Seismic Modeling, Migration and Velocity Inversion

Full Waveform Inversion

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Outline

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1. **Full Waveform Inversion**
   - The Basic Idea
2. **Marmousi Example**
   - Estimating the Initial Model
   - FWI
     - Marmousi
     - SEG AA'

Full Waveform Inversion (FWI)

Velocity inversion is based on a very simple idea.

- Find that Earth model M that best explains the recorded data D
  - Synthetic data U generated over M should match D as closely as possible
- Minimize an objective function $\| D - U \|$ where $\| - \|$ is the
  - L^1 norm
  - least squares norm
  - least squares norm of the phase difference between D and U
  - least squares norm of the envelope difference between D and U
  - least squares norm of the logarithmic difference between D and U

The Inversion Scheme

In the classical least squares case FWI is an iterative scheme

$$M^n = \mathbf{M}^{n-1} - \mathbf{R}^{n-1}\,(D - U)$$

where

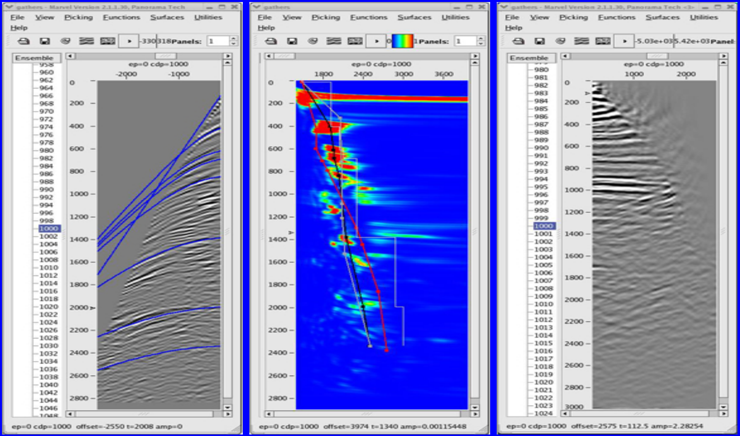
- At each iteration $\mathbf{R}^{n-1}$
  - Is a very fancy imaging condition
  - Produces an incremental ΔM
  - Is almost always some form of reverse time migration
    - But it need not be

Full Waveform Inversion

- For a given model
  - For each observed shot, synthesize data to match the real acquisition
    - Use a full two-way modeling algorithm
    - Save a trace at each model node
  - Compute the difference between the shot and the real data
    - These data are called the residuals
  - Back propagated the residuals into the model
    - Use a full two-way modeling algorithm
    - Save a trace at each model node
  - Preform a shot-profile migration of the residuals
    - The shot is the forward-propagated synthetic
    - The receiver traces are the back-propagated residuals
    - Divide the back by the forward propagated traces
  - Normalize the image above by the velocity squared
  - Add the normalized image to the current model
  - Repeat the previous steps until the norm of the model difference is small
- FWI is really a iterative migration scheme

Outline

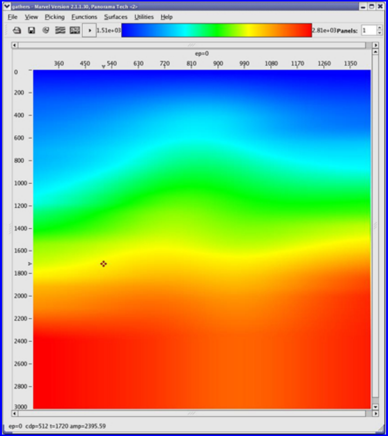
Marmousi MVA



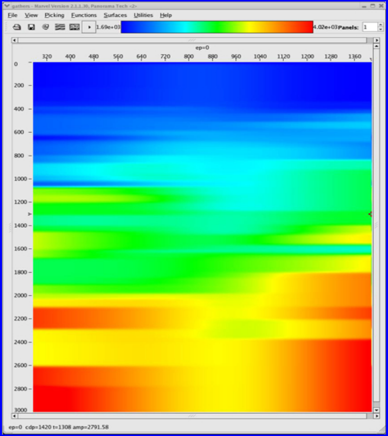
(a) Gather Picks (b) Semblance Picks (c) NMO'd Gather

Typical Marmousi gather with picks, a semblance panel with picks, and the NMO corrected gather.

Marmousi MVA



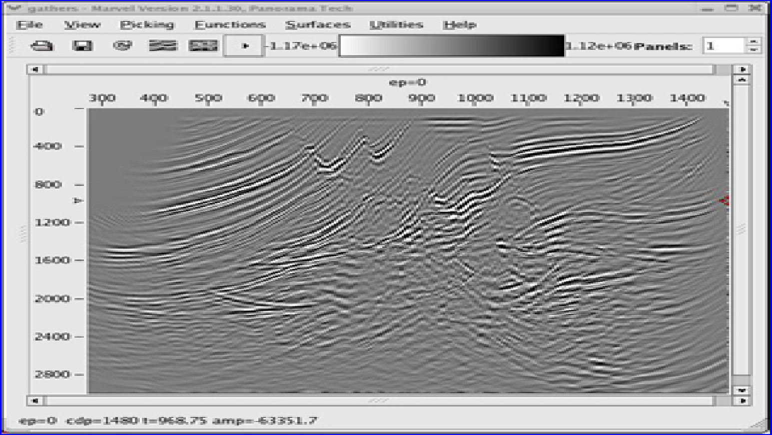
(a) Marmousi Time-RMS model



(b) Marmousi Depth-Interval model

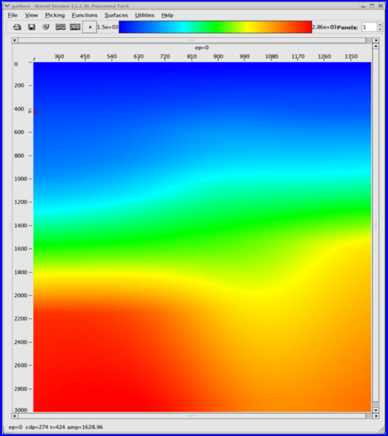
Initial stacking velocity models in time-RMS (left) and interval-depth (right).

Marmousi MVA

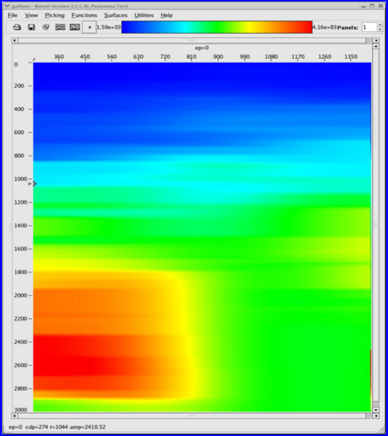


First iteration Marmousi stacking velocity based Kirchhoff migration.

Marmousi MVA



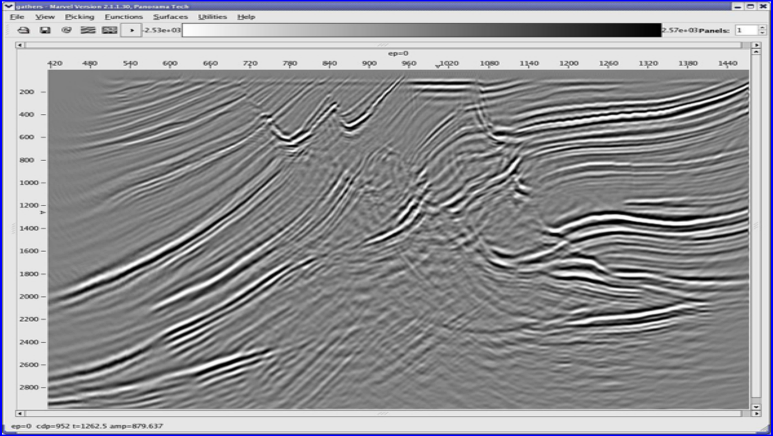
(a) Marmousi Time-RMS model



(b) Marmousi Depth-Interval model

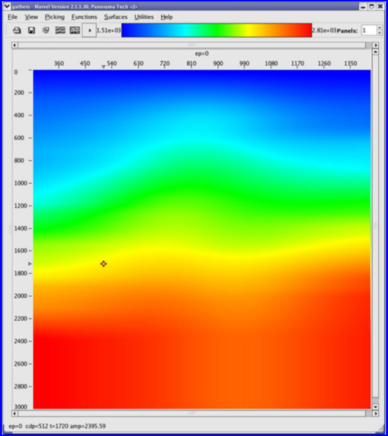
Second Kirchhoff based MVA models in time-RMS (left) and interval-depth (right).

Marmousi MVA

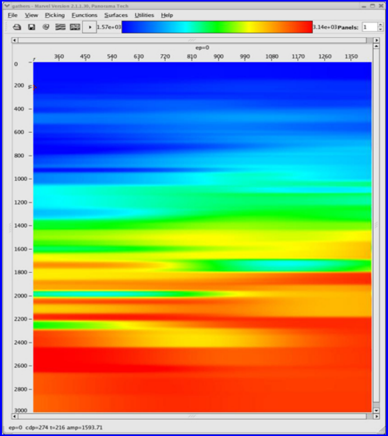


Second iteration Marmousi Kirchhoff based MVA Kirchhoff migration.

Marmousi MVA



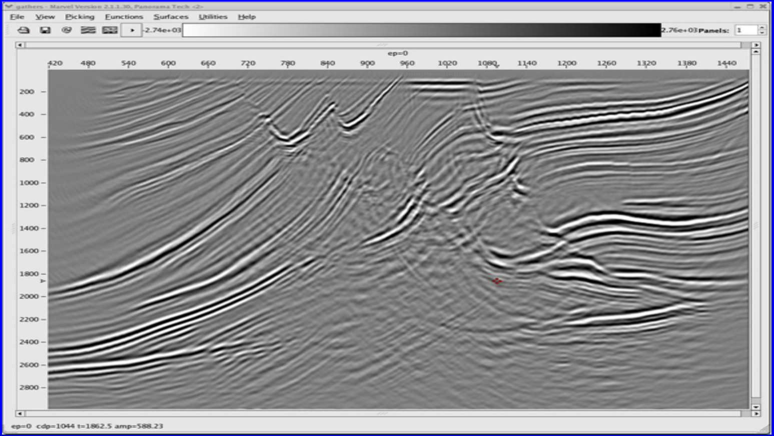
(a) Marmousi Time-RMS model



(b) Marmousi Depth-Interval model

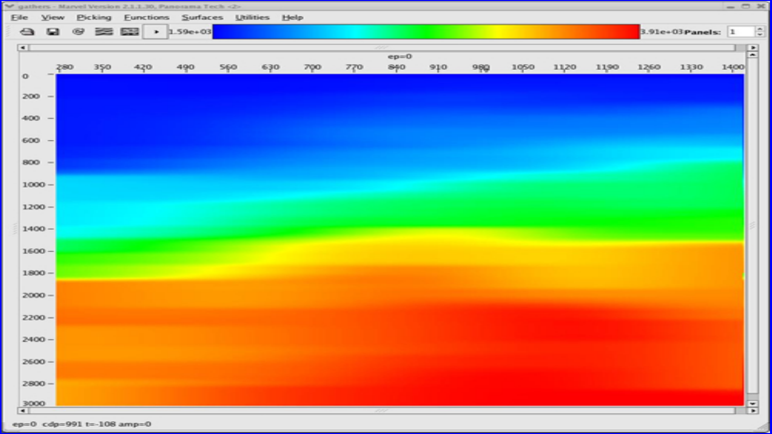
Second Kirchhoff based MVA models in time-RMS (left) and interval-depth (right).

Marmousi MVA



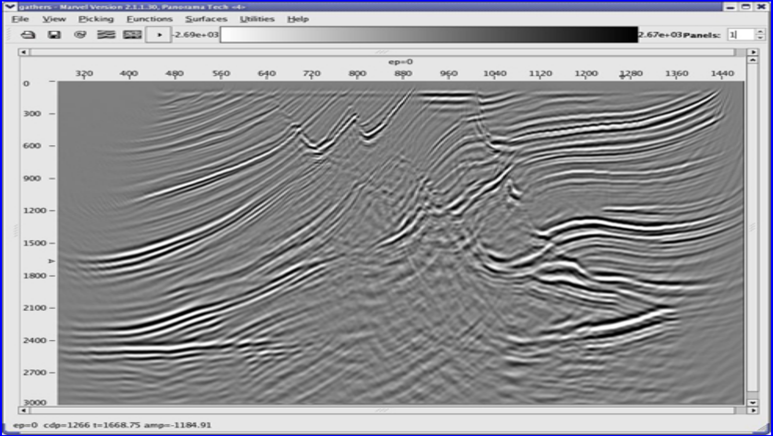
Third iteration Kirchhoff based MVA Kirchhoff migration.

Marmousi MVA



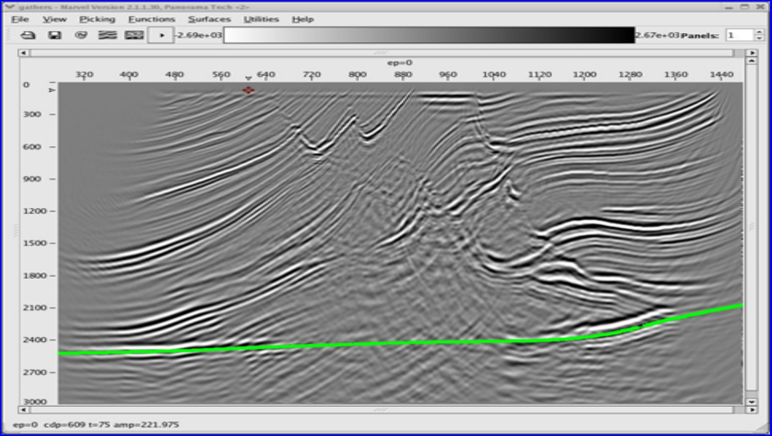
Fourth iteration Kirchhoff MVA based velocity model.

Marmousi MVA



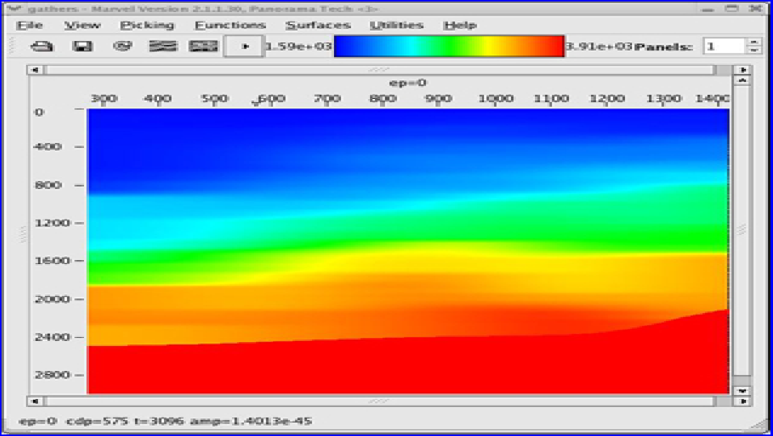
Fourth iteration Kirchhoff MVA based Kirchhoff migration.

Marmousi MVA



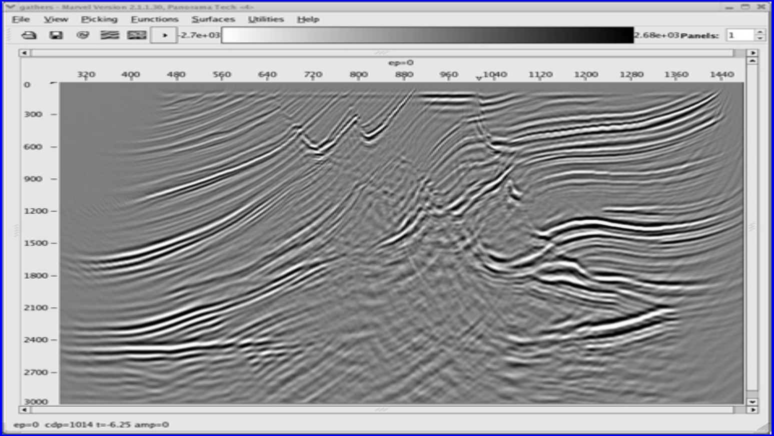
Bottom horizon for constant velocity analysis.

Marmousi MVA



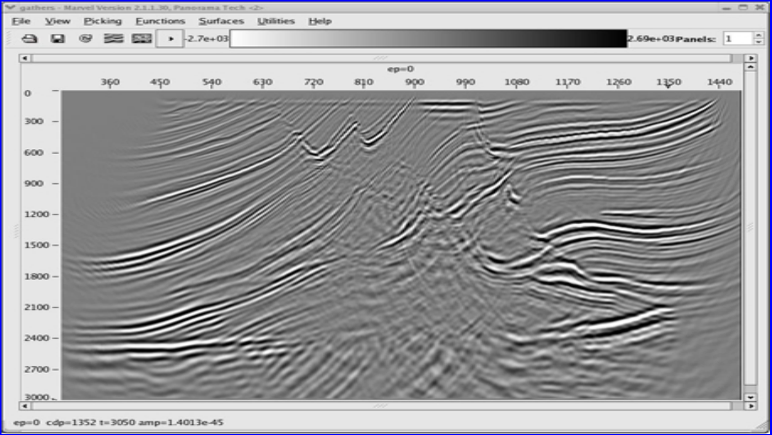
Fourth iteration Kirchhoff MVA based model with bottom horizon 4000 meter/second velocity flood.

Marmousi MVA



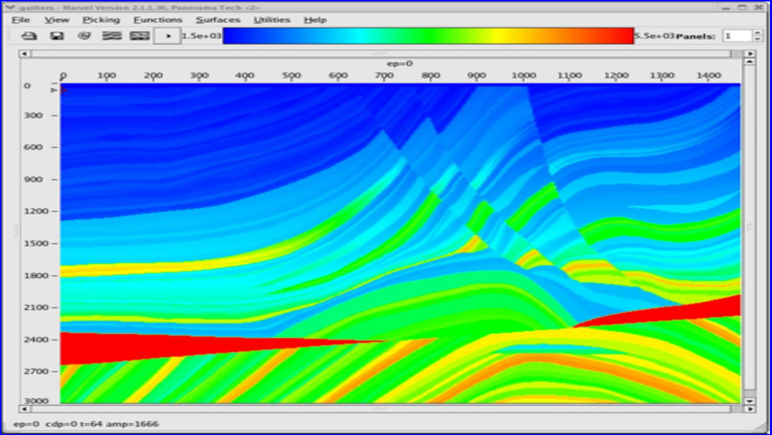
Fourth iteration Kirchhoff MVA based model with bottom horizon 4000 meter/second velocity flood migration.

Marmousi MVA



Fourth iteration Kirchhoff MVA based model with bottom horizon 5000 meter/second velocity flood migration.

Marmousi MVA

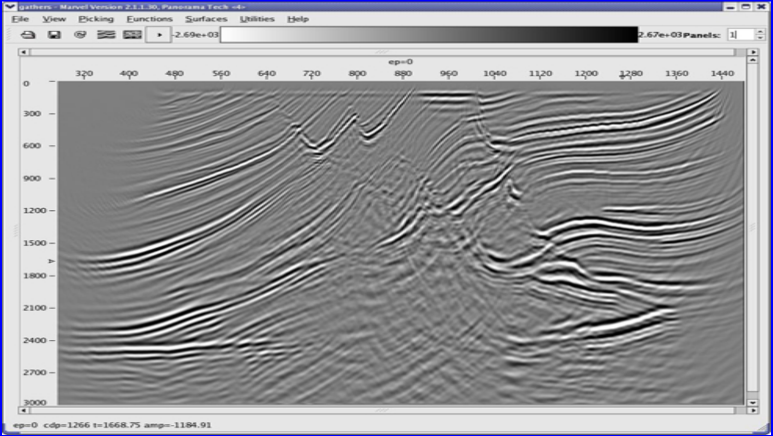


The true Marmousi model.

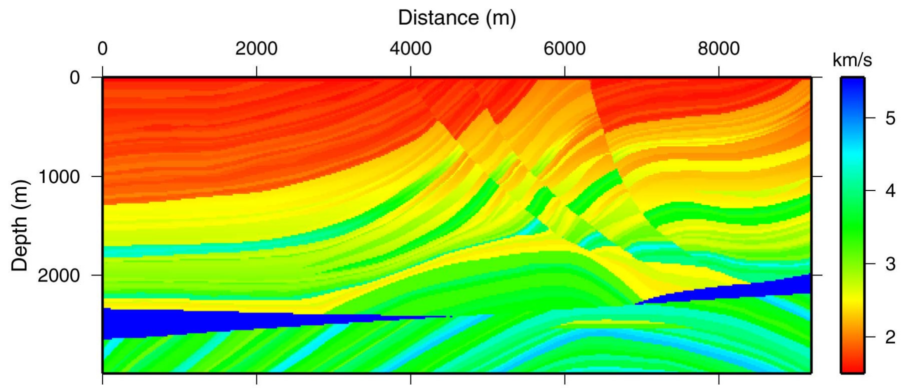
Notes

- Insufficient offset
  - Max of 2600 over 9000 km model
  - Approximately 1300 km velocity analysis basement
- Recording time too short (3 seconds)
- Long delay wavelet

Marmousi FWI



Marmousi Inversion

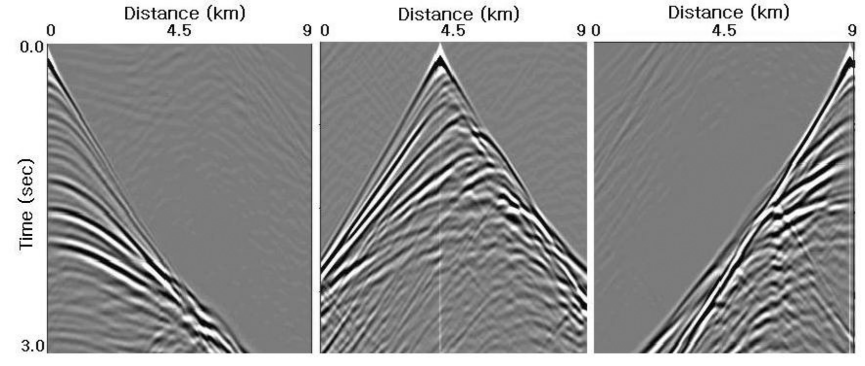


True Marmousi model.

Process Review

- The true model
  - Nine km by three km (depth)
- The *observed* data
  - Nine km offset
  - Broadband wavelet from .3 HZ to 50 HZ
    - Low frequency and long offsets are the key
  - Five second recording time
  - Model grid was 16m X 16m

The observed data



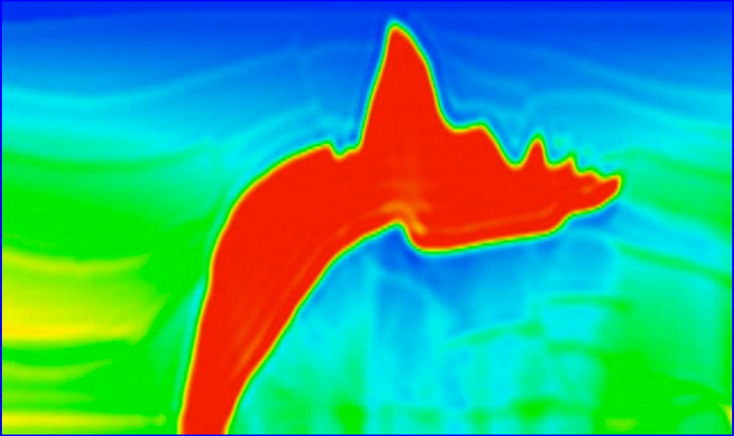
Marmousi Synthetic Data

The inversion process

- We started with a MVA model
  - Virtually no reflections
  - Reasonably accurate shallow
  - First iteration essentially muted the first breaks
  - First iteration is exactly equivalent to migrating with our initial model
    - Lailly: Migration is the first step in inversion
- We calculated a new velocity model from residuals and a synthetic shot
- We shot a new synthetic data set
- We imaged the residuals
- We repeated the exercise until model differences became negligible
- In this case the model is as good as can be expected

This kind of inversion is theoretically valid for all Earth Models.

SEG AA' FWI



We begin with a $v(z)$ model and iterated for about 100 iterations.

FWI Summary

- Requires low frequencies
  - The lower the better
- Requires long offsets
  - The longer the better
- Generally gets the slow velocities
- Many iterations for fast velocity anomalies

Questions?