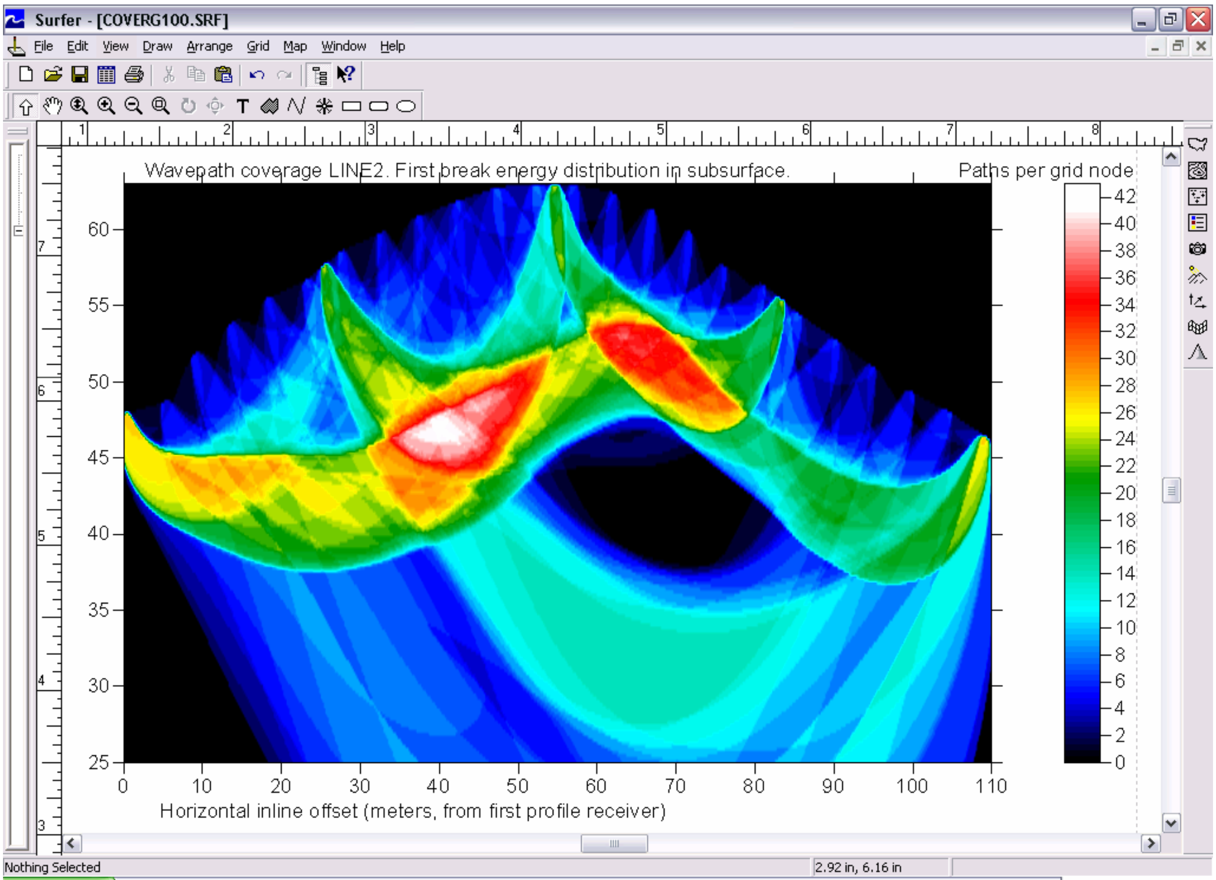
Here we show how to invert the same data set with two completely different seismic refraction methods. Please proceed as follows :

1. create a new profile database named LINE2 with a *Station spacing* of 5 meters. See our manual http://rayfract.com/help/manual.pdf chapter 1.1
2. download an archive with the original SEG-2 formatted binary trace files and Rimrock Geophysics .PIK first break pick files from http://rayfract.com/tutorials/line2.zip, into directory \RAY32\LINE2\INPUT
3. unzip archive \RAY32\LINE2\INPUT\LINE2.ZIP, and store the contents into the same directory
4. uncheck *File|Import Data Settings|Round shot station to nearest whole station*, to round to .5 station numbers e.g. 0.5, 1.0, 1.5 etc.
5. import the binary trace data and first breaks as described in our manual, chapter 1.2. Specify *Import data type* SEG-2, *Default shot hole depth* of 0.0. Leave *Default spread type* at 10:360 channels.
6. select *File|Update header data|Update First Breaks...* . Specify file \RAY32\LINE2\INPUT\BREAKS.LST
7. *File|Update header data|Update Station Coordinates...* with file \RAY32\LINE2\INPUT\COORDS.COR
8. *File|Update header data|Update Shotpoint coordinates...* with file \RAY32\LINE2\INPUT\SHOTPTS.SHO
9. invert the data with *Smooth invert|WET with gradient initial model*. Proceed as lined out in chapter 1.4
10. select *WET Tomo|Interactive WET tomography....* Click on field *Number of WET tomography iterations*
11. enter the new value of 100. Set field *Maximum valid velocity* to 3000 m/sec
12. click on button *Edit grid file generation*, and set field *Store each nth iteration only* to 20
13. click on button *Accept parameters*, and button *Start tomography processing*

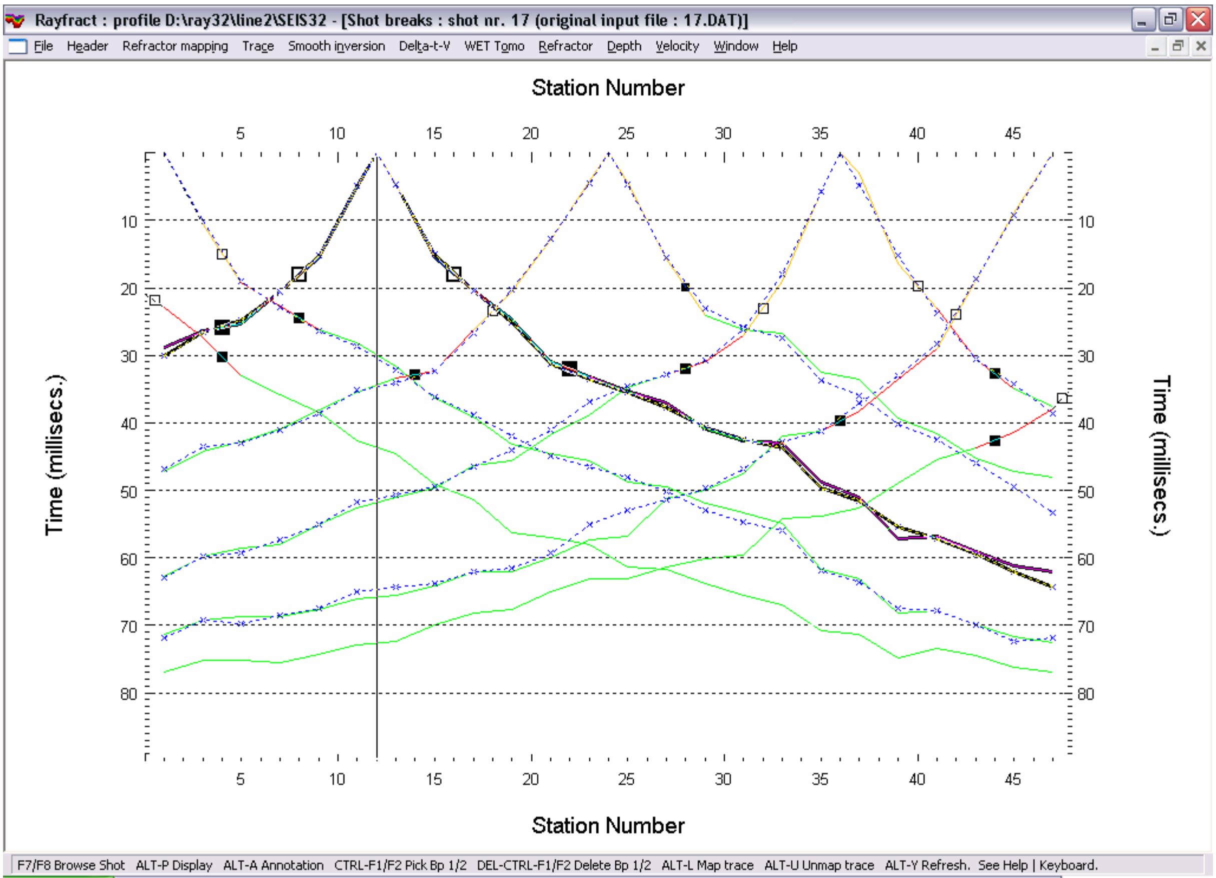
Once the WET inversion finishes, you will obtain the following velocity tomogram and wavepath coverage plot :



Smooth inversion LINE2, with 1D gradient initial model. 100 WET iterations, max. velocity 3,000 m/sec.



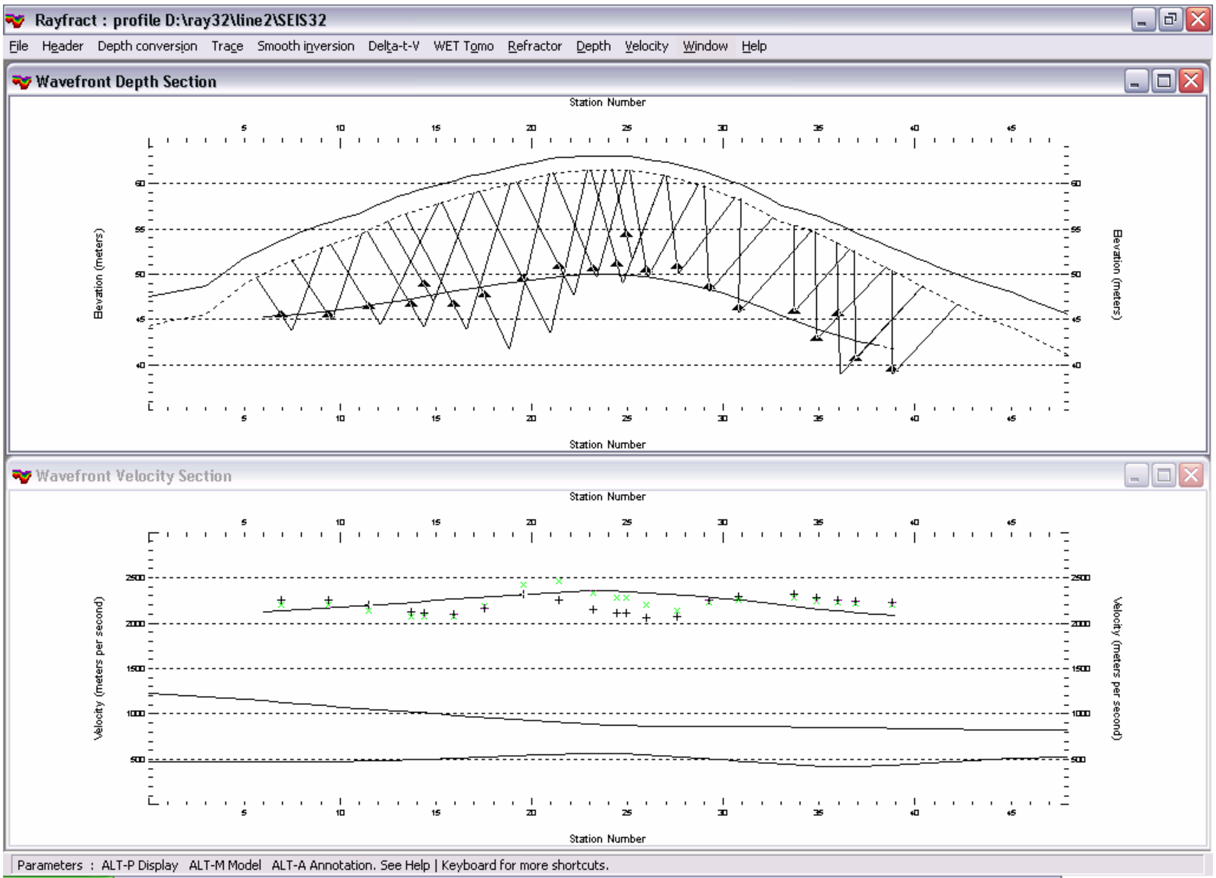
Coverage of LINE2 subsurface with first break energy, corresponding to above tomogram / 100 WET iterations.



LINE2 fit of modeled (blue) to picked (colored) traveltime curves, after 100 WET iterations. Branch points (outlined squares : red refractor 1; black filled squares : green refractor 2) have been picked interactively; see manual chapter 1.8. Yellow traveltime curve segments are mapped to the weathering layer.

Now invert the same data set with our conventional Wavefront method (Glyn M. Jones and D.B. Jovanovich 1985). Proceed as described in our manual chapters 1.8 and 1.9 :

1. position branch points defining refractor 1 and refractor 2 as shown above.
2. map traces to refractors with ALT-L.
3. select *Header|Station*, and press button *v0 from Shots.* Confirm the prompt and hit ESC.
4. select *Window|Close All* and then *Depth|Wavefront*. Confirm the following prompts.
5. select *Velocity|Wavefront* to display estimated refractor velocities.
6. select *Depth conversion|Display Wavefront rays*.
7. scale the resulting Wavefront depth and Wavefront velocity sections as described in chapter 1.6.
8. select *Window|Tile horizontal* to obtain the following plot :



Conventional Wavefront method interpretation of LINE2. Modeling of two refractors.

Note the shallow refractor 2 (i.e. basement) depth below station nr. 25, corresponding to a horizontal inline offset of about 60 meters. Above WET inversion tomogram shows a shallow high velocity anomaly at the same inline offset. This anomaly may be caused by an isolated former bedrock block.

Above WET inversion (100 iterations, 7 shots into 24 receivers i.e. 168 traces) took about 15 minutes, on a Toshiba A40 portable with a 2.8 GHz Intel Celeron processor and 512 Mbytes of RAM.

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Smooth inversion of synthetic data for thrust fault model, with Rayfract® free trial version 3.22 :

Download our free trial and install it under Windows XP/Windows 2000/Windows Vista or Windows 7.

Start up Rayfract® trial 3.22 via desktop icon. Select *File|New Profile…* . Set *File name* to `THRUST12` and click *Save button*. Specify *Station spacing* of 2 m in *Header|Profile* (Fig. 1).

Unzip archive thrust.zip in directory \RAY32\THRUST12\INPUT.

Uncheck *File|Import data Settings|Round shot station to nearest whole station number*.

Select *File|Import Data…* (Fig. 2) and specify *Import data type* `ASCII column format`. Click *button Select* and select file THRUST.ASC in \RAY32\THRUST12\INPUT. Check *box Batch import*. For ASCII.ASC import no .HDR batch file is required.

Click *button Import shots*, to import all 25 shots specified in THRUST.ASC.

Select *Refractor|Shot breaks*. Press ALT+P. Set *Maximum time* to 40 msecs. (Fig. 3). Hit ENTER key to redisplay traveltime curves. Select *Mapping|Color picked traveltime curves*. Browse curves with F7/F8 (Fig. 4).

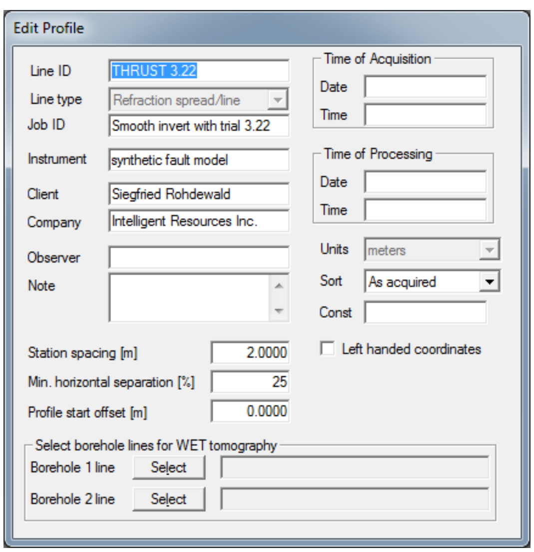

Fig. 1 : *Header|Profile*, edit profile header data

To invert the synthetic traveltime data with our *Smooth inversion* method :

- run *Smooth invert|WET with 1D-gradient initial model*
- confirm prompts to obtain Fig. 5, 6 and 7.

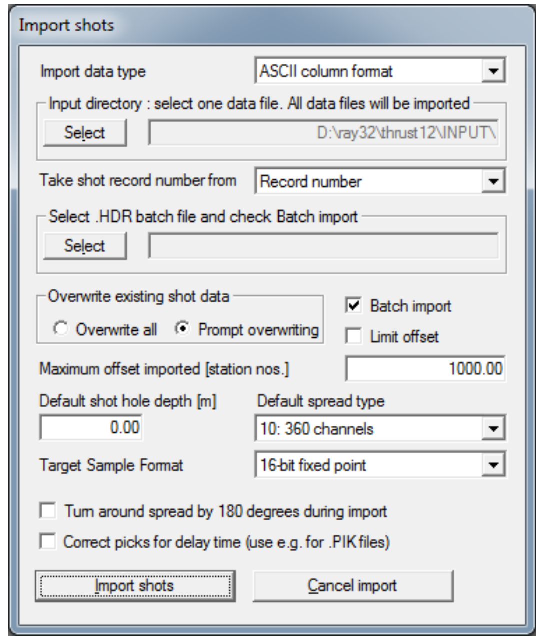

Fig. 2 : *File|Import Data…* dialog

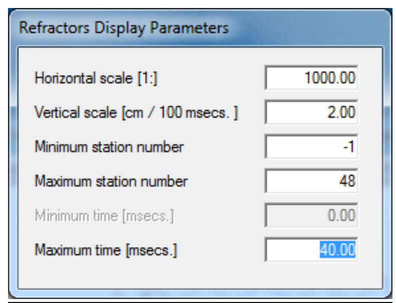

Fig. 3 : ALT+P in *Refractor|Shot breaks*, edit *Refractor Display Parameters* dialog.

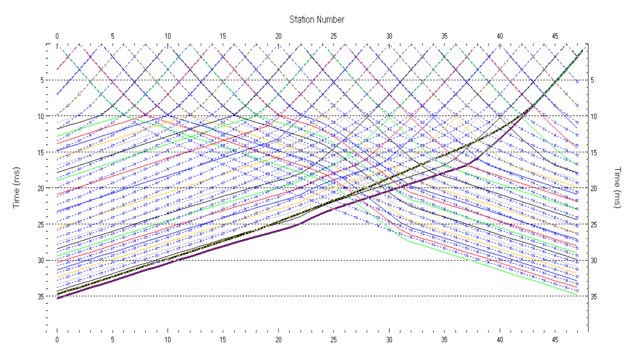

Fig. 4 : *Refractor|Shot breaks* display. Browse traveltime curves with F7/F8. Solid colored curves are picked times, dashed blue curves are modeled times, for initial model shown in Fig. 5 . RMS error is 4.1%.

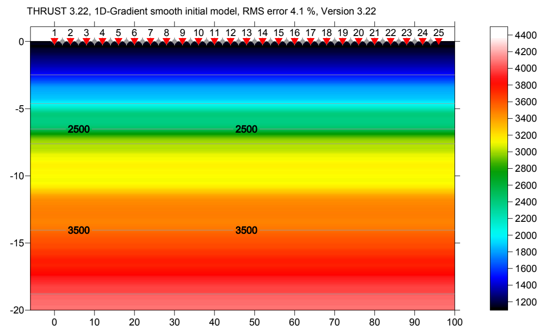

Fig. 5 : 1D initial model obtained with Smooth inversion, with default settings. RMS error is 4.1%. Horizontal/vertical axis in meters, color coding shows velocity in m/s.

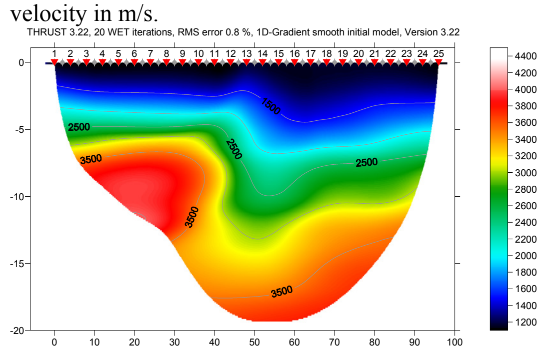

Fig. 6 : Velocity tomogram with Smooth inversion, 20 WET iterations, default settings, wavepath width 3%. RMS error is 0.8%. Initial model is Fig. 5.

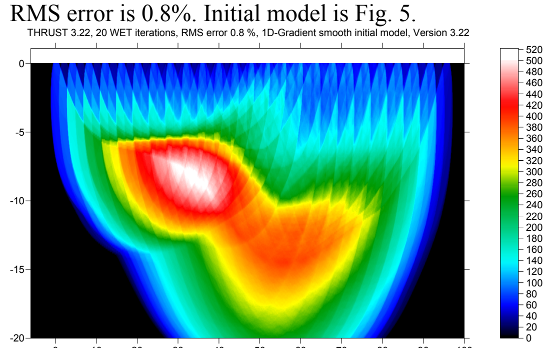

Fig. 7 : WET wavepath coverage plot obtained with Fig. 6. Color coding shows number of wavepaths per pixel / coverage of subsurface with first break energy.

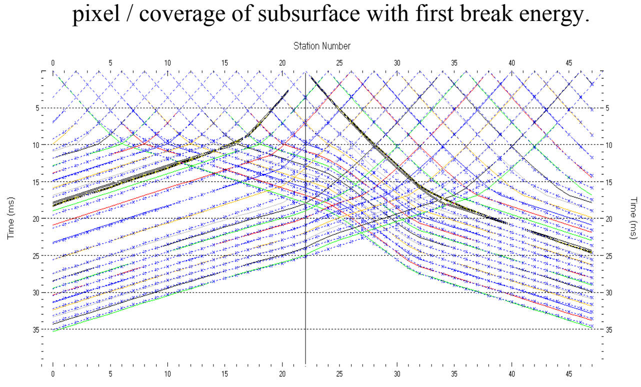

Fig. 8 : *Refractor|Shot breaks*, fit between picked (colored solid curves) and modeled (dashed blue curves) after 20 WET iterations.

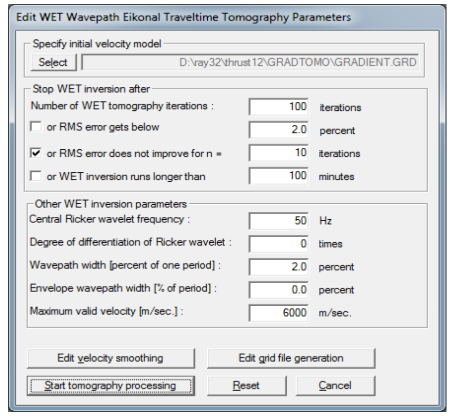

Fig. 9 : *WET Tomo|Interactive WET tomography…*

The following steps are not possible with the trial :

- uncheck *WET Tomo|WET tomography Settings|Disable wavepath scaling for short profile*, to enable scaling.
- select *WET Tomo|Interactive WET tomography*
- make sure *initial velocity model* is set to `\RAY32\THRUST12\GRADTOMO\GRADIENT.GRD`
- change *Wavepath width* from default value of 3% to 2%. See Fig. 9.
- change *Number of WET tomography iterations* from default 20 to new 100
- edit other settings in *Stop WET inversion after frame* as shown in Fig. 9
- click *Edit grid file generation button*, and change *Store each nth iteration only* to 20
- click buttons *Accept parameters* and *Start tomography processing*. Obtain Fig. 10.

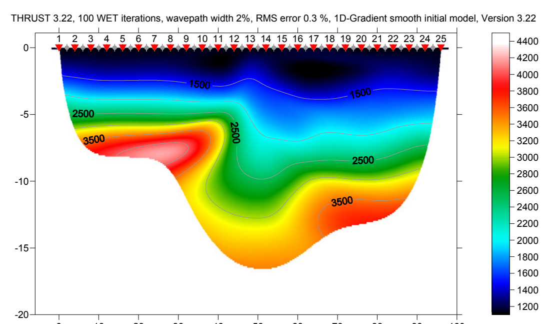

Fig. 10 : 100 WET iterations, wavepath width 2%. RMS error is 0.3%, initial model Fig. 5.

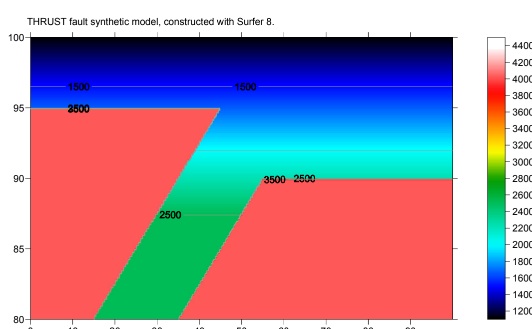

Fig. 11 : synthetic model, built in Thrust tutorial.

Compare agreement between WET inversion output and original model (Fig. 11), for Fig. 6 and Fig. 10. WET after 100 iterations (Fig. 10) more closely images the original model (Fig. 11) than after 20 iterations (Fig. 6). The traveltime misfit decreased continuously; otherwise the WET inversion would have stopped after fewer than 100 iterations. See (Fig. 9) for WET stop criteria.

Wavepath Eikonal Traveltime inversion (WET, Schuster 1999) aka Fresnel Volume Tomography (FVT) uses “fat rays” or Fresnel volumes for modeling of first break energy transport, instead of conventional “thin rays”. Thin rays assume infinite frequency of first break signal. FVT/WET assume finite frequency and correctly model loss of resolution with increasing distance from source/receiver, due to widening of wavepath/Fresnel volume (Hagedoorn 1959, Fig 1). The wavepath/Fresnel volume is the 2D subsurface volume involved in propagation of the first break pulse (Watanabe 1999, Fig. 1). For forward modeling we use the Eikonal solver described by Lecomte et al. 2000.

FVT/WET in a physically meaningful way smoothes the velocity tomogram, based on distance of the imaged pixel from source and receiver. The larger this distance, the wider the wavepath is at this pixel, and the more this tomogram region is naturally smoothed, when back-projecting traveltime residuals along wavepaths with SIRT algorithm.

Decreasing the WET wavepath width from 3% (Fig. 6) to 2% (Fig. 9 and 10) helps to more clearly image the fault zone. Decreasing the wavepath width sometimes can improve the resolution, but only if shots are spaced closely enough (at every 3rd receiver) and if first break picks are picked accurately. Otherwise decreasing the wavepath width can instead increase the amount of artefacts, and render WET inversion less stable, see bulgatrl. **Increasing the WET wavepath width is a physically meaningful way to control the non-uniqueness of the solution space**. Increasing the wavepath width will render WET output more smoothly, and diminishes the risk of imaging artefacts. Resolution will typically decrease with increased wavepath width, but maximum imaged depth can increase. See tutorial ot0608.pdf .

For wide shot spacing and inconsistent first break picks, do not decrease the wavepath width from its default setting. An optimal wavepath width suppresses WET inversion artefacts and starting model artefacts, and avoids over-fitting to noisy traveltime data including bad picks, see bulgatrl. Increasing the wavepath width helps to manage uncertainty : a smoother tomogram contains less artefacts. This can be regarded as a probabilistic imaging approach (Grandjean 2004). Don’t increase wavepath width too much, otherwise targets are imaged too smoothly or blurred, and resolution is lost. Adjusting the WET wavepath width lets you trade off resolution vs. uncertainty. Decreasing the wavepath width can result in higher resolution for consistent and redundant data, or can increase uncertainty if the inversion becomes unstable, due to too wide shot spacing, inconsistent picks or with too strong velocity variation causing diffraction at transition between weathering overburden and basement (SAGEEP11.pdf, 90 degree corner in basement surface).

Enabling WET wavepath scaling can help to improve the resolution directly below topography. But again, if shots are spaced too widely and/or first break picks are inaccurate, this may instead cause artefacts in the WET output. XTV inversion can work well in case of homogeneous overburden with little lateral velocity variation, e.g. in marine settings. See tutorial jenny10.pdf .

Pseudo-2D DeltatV and XTV inversion are more sensitive to bad picks than Smooth inversion. Identify bad picks in *Trace|Offset gather* according to reciprocity principle. See tutorials riveral8.pdf and GEOXMERC.pdf . Then correct single trace picks in *Trace|Shot gather* and *Trace|Offset gather*, or correct *Trigger delay* in *Header|Shot*, for all traces of one shot.

As shown by (Watanabe 1999, Fig. 4) for crosshole surveys, it is not possible to reliably image seismic subsurface velocity at a resolution smaller than one wavelength of dominant frequency of the first break pulse. E.g. with 100 Hz and basement velocity of 4,000 m/s, one wavelength is 4000/100 = 40m. In case of bad or noisy picks, resolution will not be better than two wavelengths. For refraction surveys, resolution at bottom and edges of tomogram is further reduced, because here rays and wavepaths are aligned predominantly parallel to each other (White 1989).

As shown above and in tutorials thrust.pdf, broadepi.pdf, epikinv.pdf and fig9inv.pdf, our Smooth inversion method is capable of imaging strong lateral velocity variation, if shots are spaced closely enough. If first break picks don’t obey the laws of physics (reciprocity principle) or shots are spaced too wide apart then inversion becomes highly non-unique, as shown by Dr. Palmer in his SAGEEP 2012 presentation, and in our bulgatrl.pdf. To reduce this non-uniqueness and uncertainty, space shot points closely enough and pick first breaks accurately. Position a shot point at every 3rd receiver, and use at least 24 channels. The 1D smooth starting model (Fig. 5) used by our Smooth inversion is mandatory for robust WET inversion, to prevent artefacts caused by the starting model (Sheehan et al. 2005, Fig. 1).

Process synthetic data BROADEPI.ASC contained in archive broadepi.zip and described in broadepi.pdf and epikinv.pdf just as above THRUST.ASC, in a separate profile database named e.g. EPIK12.

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Interpretation of 6 shots into 12 channels, sent by Milko Rivera at Guyana Goldfields Inc., with Rayfract® version 3.20 :

To invert the data, start up Rayfract® via desktop icon. Select *File|New Profile…* . Set *File name* to RIVERAL8 and click *Save button*. Specify *Station spacing* of 10 m in *Header|Profile* (Fig. 1).

Unzip archive riveral8.zip in directory \RAY32\RIVERAL8\INPUT . Select *File|Import Data…* and specify *Import data type* SEG-2. Click *button Select* and select one of the .DAT files in \RAY32\RIVERAL8\INPUT (Fig. 2).

Click *button Import shots*. Specify *Shot pos.* 0.5, 1, 3, 6, 9 and 12 for shots 1 to 6. Leave *Layout start* at 1.0. Click *button Read* to import each of these shots into the profile database.

Select *File|Update header data|Update Station Coordinates…* and COORDS.COR in \RAY32\RIVERAL8\INPUT directory.

Select *File|Update header data|Update First Breaks…* and BREAKS.LST contained in \RAY32\RIVERAL8\INPUT directory.

Select *Trace|Shot gather*. Zoom time axis with F1. Zoom trace amplitude with CTRL+F1. Browse shots with F7/F8 (Fig. 3 and Fig. 4). Toggle trace fill mode with CTRL+F3.

Apply a *band-pass frequency filter* to better recognize the first breaks (Fig. 10).

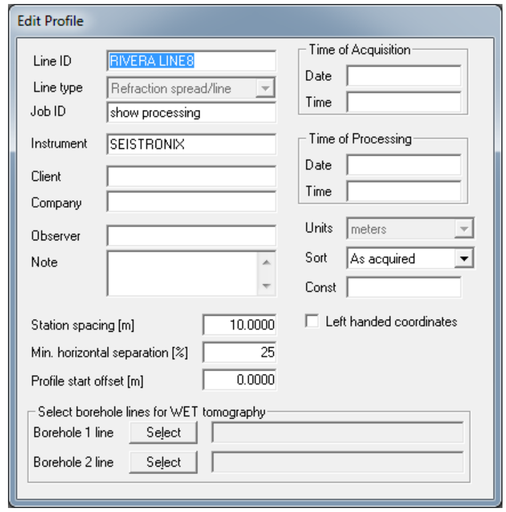

Fig. 1 : *Header|Profile*, edit profile header data

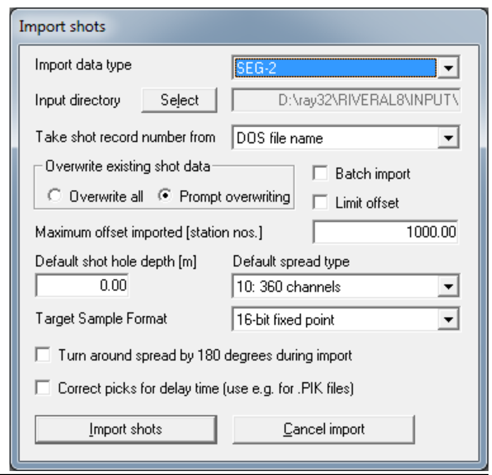

Fig. 2 : *File|Import Shots…* dialog

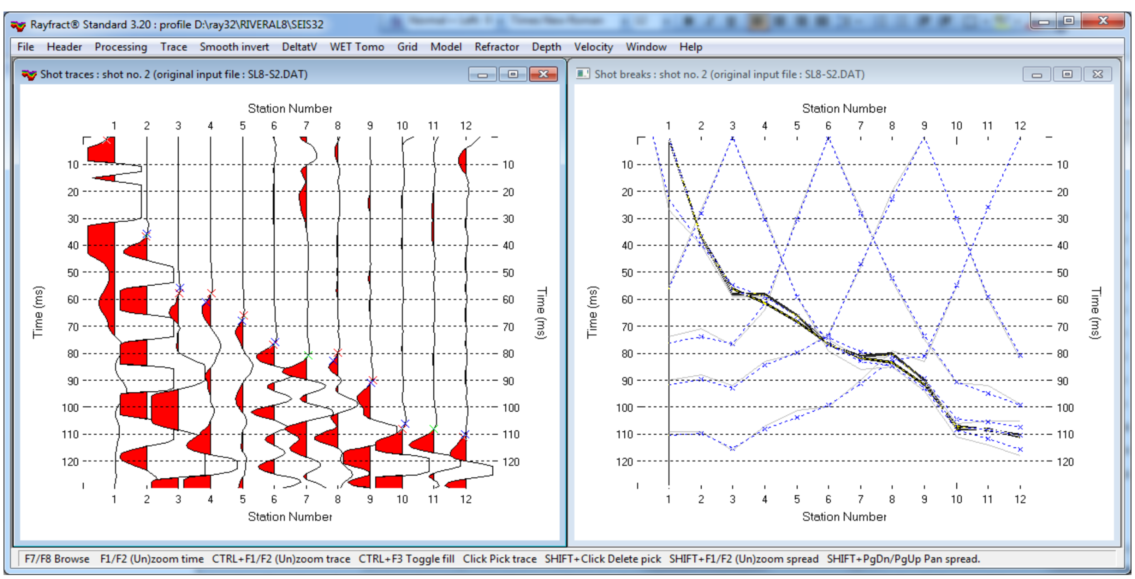

Fig. 3 : first break picking in *Trace|Shot gather* (left), shot no. 2. Red crosses are picked times, blue are modeled picks. Traveltime curves in *Refractor|Shot breaks* (right). Grey curves are picked times, dashed blue are modeled times.

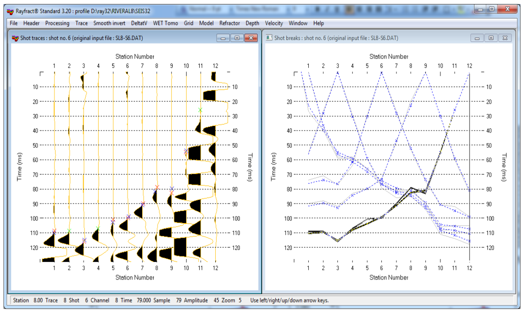

Fig. 4 : First breaks for shot no. 6, see Fig. 3

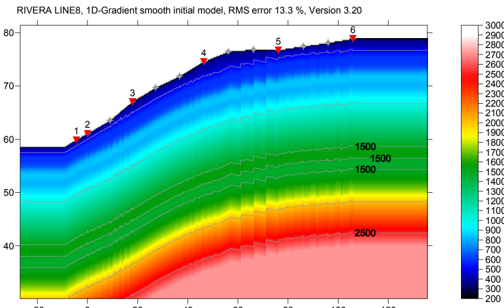

Fig. 5 : initial 1D velocity model, averaged DeltatV

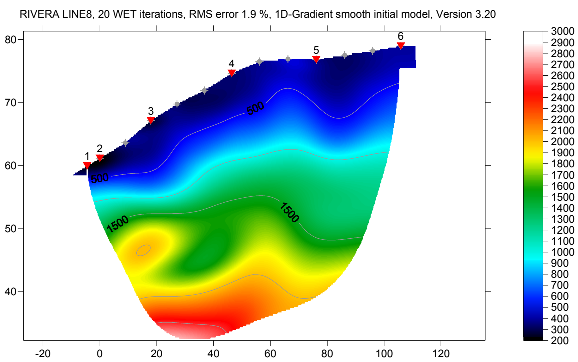

Fig. 6 : Smooth inversion, default WET settings, 20 WET iterations, wavepath width 11%

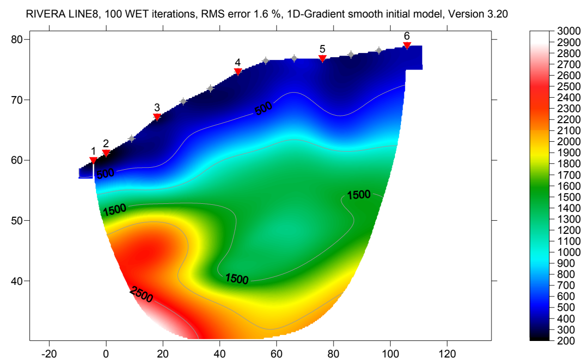

Fig. 8 : 100 WET iterations, wavepath width 11%

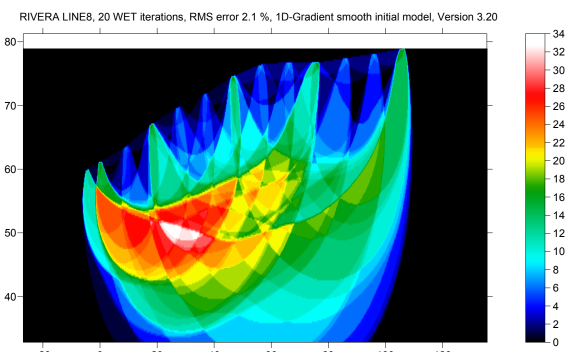

Fig. 7 : WET wavepath coverage plot. Coverage of subsurface with first break energy. WET settings as in Fig. 6 above.

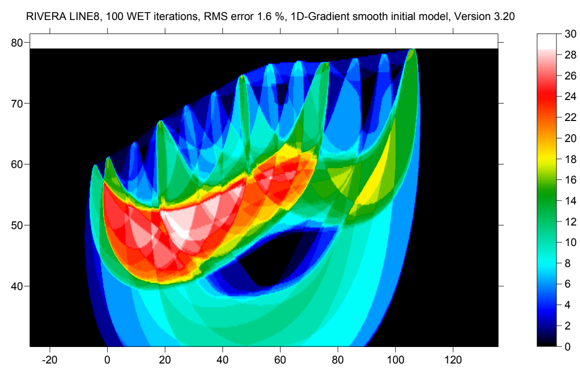

Fig. 9 : WET wavepath coverage plot. Coverage of subsurface with first break energy. WET settings as in Fig. 8 above.

To obtain above figures :

- run *Smooth invert|WET with 1D-gradient initial model*, to obtain Fig. 5, 6 and 7
- select *WET Tomo|Interactive WET tomography…*
- set *Number of WET tomography iterations* to 100
- click *button Edit grid file generation*
- set *Store each nth iteration only* to 20
- click *buttons Accept parameters* and *Start tomography processing* to obtain Fig. 8 and 9

Note the step-shaped basement depression at bottom of Fig. 8, after 100 WET iterations. This is not yet visible in Fig. 6 after just 20 WET iterations, due to incomplete **removal of horizontal layering artefacts of the 1D initial model** (Fig.5). We recommend using at least 24 receivers instead of just 12 receivers per spread, for more reliable interpretation. Or use overlapping receiver spreads for recording of shots.

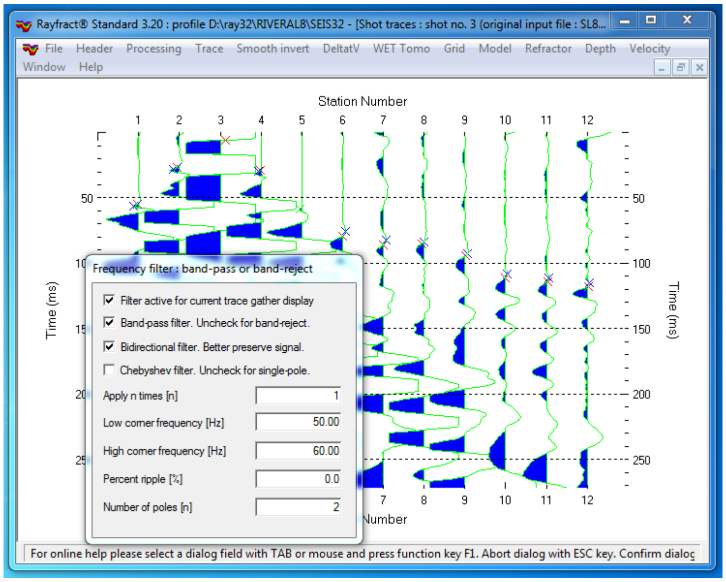

Fig. 10 : band-pass frequency filtering in *Trace|Shot gather*, shot no. 3. Press SHIFT+Q to show band-pass dialog.

To **quality-check your first breaks with the traveltime reciprocity principle**, use *Trace|Offset gather* (Fig. 11). Browse common-offset sorted trace gathers with F7/F8. The common offset is displayed in the title bar, in meters. According to the reciprocity principle, **seismic first break times, rays and wave paths are identical when swapping source and receiver positions, for each recorded trace**. So in Fig. 11, traces with same common offset and common midpoint (station number) should have the same first break pick time, according to the laws of physics.

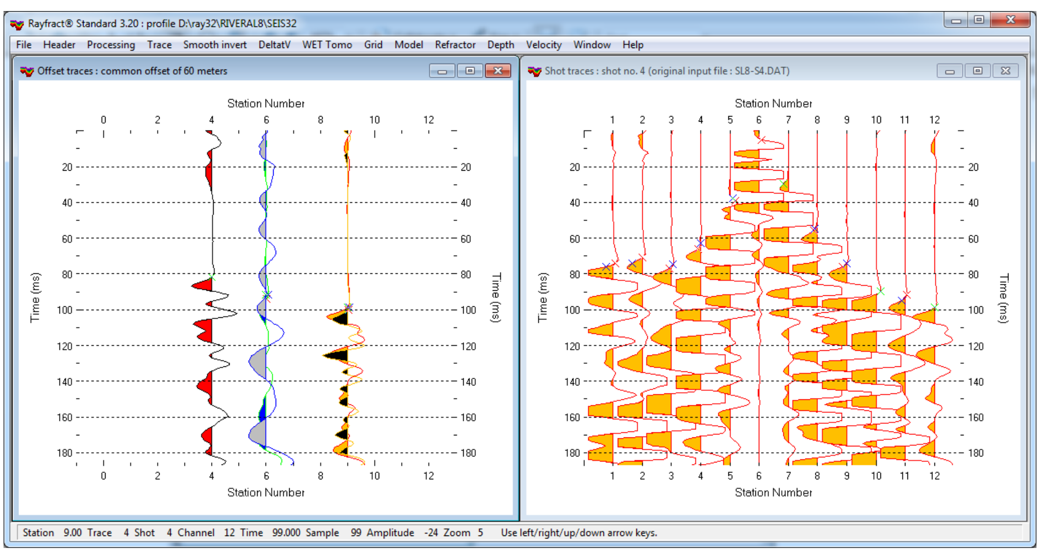

Fig. 11 : *Trace|Offset gather*, offset 60m (left). *Trace|Shot gather*, shot no. 4 (right). Browse traces with arrow-left and arrow-right keys. Trace attributes are displayed in status bar, at bottom of screen. Channel #12 of shot #4 (99 ms, yellow) has almost same time as channel #6 of shot #6 (100 ms, black), so these two picks regard the reciprocity principle.

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JOANNEUM OT0608 refraction line : Smooth inversion vs. 1.5D XTV inversion :

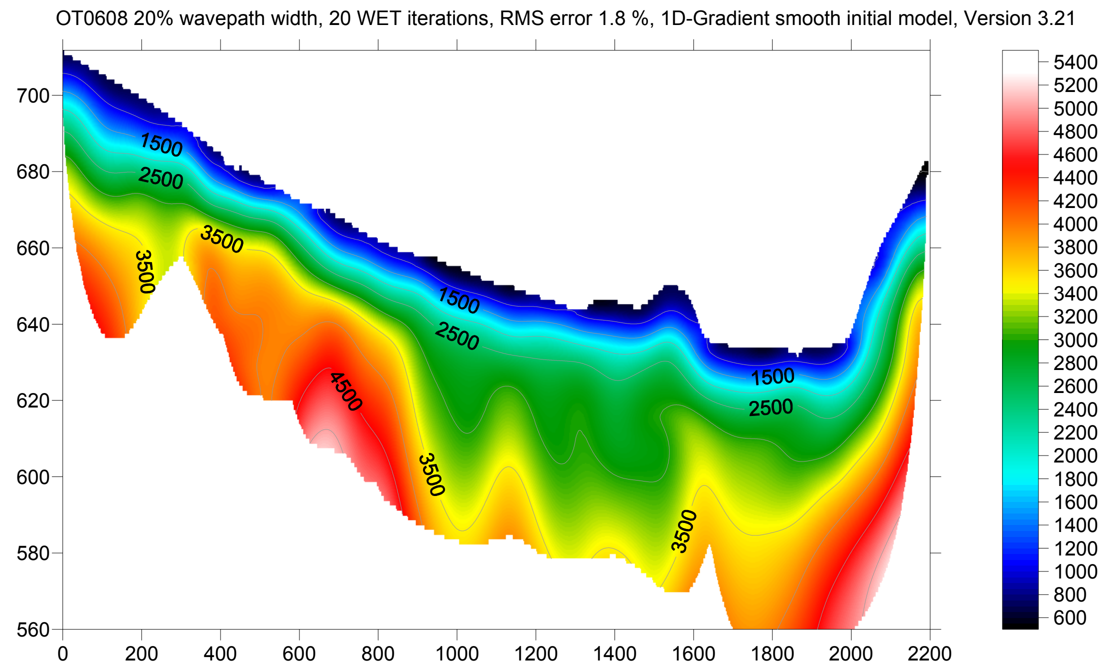

Fig. 1 : Smooth inversion 3.20, wavepath width 20%, 20 WET iterations. Fig. 3 shows 1D initial model used for Fig. 1.

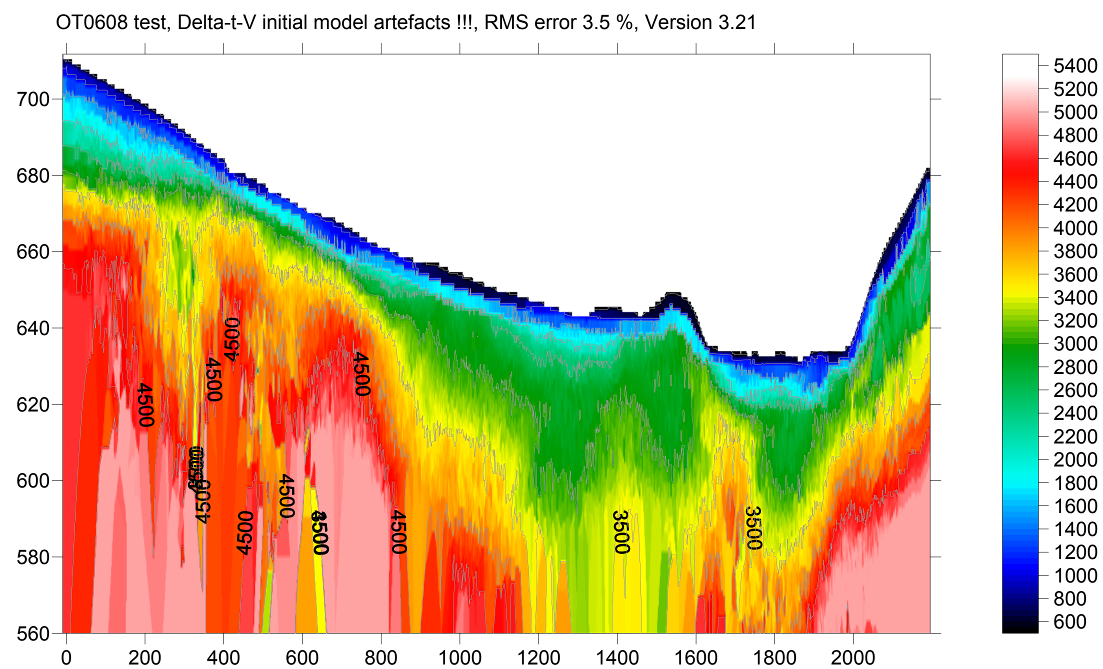

Fig. 2 : XTV inversion OT0608, with Rayfract® version 3.20 . CMP stack width 150, Inverse CMP offset power 0.20, Surface-consistent static corrections. Enabled Dix inversion, Intercept-time inversion in addition to DeltatV inversion for gradient layers. See http://rayfract.com/xtv_inversion.pdf . For all parameter settings see XTV .par file in ot0608.zip .

We thank Dr. Grassl, JOANNEUM RESEARCH Forschungsges.mbH, Austria, for making available this dense and consistently picked data set, with 275 shots into 200 or more channels. For .ASC, .COR and .SHO files see ot0608.zip . Process as gs0801.pdf . Set *Station spacing* to 3m in *Header|Profile*, then import .ASC , and update with .COR and .SHO.

See Fig. 3 for 1D initial model, obtained during Smooth inversion and resulting in Fig. 1. Fig. 4 shows WET wavepath coverage, also obtained with Smooth inversion and Fig. 1.

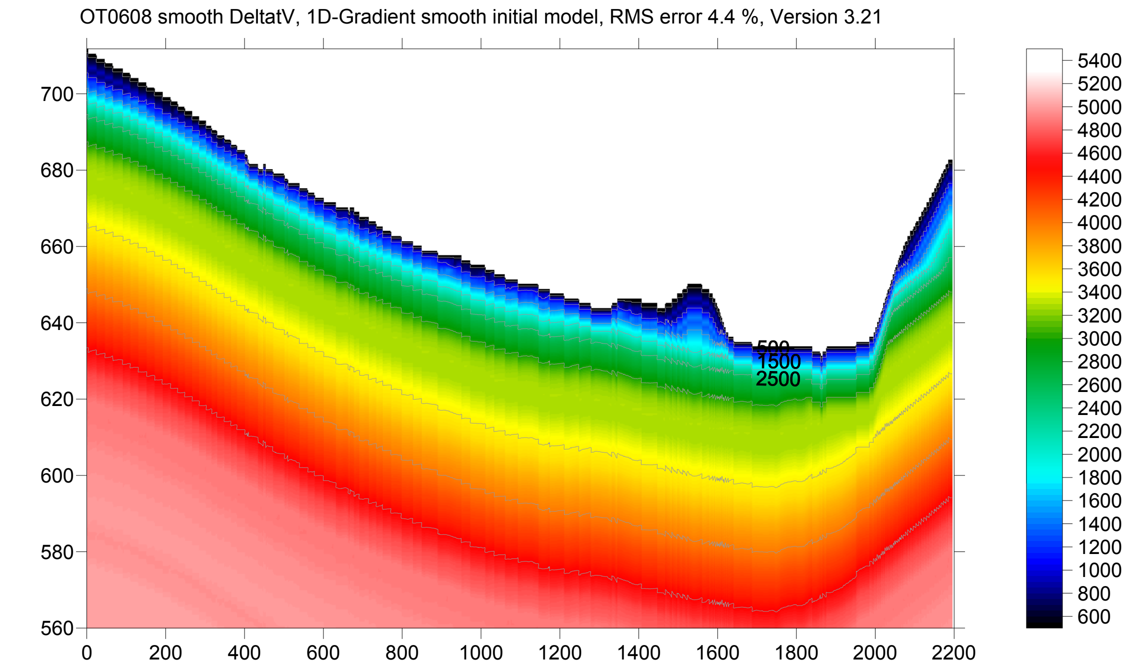

Fig. 3 : 1D initial model used for Fig.1, with Smooth inversion. Lateral DeltatV averaging, smooth DeltatV settings.

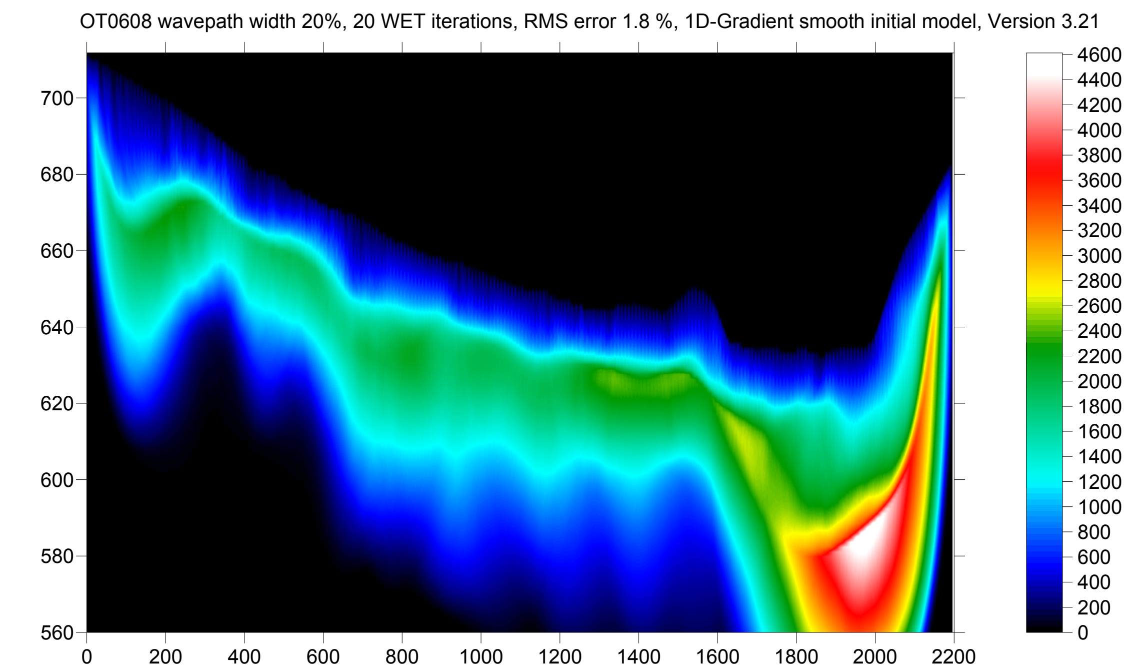

Fig. 4 : WET wavepath coverage, obtained with Smooth inversion (Fig. 1). Coverage of subsurface with first break energy.

Note the low wavepath coverage at offset 1000m and elevation 580m (Fig. 4). This is the only location where Fig. 1 and Fig. 2 differ. Low wavepath coverage means locally higher uncertainty, in the obtained WET velocity tomogram (Fig. 1). Wavepaths are almost vertical, similar to reflected rays (Fig. 4).

Processing time for default Smooth inversion (Fig. 1) was about 1 hour on an Intel Core i3. Fig. 2 was obtained in minutes. But DeltatV parameters need to be tuned, to approach Smooth inversion output. So DeltatV imaging is an iterative and more interactive process, when compared to Smooth inversion.

The good match between Fig. 1 and Fig. 2 confirms these two interpretations, obtained with quite different methods.

On the next page, we detail all processing steps required to obtain above output :

First, import the data and review shot-sorted traveltime curves :

- Start up Rayfract® via desktop icon. Select *File|New Profile…*
- Set *File name* to OT0608 and click *Save button*
- Specify *Station spacing* of 3 m in *Header|Profile*
- Unzip archive ot0608.zip in directory \RAY32\LINE8\INPUT
- Uncheck *File|Import Data Settings|Round shot station to nearest whole station number*
- Select *File|Import Data…* and specify *Import data type* ASCII column format
- Click *button Select* and select file OT0608_ASCII.asc in directory \RAY32\OT0608\INPUT
- Check option *Batch import* . This option is supported for ASCII.ASC files only.
- Leave *Default spread type* at *10: 360 channels*
- Click *button Import shots*, and confirm prompt
- *File|Update header data|Update Station Coordinates...* with \RAY32\OT0608\INPUT\OT0608_COR.COR
- *File|Update header data|Update Shotpoint coordinates…* with \RAY32\OT0608\INPUT\OT0608_SHO.SHO
- Select *Refractor|Shot breaks* to display traveltime curves

Now run Smooth inversion, with default parameters :

- Select *Smooth invert|WET with 1D-gradient initial model*, and obtain 1D initial model
- Confirm prompts, for default WET output after 20 iterations (Fig. 5 and 6)
- Note artefact in Fig. 5, at offset 500m and elevation 600m. This is due to low wavepath coverage (Fig. 6).

Next, configure smoother DeltatV settings (Fig. 7) :

- Check *Smooth invert|Smooth inversion Settings|Wide CMP stack for 1D-gradient initial model*
- Check *Smooth invert|Smooth inversion Settings|Allow unsafe pseudo-2D Delta-t-V inversion*
- Check *DeltatV|DeltatV Settings|Enforce monotonically increasing layer bottom velocity*
- Check *DeltatV|DeltatV Settings|Suppress velocity artefacts*
- Check *DeltatV|DeltatV Settings|Process every CMP offset*
- Check *DeltatV|DeltatV Settings|Smooth CMP traveltime curves*

Select *DeltatV|Interactive DeltatV…* and confirm prompt. Configure smoother *DeltatV Static corrections* (Fig. 8) :

- Click button *Static corrections*
- *Check Surface consistent corrections*
- Increase *Weathering crossover* to 20 stations
- Increase *Topography filter* to 200 stations
- Decrease *Inverse CMP offset power* to 0.2, click *Accept button*
- Click Esc key, to exit from *interactive DeltatV inversion* without running it

Redo Smooth inversion with **smoother DeltatV initial model**, and **increased WET wavepath width 20%** :

- Select *Smooth invert|WET with 1D-gradient initial model*, obtain 1D initial model (Fig. 3)
- When prompted to continue with *WET tomography*, click *No button*
- Select *WET Tomo|Interactive WET tomography…*
- Set *Wavepath width* to 20%, click *button Start tomography processing*
- Confirm prompts to obtain smooth WET output with 20 iterations (Fig. 1 and 4)
- Note **removed artefact** at offset 500m and elevation 600m. Also note **deeper imaging**, compared to Fig. 5.
- Uncheck *DeltatV|DeltatV Settings|Enforce monotonically increasing layer bottom velocity*

Select *DeltatV|XTV parameters for constant-velocity layers*, and configure *XTV options* as follows (Fig. 9) :

- Check *Enable Modified Dix layer inversion*
- Check *Enable Intercept time layer inversion*
- Check *Allow adjacent Intercept layer inversion*
- Check *Prefer measured layer top velocity over inverted*

Select *DeltatV|Interactive DeltatV…* and confirm prompt. Reconfigure *DeltatV Static corrections* (Fig. 8) :

- Click button *Static corrections*
- Leave *Surface consistent corrections* checked
- Reset *Weathering crossover* to 10 stations
- Reset *Topography filter* to 100 stations
- Leave *Inverse CMP offset power* at 0.2, click *Accept button*

Now configure and run *DeltatV inversion*, with XTV inversion enabled :

- Set *CMP curve stack width* to 150
- Set *Export Options|Gridding method* to *Nearest Neighbor*, click *Accept button*
- Click *button DeltatV inversion*, and confirm prompts, to obtain Fig. 2

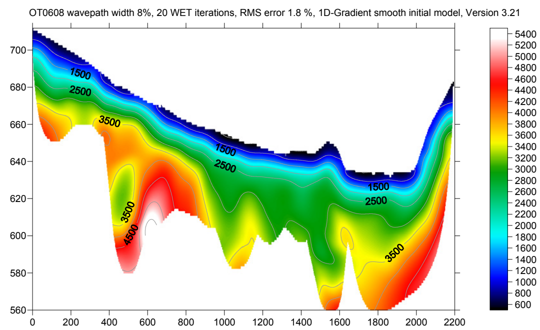

Fig. 5 : Default *Smooth inversion*, wavepath width 8%

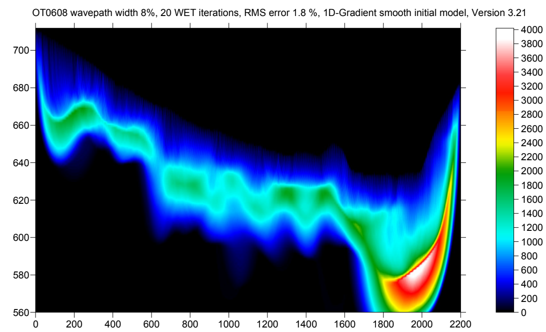

Fig. 6 : wavepath coverage obtained with Fig. 5

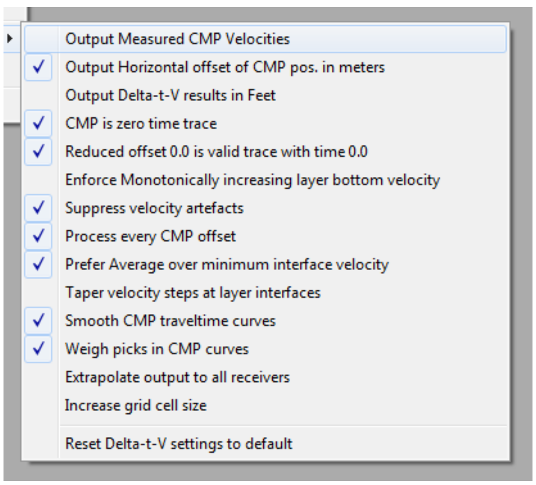

Fig. 7 : *DeltatV|DeltatV settings*

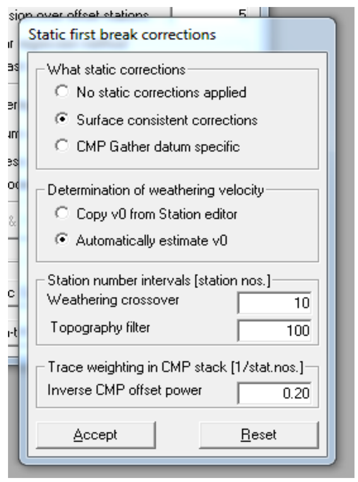

Fig. 8 : *DeltatV|Interactive DeltatV…|Static Corrections*

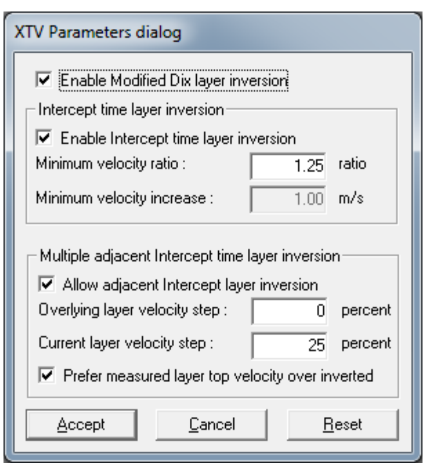

Fig. 9 : *DeltatV|XTV parameters*

For Wavefront refraction method interpretation :

- Select *Refractor|Midpoint breaks*
- Press ALT+M, to edit *Mapping dialog* (Fig 10)
- Click *Map traces button*, confirm prompt
- Press ALT+G, to edit *Crossover dialog* (Fig. 11)
- Click *Accept*, to smooth refractors (Fig. 10)
- Check *Depth|Depth conversion Settings|Link traveltime curves for Wavefront*
- Select *Depth|Wavefront…* (Fig. 13)
- ALT+P, set *min./max. elevation* to 580/700m
- ALT+M, edit *Wavefront parameters* (Fig. 12)
- Select *Velocity|Wavefront…* (Fig. 13)
- ALT+P, set *maximum velocity* to 5000 m/s

Note the good match between Wavefront refraction (Fig. 13), WET inversion (Fig. 1) and XTV (Fig. 2).

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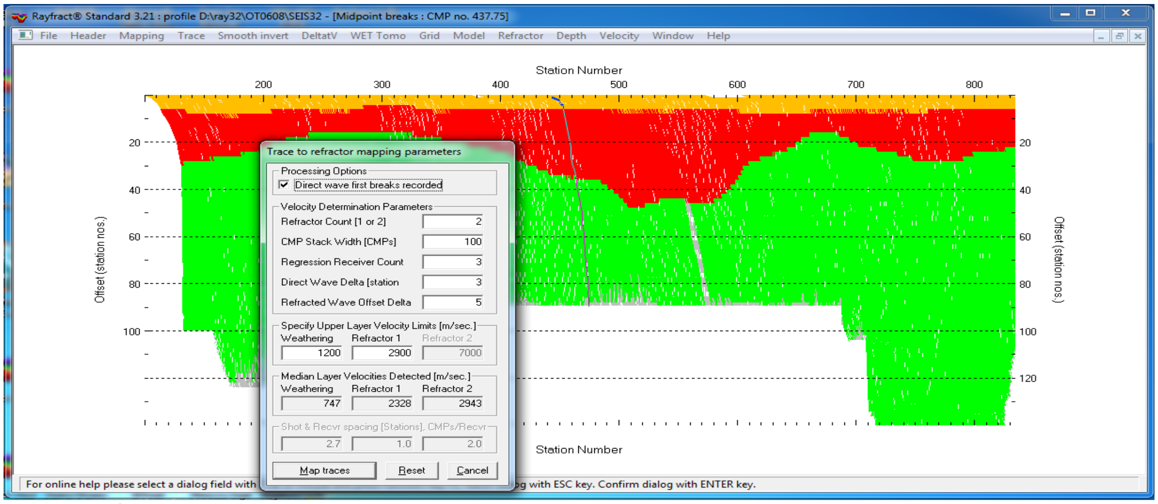

Fig. 10 : *Refractor|Midpoint breaks*, press ALT+M to edit *mapping dialog*

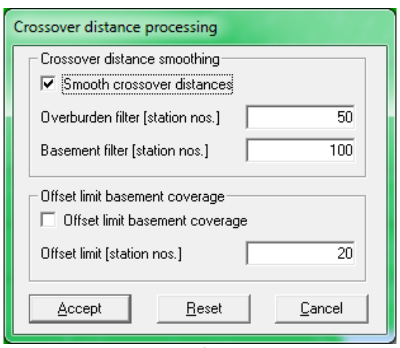

Fig. 11 : press ALT+G to edit *crossover dialog*

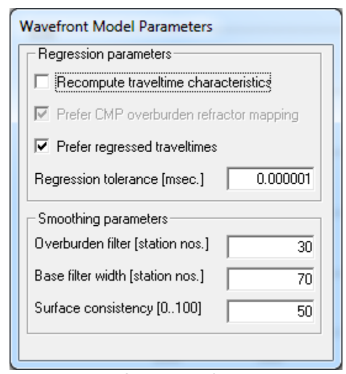

Fig. 12 : ALT+M for *Wavefront params*.

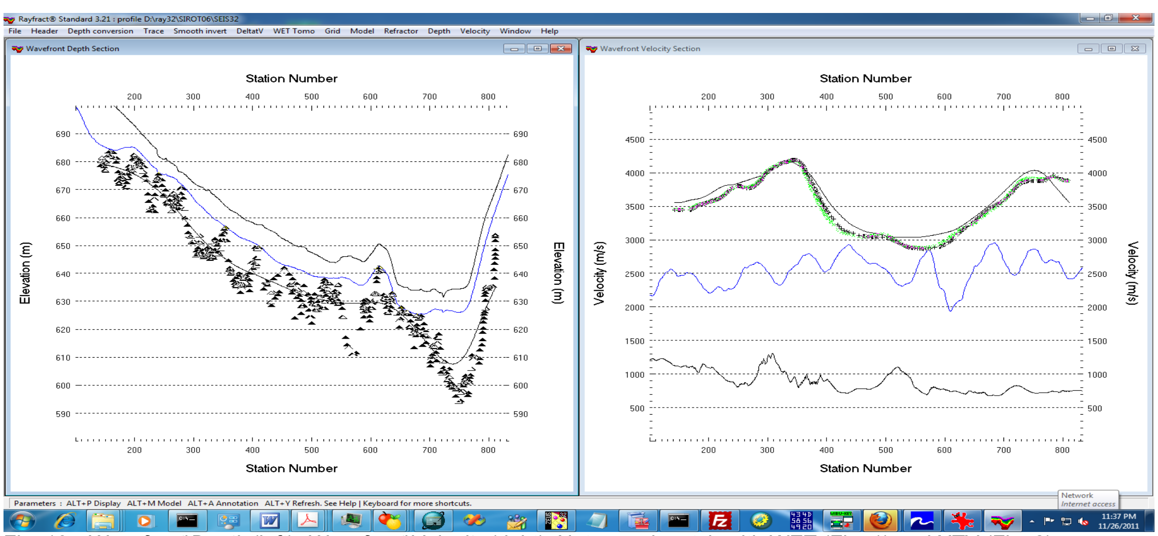

Fig. 13 : *Wavefront|Depth* (left), *Wavefront|Velocity* (right). Note good match with WET (Fig. 1) and XTV (Fig. 2).

Smooth inversion of Mt. Bulga data, with Rayfract® free trial version 3.22 :

Download our free trial and install it under Windows XP/Windows 2000/Windows Vista or Windows 7.

Start up Rayfract® trial 3.22 via desktop icon. Select *File|New Profile…* . Set *File name* to `BULGATRL` and click *Save button*. Specify *Station spacing* of 5 m in *Header|Profile* (Fig. 1).

Unzip archive mtbulga.zip in directory \RAY32\BULGATRL\INPUT.

Select *File|Import Data…* (Fig. 2) and specify *Import data type* `Interpex GREMIX .GRM`. Click *button Select* and select file MTBULGA.GRM in \RAY32\BULGATRL\INPUT.

Click *button Import shots*. Click *button Read* 9 times to import all 9 shots specified in MTBULGA.GRM. Do not edit any header fields.

Select *Refractor|Shot breaks*. Press ALT+P. Set *Maximum time* to 150 msecs. Hit ENTER key to redisplay traveltime curves. Select *Mapping|Color picked traveltime curves*. Browse curves with F7/F8 (Fig. 4).

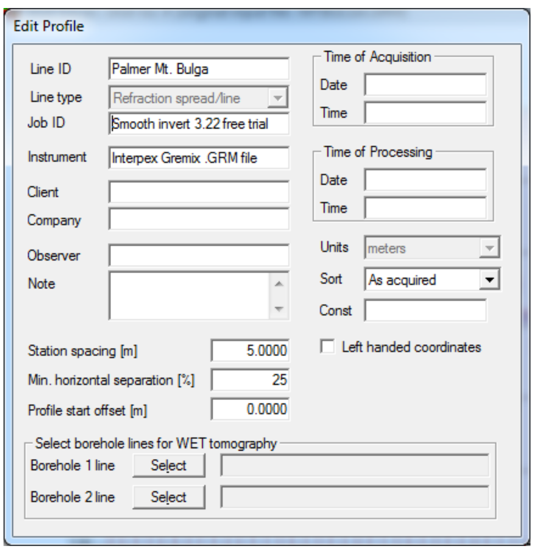

Fig. 1 : *Header|Profile*, edit profile header data

To invert the synthetic traveltime data with our *Smooth inversion* method :

- check *Smooth invert|Smooth inversion Settings|Wide smoothing filter for 1D initial velocity profile*
- run *Smooth invert|WET with 1D-gradient initial model*
- read *Shot point spacing is too wide warning prompt* (Fig. 3), recommending to position a shot at every 6th receiver instead of every 12th . Click *Yes button* to continue with Smooth inversion.
- confirm prompts to obtain Fig. 5, 6 and 7.

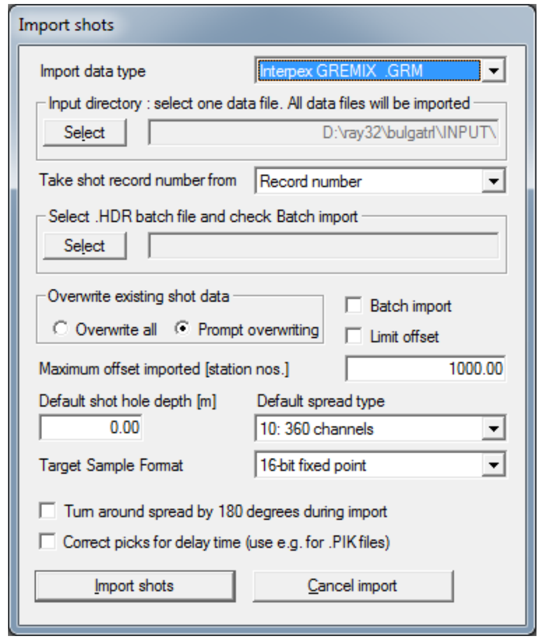

Fig. 2 : *File|Import Data…* dialog

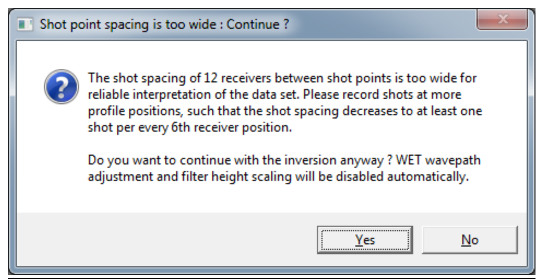

Fig. 3 : *Shot point spacing is too wide* warning prompt. Continue at your own risk.

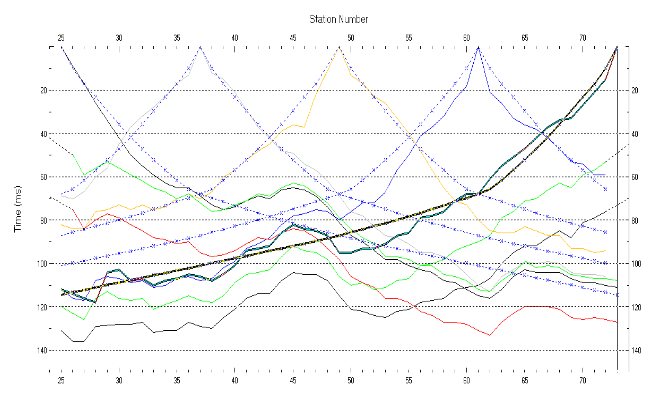

Fig. 4 : *Refractor|Shot breaks* display. Browse traveltime curves with F7/F8. Solid colored curves are picked times, dashed blue curves are modeled times, for starting model shown in Fig. 5 . RMS error is 7.1%.

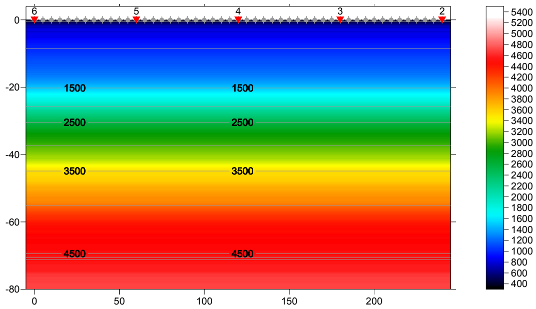

Fig. 5 : 1D starting model obtained with Smooth inversion, with default settings. RMS error is 7.1%. Horizontal/vertical axis in meters, color coding shows velocity in m/s.

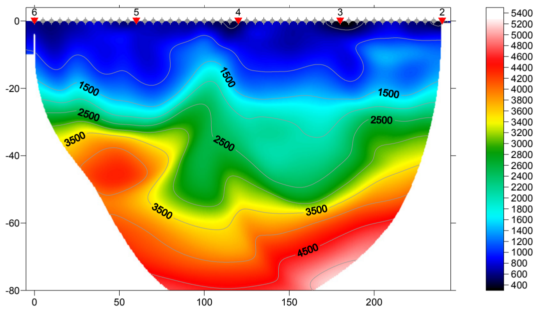

Fig. 6 : Velocity tomogram with Smooth inversion, 20 WET iterations, default settings, wavepath width 5.5%. RMS error is 2%. Starting model is Fig. 5.

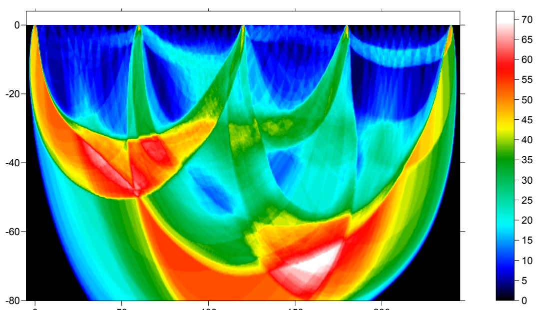

Fig. 7 : WET wavepath coverage obtained with Fig. 6. Color coding shows number of wavepaths per pixel / coverage of subsurface with first break energy.

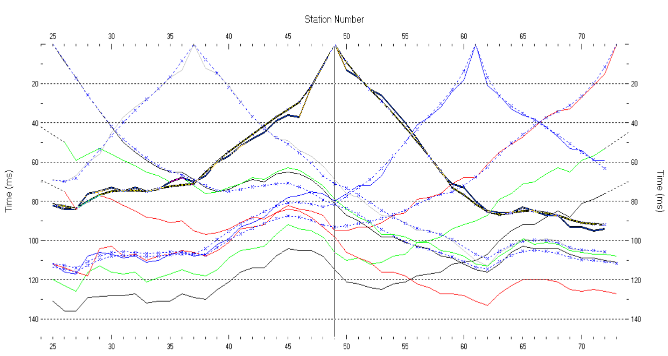

Fig. 8 : *Refractor|Shot breaks*, fit between picked (colored solid curves) and modeled (dashed blue curves) after 20 WET iterations. RMS error is 2%.

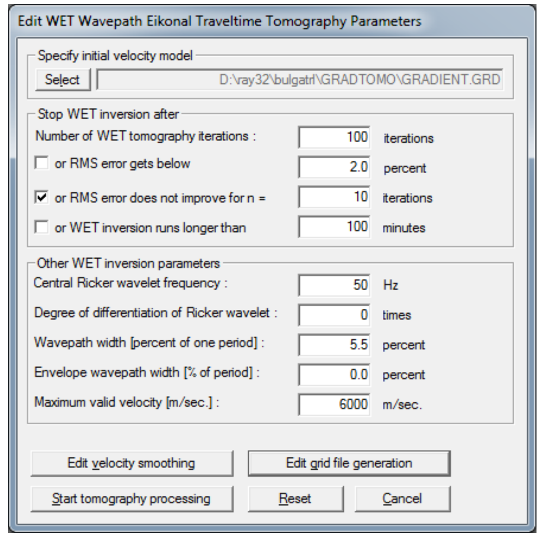

Fig. 9 : *WET Tomo|Interactive WET tomography…*

The following steps are not possible with the trial :

- select *WET Tomo|Interactive WET tomography*
- make sure *initial velocity model* is set to `\RAY32\BULGATRL\GRADTOMO\GRADIENT.GRD`
- change *Number of WET tomography iterations* from default 20 to new 100 (Fig. 9)
- edit other settings in *Stop WET inversion after frame* as shown in Fig. 9
- click *Edit grid file generation button*, and change *Store each nth iteration only* to 20
- click buttons *Accept parameters* and *Start tomography processing*. Obtain Fig. 10 and 11.

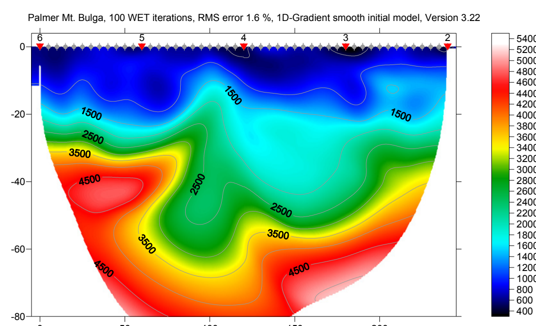

Fig. 10 : 100 WET iterations, wavepath width 5.5%. RMS error is 1.6%, starting model is Fig. 5.

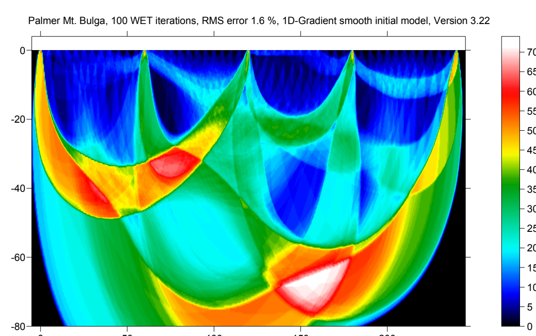

Fig. 11 : WET wavepath coverage shown with Fig. 10.

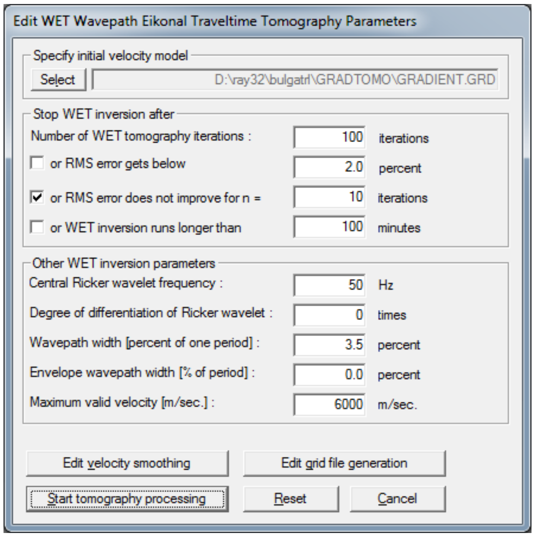

Fig. 12 : *WET Tomo|Interactive WET tomography…* , decrease *wavepath width* from default 5.5% to 3.5%

Next we decrease WET wavepath width (Fig 12) :

- select *WET Tomo|Interactive WET tomography*
- change *Wavepath width* from default 5.5% to new 3.5%
- click buttons *Accept parameters* and *Start tomography processing*. Obtain Fig. 13 and 14.

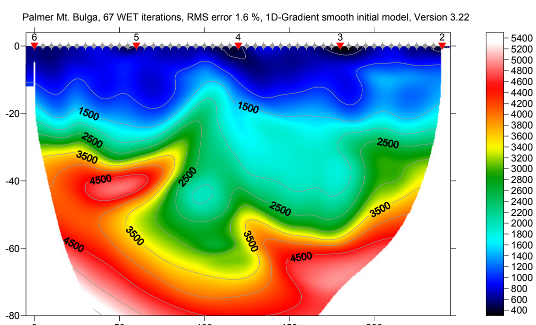

Fig. 13 : 67 WET iterations, wavepath width 3.5%. RMS error is 1.6%, starting model is Fig. 5.

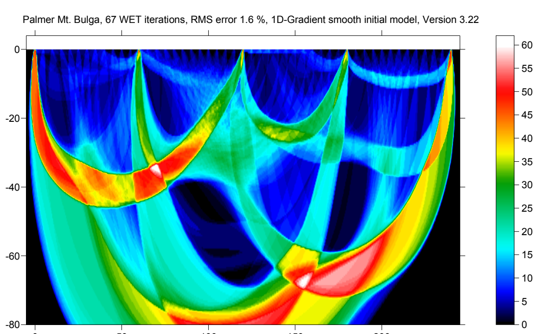

Fig. 14 : WET wavepath coverage shown with Fig. 13.

Next we increase WET wavepath width (Fig 15) :

- select *WET Tomo|Interactive WET tomography*

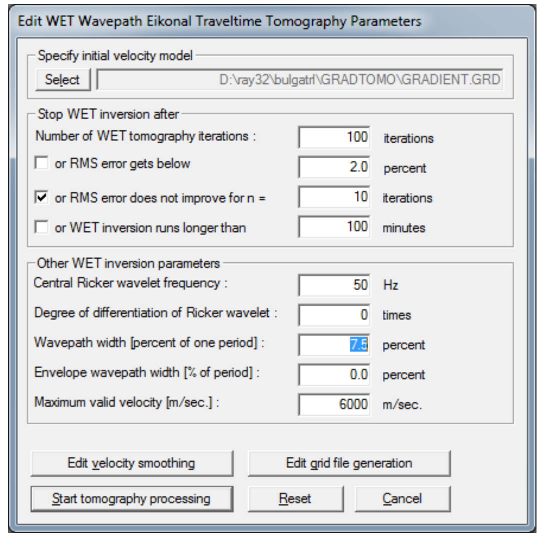

Fig. 15 : *WET Tomo|Interactive WET tomography…* , increase *wavepath width* from default 5.5% to 7.5%

- change *Wavepath width* from 3.5% to new 7.5%
- click buttons *Accept parameters* and *Start tomography processing*. Obtain Fig. 16 and 17.

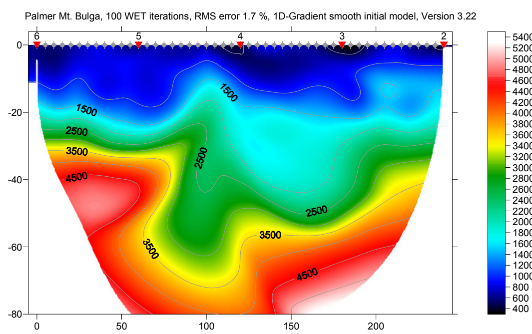

Fig. 16 : 100 WET iterations, wavepath width 7.5%. RMS error is 1.7%, starting model is Fig. 5.

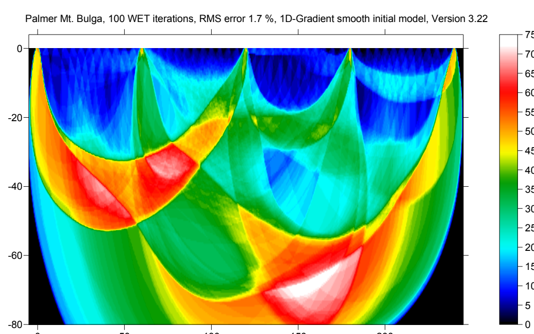

Fig. 17 : WET wavepath coverage shown with Fig. 16.

Next increase WET wavepath width to 15% (Fig. 18) :

- select *WET Tomo|Interactive WET tomography*
- change *Wavepath width* from 7.5% to new 15%
- click buttons *Accept parameters* and *Start tomography processing*. Obtain Fig. 19 and 20.

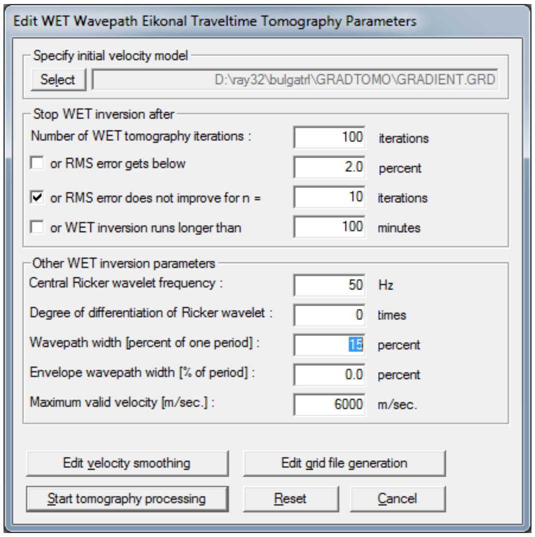

Fig. 18 : *WET Tomo|Interactive WET tomography…* , increase *wavepath width* from default 5.5% to 15%

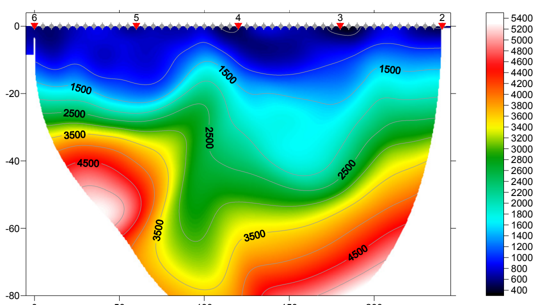

Fig. 19 : 100 WET iterations, wavepath width 15%. RMS error is 2%, starting model is Fig. 5.

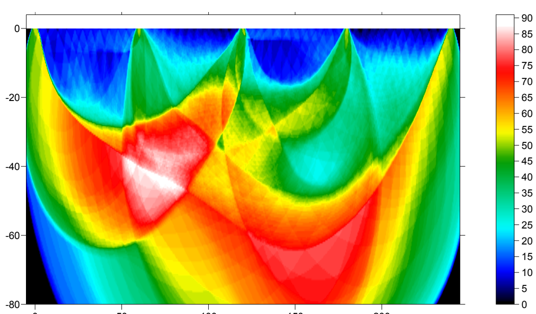

Fig. 20 : WET wavepath coverage shown with Fig. 19.

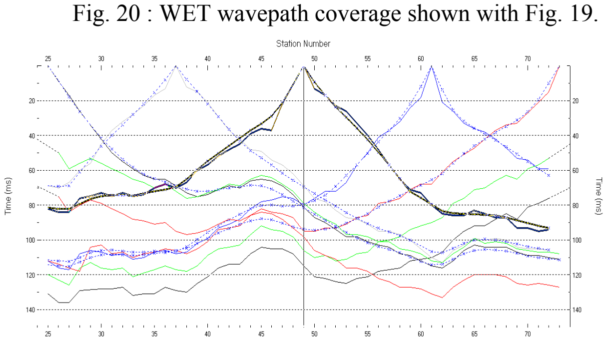

Fig. 21 : *Refractor|Shot breaks*, misfit after 100 WET iterations, wavepath width 15%. Compare Fig. 8.

Next we show WET output with same settings as in Fig. 18 and starting model Fig. 5, but with WET wavepath width increased to 30%, 50% and 100%.

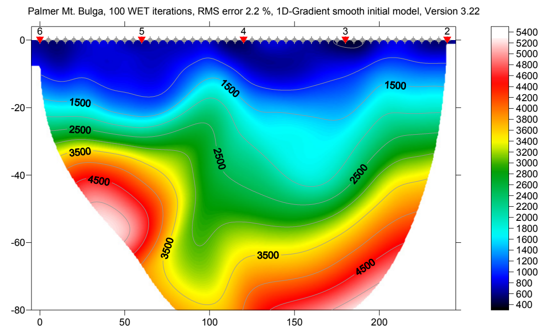

Fig. 22 : 100 WET iterations, wavepath width 30%. RMS error is 2.2%, starting model is Fig. 5.

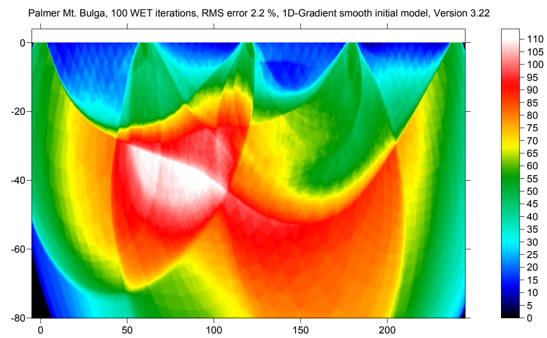

Fig. 23 : WET wavepath coverage shown with Fig. 22.

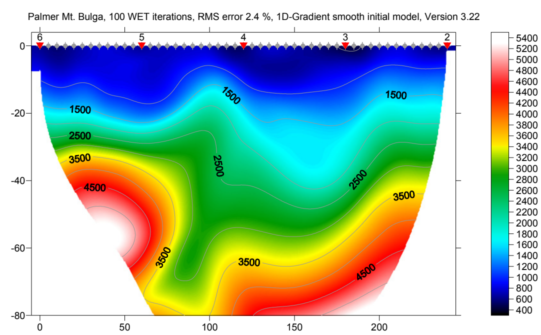

Fig. 24 : 100 WET iterations, wavepath width 50%. RMS error is 2.4%, starting model is Fig. 5.

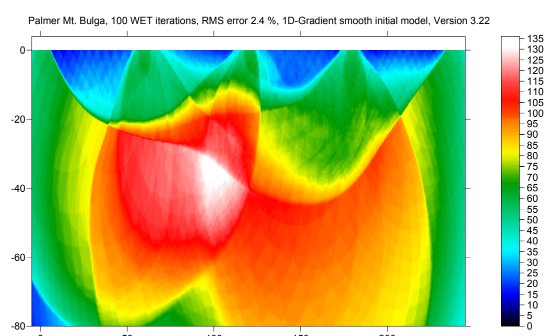

Fig. 25 : WET wavepath coverage shown with Fig. 24.

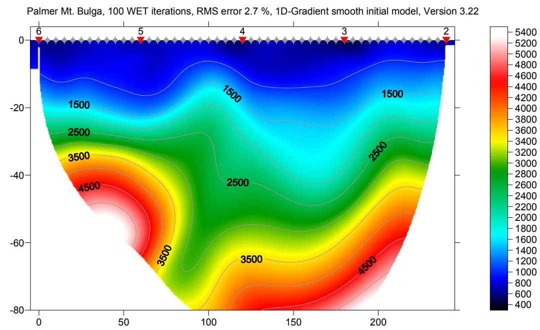

Fig. 26 : 100 WET iterations, wavepath width 100%. RMS error is 2.7%, starting model is Fig. 5.

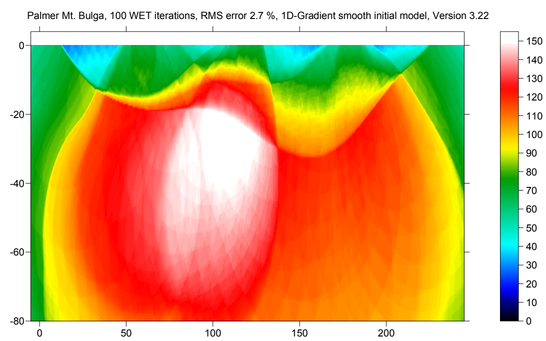

Fig. 27 : WET wavepath coverage shown with Fig. 26.

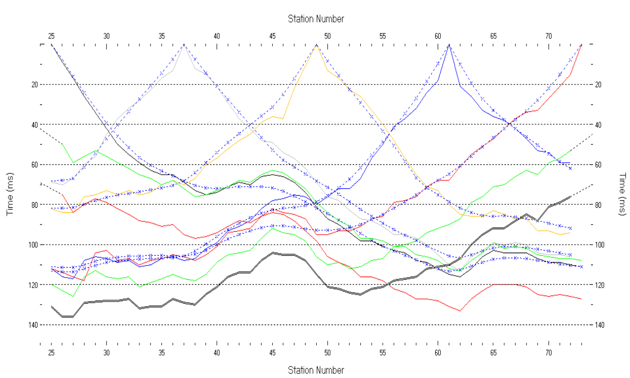

Fig. 28 : *Refractor|Shot breaks*, misfit after 100 WET iterations, wavepath width 100%. Compare Fig. 21.

We have shown how to explore the non-uniqueness of the model space, by varying WET wavepath width. Wider wavepath width results in less imaging artefacts, and smoother tomograms. This also decreases risk of unstable inversion and over-fitting to noisy or inconsistent (reciprocity, 2D assumption) traveltime data with bad picks.

The sub-vertical low-velocity fault zone remains visible throughout above tomogram series, while increasing wavepath width up to maximum possible value of 100%. So this fault zone is most certainly not an artefact of the processing, and is required to explain the traveltime data, even under minimum-structure assumption.

See our earlier interpretation mtbulga.pdf , showing layer-based Wavefront method and Smooth inversion with 999 iterations, using default wavepath width 5.5%. 100 iterations should be enough.

Run WET with 100 iterations and wide *wavepath width* of 50%. Then select tomogram grid `\RAY32\BULGATRL\GRADTOMO\VELOIT100.GRD` as starting model in Fig. 18, with *Select button*. Set *wavepath width* to smaller value e.g. 10% and do another 100 WET iterations. This gives a good image at bottom of tomogram due to wide wavepath width during 1st WET run, and also a good traveltime fit at near-offset channels due to more narrow width during 2nd WET run.

For inversion of synthetic traveltime data sets generated for known models, see tutorial thrust12, thrust, jenny10, epikinv, broadepi, fig9inv and SAGEEP11.pdf .

For more information on and instructions regarding our Smooth inversion method, see our short course notes SAGEEP10.pdf .

The best method to mitigate non-uniqueness of traveltime data interpretation is to **space shot points closely enough, at every 3rd receiver**. See SAGEEP10.pdf slide **Survey Design Requirements and Suggestions** on page 19 of 61**.** Also **pick traveltimes physically consistently**, regarding the reciprocity principle, to control non-uniqueness.

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XTV inversion of synthetic data for layered model sent by Jacques Jenny in 2010, with Rayfract® version 3.22 :

Start up Rayfract® via desktop icon. Select *File|New Profile…* . Set *File name* to `JENNY10` and click *Save button*. Specify *Station spacing* of 5 m in *Header|Profile* (Fig. 1).

Unzip archive jenny10.zip in directory \RAY32\JENNY10\INPUT . Select *File|ASCII column format…* . Set *Column 5* to *Receiver elevation*, *Column 6* to *Shot elevation* (Fig. 2).

Uncheck *File|Import data Settings|Round shot station to nearest whole station number*.

Select *File|Import Data…* and specify *Import data type* `ASCII column format`. Click *button Select* and select file THEORIC2.ASC in \RAY32\JENNY10\INPUT (Fig. 3).

Click *button Import shots*. Click *button Read* to import each of 11 shots into the profile database, without editing any field.

Select *Refractor|Shot breaks*. Press ALT+P. Set *Maximum time* to 110 msecs. (Fig. 4). Hit ENTER key to redisplay traveltime curves. Select *Mapping|Color picked traveltime curves*. Browse curves with F7/F8 (Fig. 5).

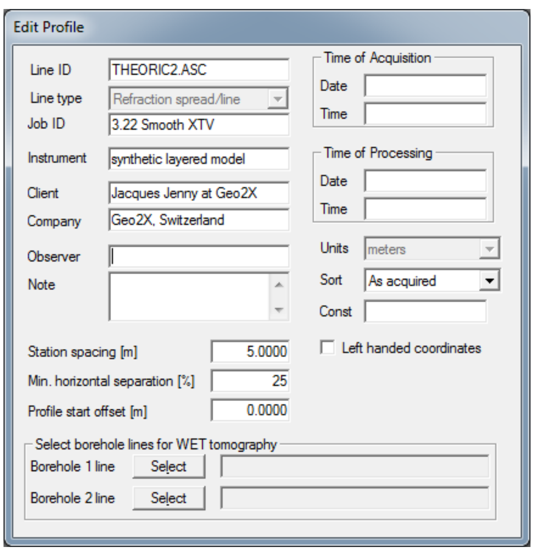

Fig. 1 : *Header|Profile*, edit profile header data

- check *Smooth invert|Smooth inversion Settings|Allow XTV inversion for 1D initial model*
- uncheck *Smooth invert|Smooth inversion Settings|Interpolate velocity for 1D-gradient initial model*
- uncheck *DeltatV|DeltatV Settings|Reduced offset 0.0 is valid trace with time 0.0*
- select *DeltatV|XTV parameters for constant-velocity layers…* to display XTV parameters dialog (Fig. 7)
- check box *Enable Modified Dix layer inversion*
- check box *Enable Intercept time layer inversion*
- check box *Allow adjacent Intercept time layer inversion*
- set *Minimum velocity ratio* to 1.01
- click *Accept button*
- run *Smooth invert|WET with 1D-gradient initial model* to obtain Fig. 6, 8 and 9.

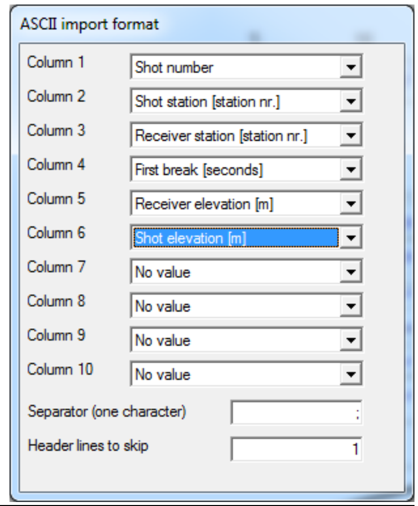

Fig. 2 : *File|ASCII column format…* dialog

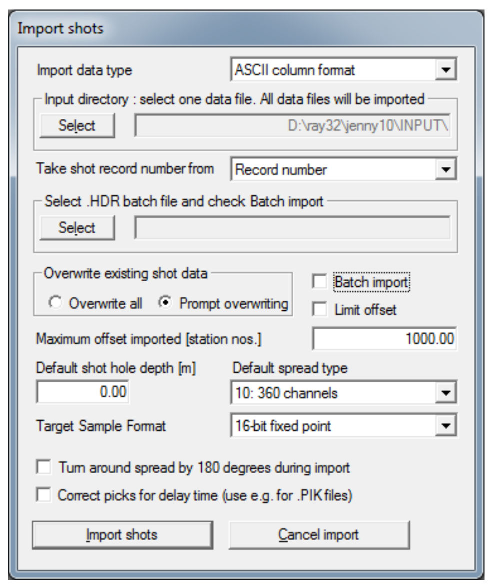

Fig. 3 : *File|Import Data…* dialog

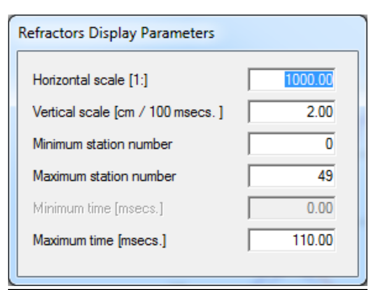

Fig. 4 : ALT+P in *Refractor|Shot breaks*, edit *Refractor Display Parameters* dialog.

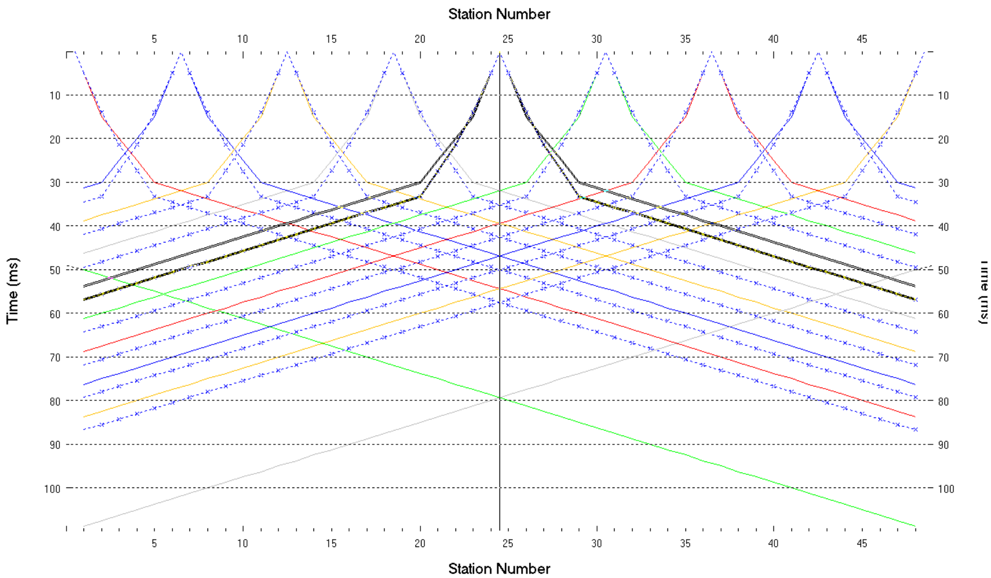

Fig. 5 : *Refractor|Shot breaks* display. Browse traveltime curves with F7/F8. Solid colored curves are picked times, dashed blue curves are modeled times, for 1D initial model shown in Fig. 6 .

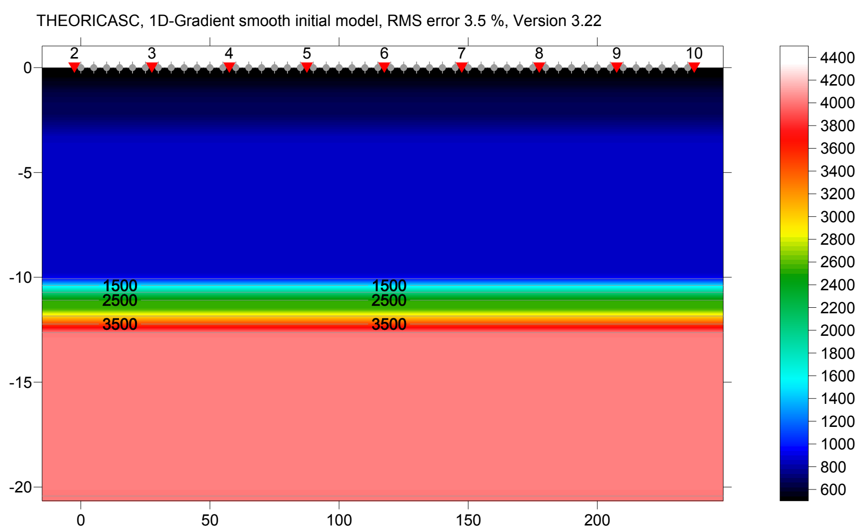

Fig. 6 : 1D initial model obtained with Smooth inversion, with XTV inversion enabled . RMS error is 3.5%. Horizontal/vertical axis in meters, color coding shows velocity in m/s.

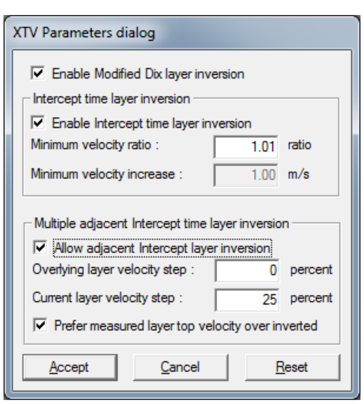

Fig. 7 : *DeltatV|XTV parameters for constant-velocity layers…*

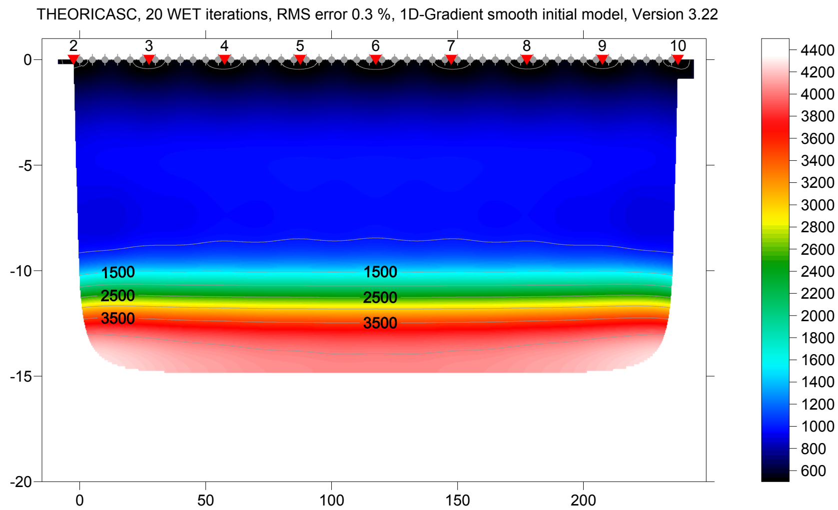

Fig. 8 : Smooth XTV inversion, velocity tomogram obtained with 20 WET iterations. RMS error is 0.3%. Compare with initial model (Fig. 6). Horizontal/vertical axis in meters, color coding shows velocity in m/s.

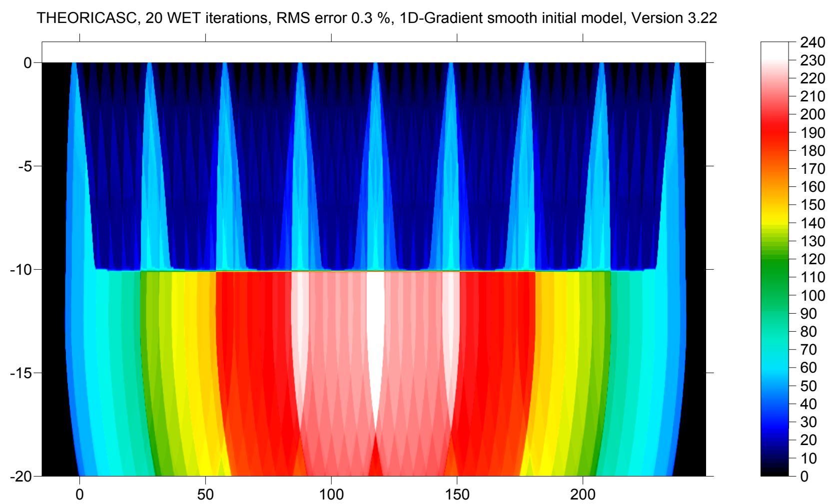

Fig. 9 : WET wavepath coverage plot obtained with Fig. 8. Color coding shows number of wavepaths per pixel.

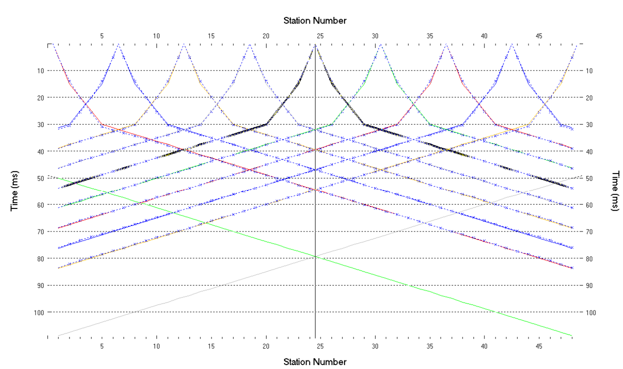

Fig. 10 : *Refractor|Shot breaks*, fit between picked times (solid colored curves) and forward-modeled times (dashed blue curves) obtained with last WET iteration (Fig. 8).

Compare with Fig. 5, showing traveltime fit for 1D initial model (Fig. 6).

Below we show pseudo-2D XTV inversion (Fig. 14), which is the basis for the 1D initial model (Fig. 6), without the horizontal averaging step. Also, we show how gridding the depth vs. velocity data points with Golden Software Surfer® version 8 can generate artefacts, caused solely by the gridding algorithm and not the data (Fig. 16).

- check *Smooth invert|Smooth inversion Settings|Allow unsafe pseudo-2D DeltatV inversion*
- select *DeltatV|Interactive DeltatV…*
- click on *Reset button* to reset settings (Fig. 11)

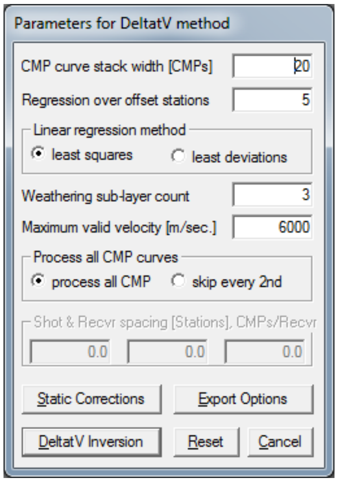

Fig. 11 : *DeltatV|Interactive DeltatV…*

- click on *Export Options button* (Fig. 12)
- set *Gridding method* to `Natural Neighbor`
- click *Accept button*
- click *DeltatV Inversion button*
- in *Save DeltatV dialog* (Fig. 13) , set *File name* to `XTVNaturalNeighbor` and click *Save button*

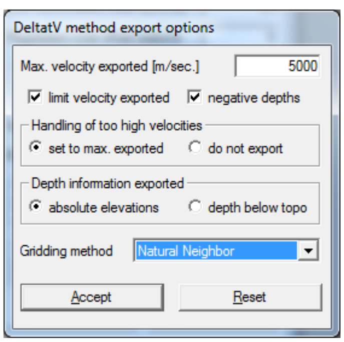

Fig. 12 : DeltatV export options

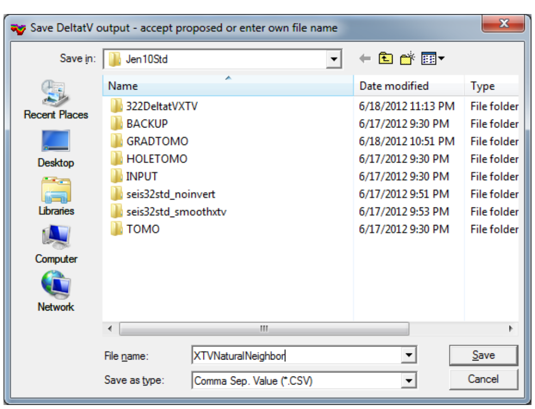

Fig. 13 : Save DeltatV dialog

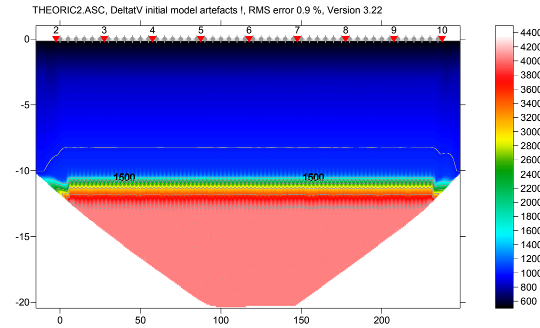

Fig. 14 : pseudo-2D XTV inversion, imaged with Natural Neighbor gridding method. RMS error is 0.9%

- select *Model|Forward model traveltimes..*
- select file XTVNaturalNeighbor.GRD
- click *Open button*
- select *Grid|Image and contour velocity and coverage grids…*
- select again file XTVNaturalNeighbor.GRD and click *Open button* to obtain Fig. 14
- select *Refractor|Shot breaks* to obtain Fig. 15

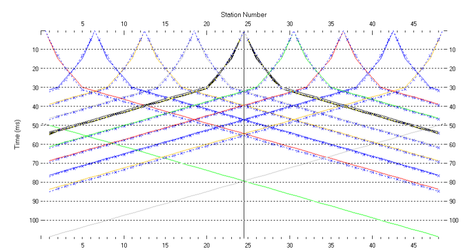
Fig. 15 : traveltime fit for Fig. 14

- go back to Fig. 12 and set *Gridding method* to `Kriging`
- click *buttons Accept & DeltatV inversion*
- save DeltatV output as file `XTVKriging.CSV`
- obtain Fig. 16. Note strong artefacts, caused by Surfer kriging algorithm.

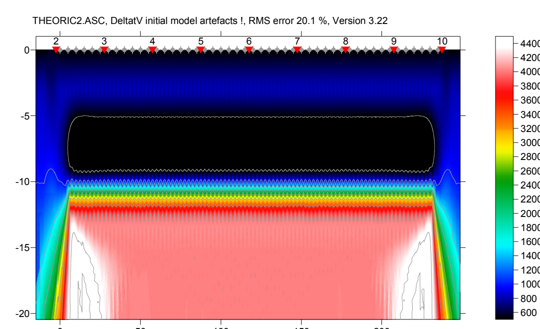

Fig. 16 : pseudo-2D XTV inversion, imaged with Kriging gridding method. RMS error 20.1% ! Note strong artefacts, when comparing to Fig. 14.

Compare data files XTVNaturalNeighbor.CSV and XTVKriging.CSV in jenny10.zip with fc command in a command prompt. These files are identical.