Full waveform inversion of OBS data for gas hydrate exploration in SW Taiwan

Kun-Sung Li and How-Wei Chen

Outline

- Introduction and Motivation
- Theoretical Background and Verification
- Preprocessing of Marine Seismic Data
- Application of Marine Seismic Survey
- Conclusions and Discussion

Pre-stack vs. Post-stack

Standard Processing	Proposed Pre-stack Processing
• Demultiplex • Preprocessing • Elevation Static Correction • Common Mid-point Sorting • **Velocity Analysis** • Residual Statics Correction • Normal Moveout Correction • Dip Moveout Correction • Stacking • Post-stack Migration	• Demultiplex • Preprocessing • **Velocity Analysis** • Pre-stack Depth Migration • Stacking

Literature Reviews

- **Claebout (1976) suggested adjoint-state method for seismic data migration and imaging**
- **Lailly (1983) and Tarantola (1984)**
  - **Adjoint-state Method to Calculate Directional Gradient**
  - **Steepest Descent Method**
- **Tarantola (1984) Suggests Reverse-Time Imaging and Velocity Reconstruction of Waveform Residuals**
- **Mora (1987, 1988), Tarantola (1986, 1987), Sun and McMechan (1988), Pratt (1990), Pratt et al. (1998), Sirgue and Pratt (2004), Operto et al. (2006), Sheen et al. (2006), Shine and Ha (2008), Brossier et al. (2009), Virieux and Operto (2009), ...**

Full Waveform Inversion

- **FWI is a technique for seismic depth imaging, for velocity-model building, and for obtaining models of physical properties in the sub-surface at high spatial resolution.**
- **Prestack, Wide-aperture, Common- Shot/Receiver Seismic Data**
- **No Travel-time Picking and Phase Identification are Required**
- **Direct Wavefield Imaging of Velocity Distribution Using Either SH or Acoustic Responses**
- **Efficient FD Computation for Both Forward and Reverse-time Extrapolations**
- **No Explicit Process of Multiples, Diffractions, and Non-Physical Wavefields**
- **Imaging Conditions Based on Diffracted Wavefield by Adjoint–state Method**

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Wavefield Extrapolation Approach 1

Pressure/Acoustic Wave Equation

$$\frac{1}{v^2(x,z)}\frac{\partial p(x,z)}{\partial t^2} - \rho(x,z)\nabla \cdot \left[\frac{1}{\rho(x,z)}\nabla p(x,t)\right] = s(t)$$

Where

- p : Pressure Wavefield
- v : Velocity Distribution
- s : Source Time Function
- ρ : density

Wavefield Extrapolation Approach 2

Velocity-Pressure Wave Equation

$$\begin{cases} \dfrac{\partial \boldsymbol{v}_x}{\partial t} = \boldsymbol{b}(\boldsymbol{x},\boldsymbol{z})\dfrac{\partial \boldsymbol{P}(\boldsymbol{x},\boldsymbol{z})}{\partial \boldsymbol{x}} + \boldsymbol{f}_x \\ \dfrac{\partial \boldsymbol{v}_z}{\partial t} = \boldsymbol{b}(\boldsymbol{x},\boldsymbol{z})\dfrac{\partial \boldsymbol{P}(\boldsymbol{x},\boldsymbol{z})}{\partial \boldsymbol{z}} + \boldsymbol{f}_z \\ \dfrac{\partial \boldsymbol{P}(\boldsymbol{x},\boldsymbol{z})}{\partial t} = \boldsymbol{\kappa}(\boldsymbol{x},\boldsymbol{z})\left(\dfrac{\partial \boldsymbol{v}_x}{\partial \boldsymbol{x}} + \dfrac{\partial \boldsymbol{v}_z}{\partial \boldsymbol{z}}\right) \\ \dfrac{\partial \boldsymbol{P}(\boldsymbol{x},\boldsymbol{z})}{\partial t} = \boldsymbol{\kappa}(\boldsymbol{x},\boldsymbol{z})\left(\dfrac{\partial \boldsymbol{v}_x}{\partial \boldsymbol{x}} + \dfrac{\partial \boldsymbol{v}_z}{\partial \boldsymbol{z}}\right) \end{cases}$$

Where

$\boldsymbol{P}(\boldsymbol{x},\boldsymbol{z})$: Pressure

$\boldsymbol{v}$: Velocity

$\boldsymbol{b}$: Buoyancy

$\boldsymbol{k}$: Bulk modulus

$\boldsymbol{F}_x, \boldsymbol{F}_z$: Hori. and Vert. Comp. Force

Generalized Nonlinear Inverse Problems: Solved Through Least Squares Criterion

d=Gm **Δd=dobs-dsyn** **Misfit Function** $S(m) = \frac{1}{2}\Delta\mathbf{d}^{\dagger}\Delta\mathbf{d}$

$$S(\mathbf{m}_0 + \mathbf{\Delta m}) = S(\mathbf{m}_0) + \sum_{j=1}^{M} \frac{\partial S(\mathbf{m}_0)}{\partial m_j}\Delta m_j + \frac{1}{2}\sum_{j=1}^{M}\sum_{k=1}^{M} \frac{\partial^2 C(\mathbf{m}_0)}{\partial m_j \partial m_k}\Delta m_j \Delta m_k + \mathcal{O}(m^3)$$

$$\Delta m = -\left[\frac{\partial^2 S(\mathbf{m}_0)}{\partial m^2}\right]^{-1} \frac{\partial S(m_0)}{\partial m} = H^{-1}(m)\gamma(m)$$

$$H^{-1}(m) = \left[\frac{\partial^2 S(\mathbf{m}_0)}{\partial m^2}\right]^{-1} \qquad \gamma(m) = -\frac{\partial S(m_0)}{\partial m}$$

Frechét Derivative

$$\gamma(m) = \sum_{s} \int \dot{p}_{cal}(m)\dot{p}'_{res}(m)\, dt$$

Using Cross-correlation to Estimate Frechét Derivative (Tarantola, 1984)

Optimization

Conjugate Gradient Method

$$\mathbf{m}^{(n)} = \mathbf{m}^{(n-1)} - \alpha^{(n)}\phi^{(n)}(\mathbf{m})$$

$$\phi^{(n)}(\mathbf{m}) = \gamma^{(n)}(\mathbf{m}) + \beta^{(n)}\phi^{(n-1)}(\mathbf{m})$$

$$\alpha^{(n)} = \frac{[F_n\phi^{(n)}(\mathbf{m})]^t \Delta\mathbf{d}}{[F_n\phi^{(n)}(\mathbf{m})]^t[F_n\phi^{(n)}(\mathbf{m})]}$$

$$F_n\phi^n(\mathbf{m}) = \lim_{\varepsilon\to 0}\frac{\phi(\mathbf{m}+\boldsymbol{\varepsilon}\mathbf{m}) - \phi(\mathbf{m})}{\varepsilon}$$

$$\beta^{(n)} = \frac{[\gamma^{(n)}(\mathbf{m}) - \gamma^{(n-1)}(\mathbf{m})]^t[\gamma^{(n)}(\mathbf{m})]}{[\gamma^{(n-1)}(\mathbf{m})]^t[\gamma^{(n-1)}(\mathbf{m})]}$$

Restarting, Polak and Ribiere (1969)

$$\beta^{(n)} = \max\{\beta^{(n)}, 0\}$$

Steepest Descent Method

$$\mathbf{m}^{(n)} = \mathbf{m}^{(n-1)} - \alpha^{(n)}\gamma^{(n)}(\mathbf{m})$$

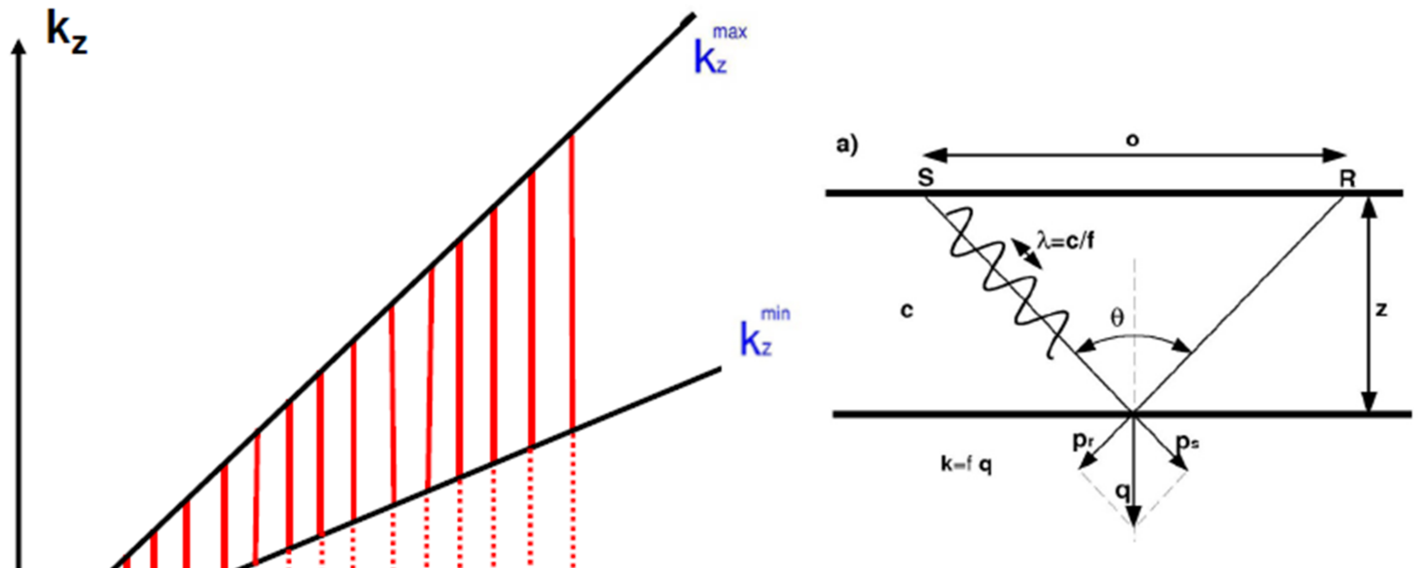
Regularization and Precondition

- **Total Variation Regularization**

$$V(y) = \sum_{i,j} \sqrt{\left|y_{i+1,j} - y_{i,j}\right|^2 + \left|y_{i,j+1} - y_{i,j}\right|^2}$$

- **Precondition**
  - $W(x, z) = \left(\rho(x, z) v^3(x, z)\right)^{-1}$
  - **Castellanos et al. (2011)**
  - **Weighting for Correct Self-Adjoint**

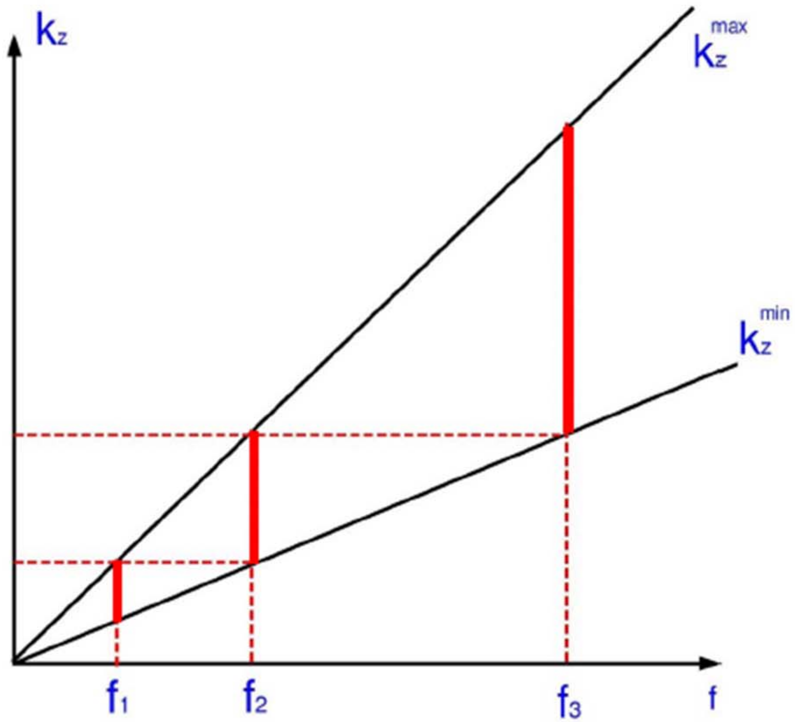
Multi-scale Consideration Through Frequency-domain FWI Approach



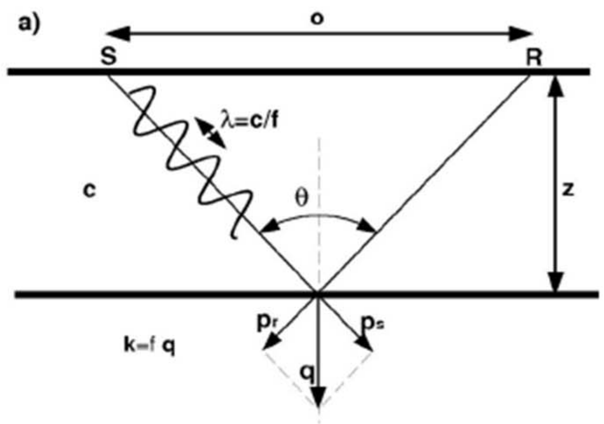
$$k_z = \frac{2f}{c}\cos(\frac{\theta}{2})$$

From Sirgue & Pratt (2004)

CPU-efficient Frequency-domain FWI



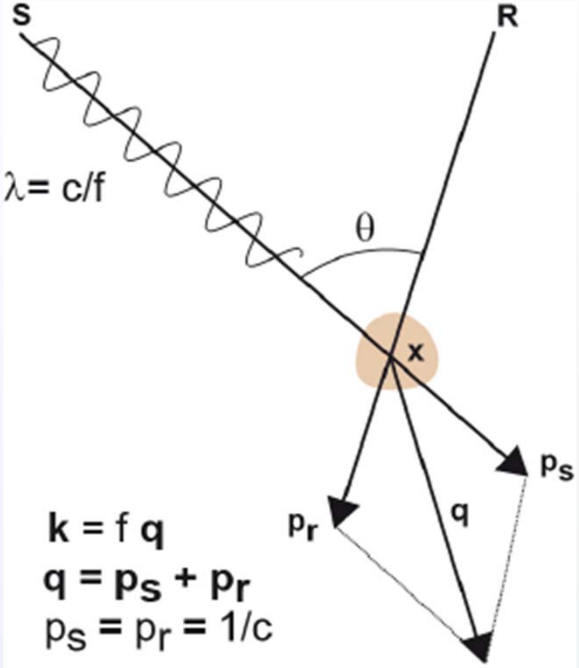
Keeping lower frequencies during iterations (Bunks, 1995)



$$k_z = \frac{2f}{c}\cos(\frac{\theta}{2})$$

From Sirgue & Pratt (2004)

Fresnel Zone/FK Resolution Analysis

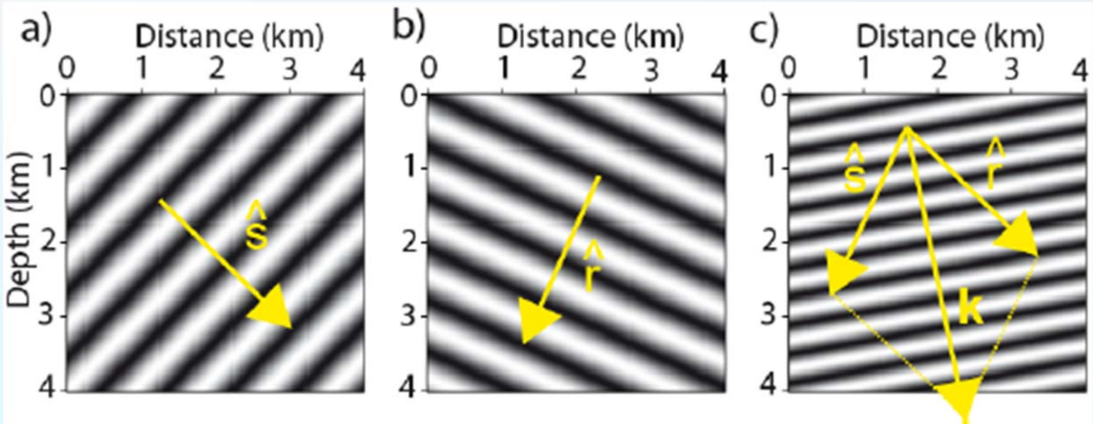


Wavenumber Illumination

$$k = \frac{2f}{c}\cos\left(\frac{\theta}{2}\right)n$$

Depends on Aperture Angle θ and Angular Frequency f

Expected Optimal Resolution $\lambda/2$



Sirgue and Pratt, 2004

One frequency and one aperture in the data space map one wavenumber in the model space. Therefore, frequencies and apertures have a redundant control on the wavenumber coverage.

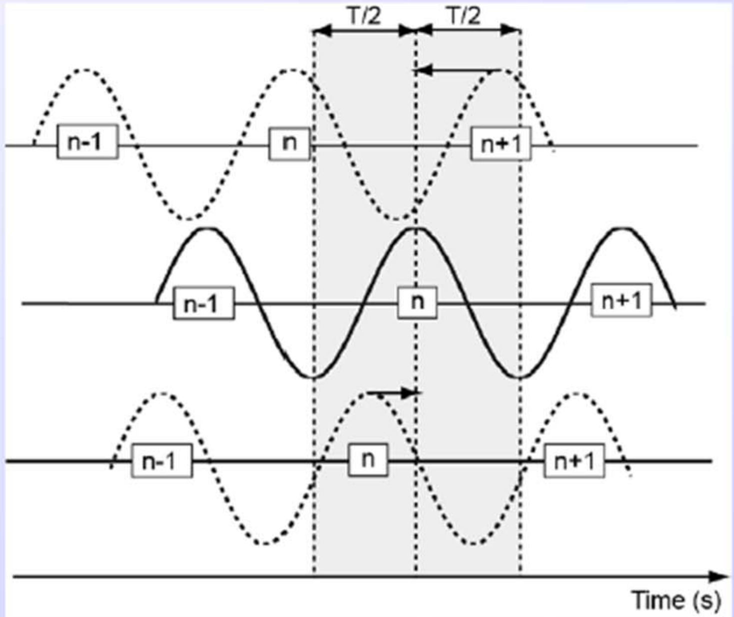
Problems in Cycle-skipping

Solid line: « Recorded » monochromatic seismogram.

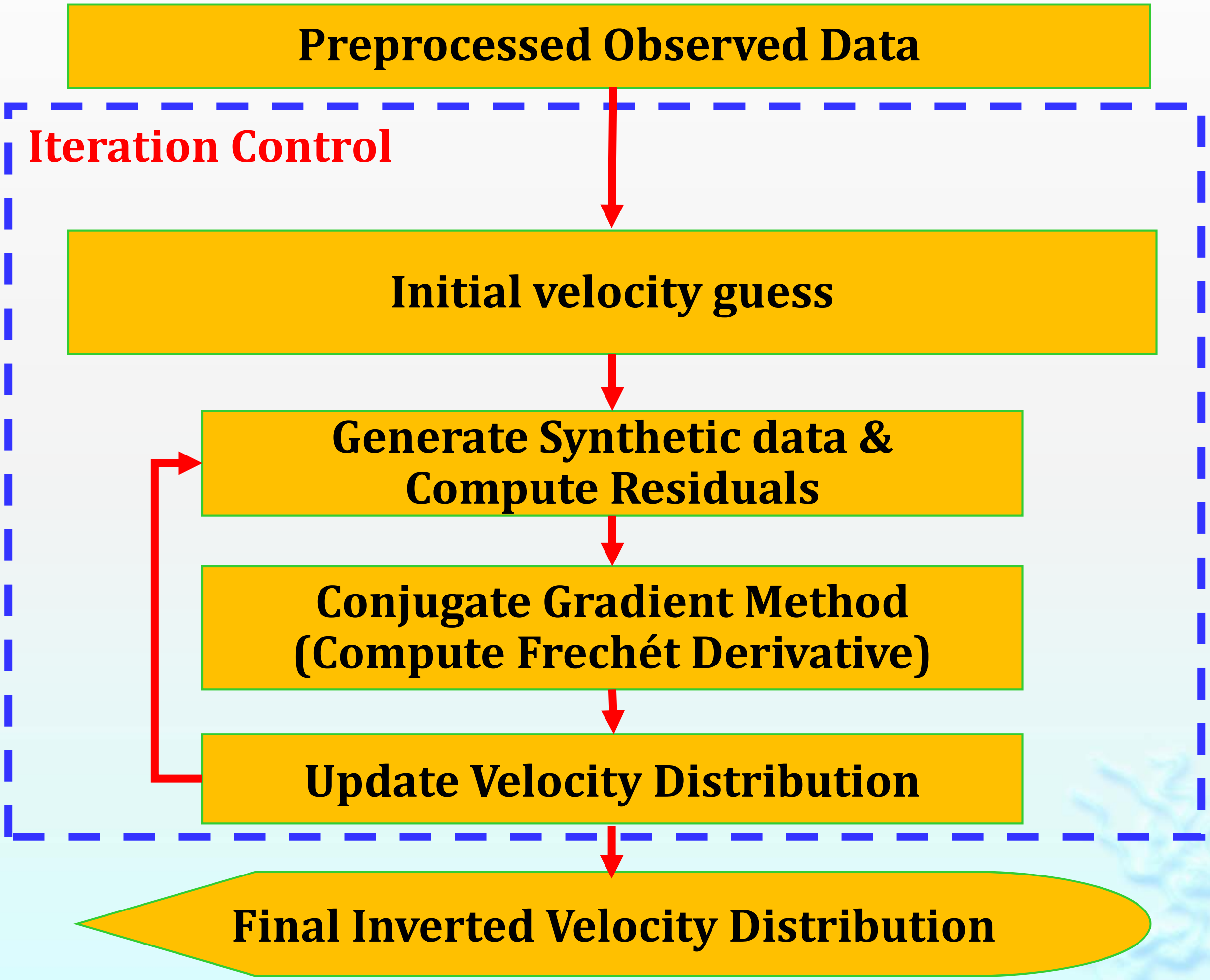
Dash lines: « Computed » monochromatic seismograms.

Top: the error exceeds half a period. Computed cycle *n+1* is matched with cycle *n* leading to cycle skipping.

Bottom: the error is smaller than half a period. The recorded and modeled cycles *n* are matched.

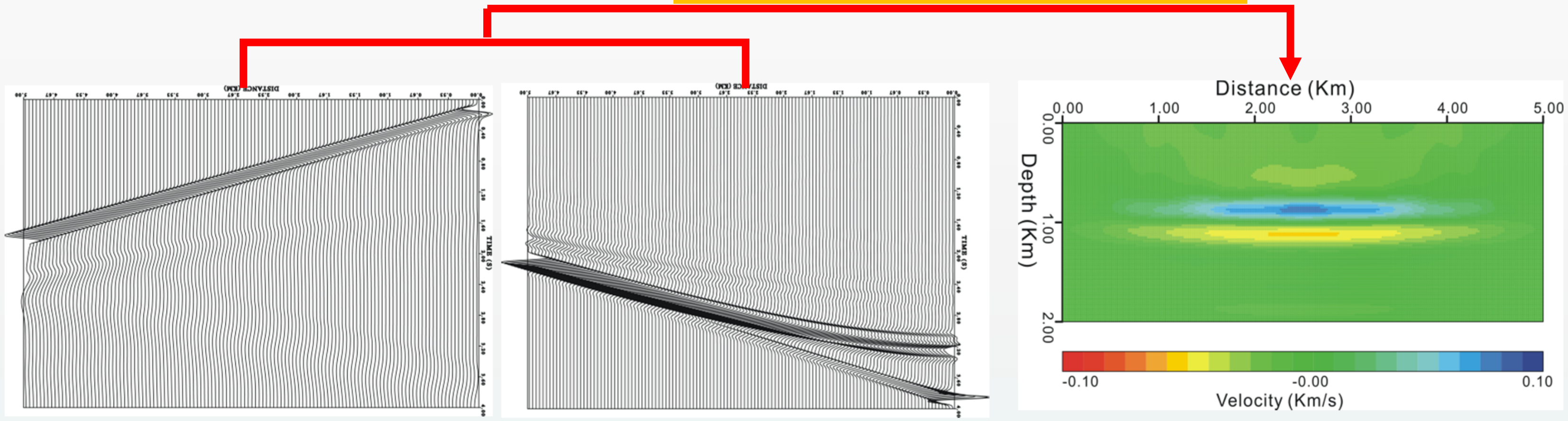


Inversion Scheme



Frechét Derivative

Cross-correlation

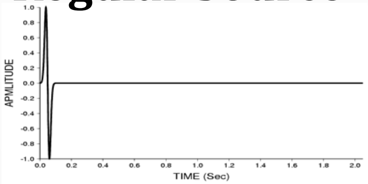


Forward **Backward** **Frechét Derivative**

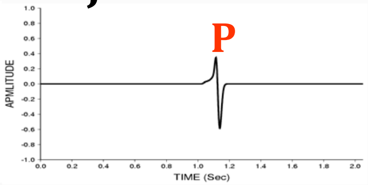
Forward Extrapolation → Predicted Seismograms
Backward Extrapolation → Time Reversed Propagation of Residual Seismograms

Sensitivity Kernel

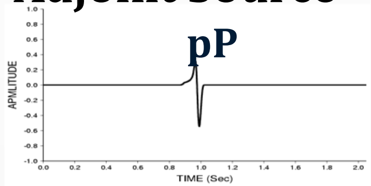
Regular Source



Adjoint Source

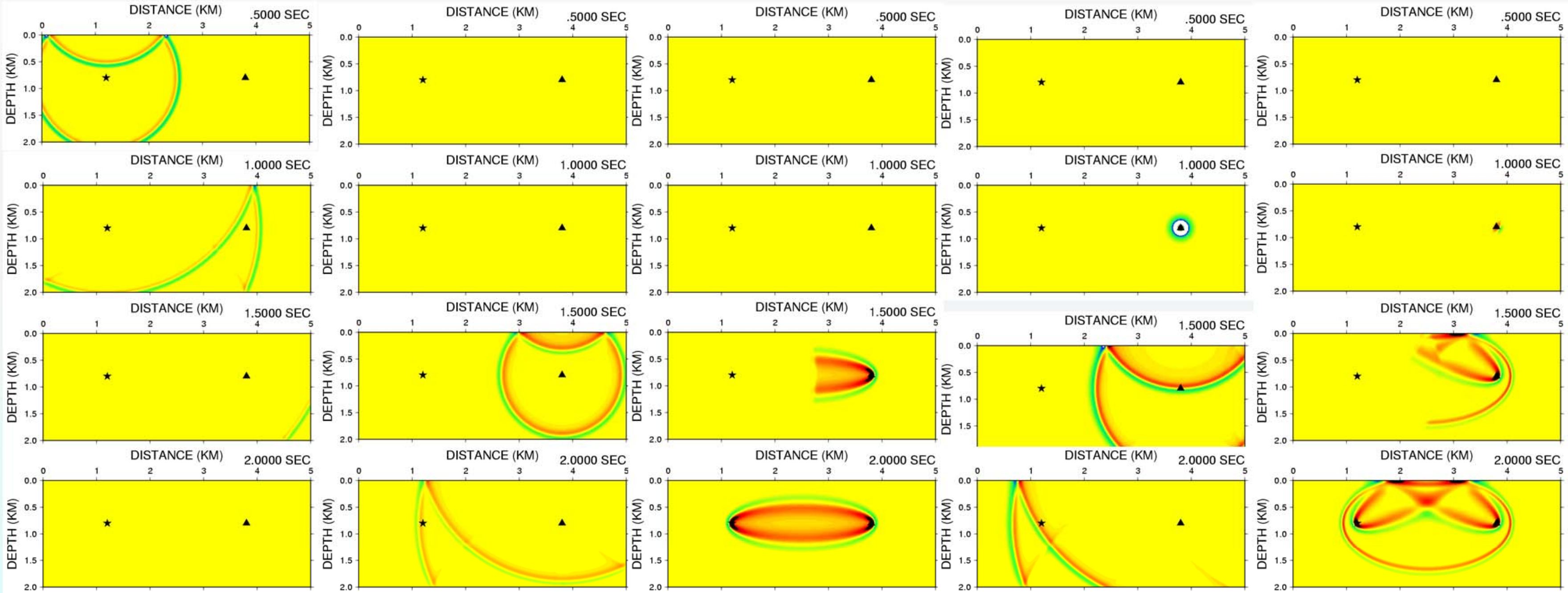


Adjoint Source

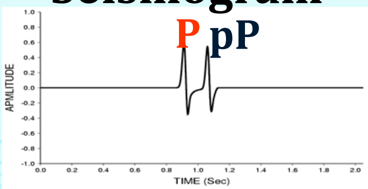


Direct wave — Forward, Backward, Kernel

Reflected wave — Backward, Kernel

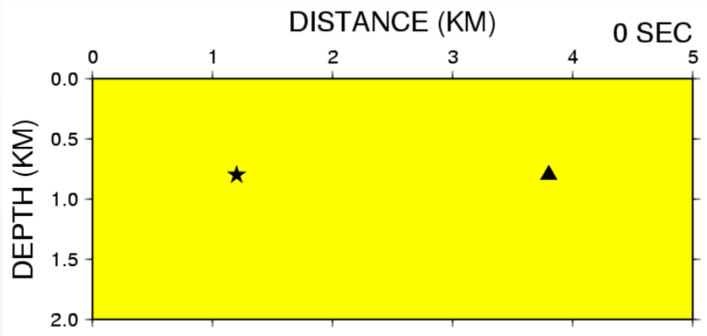


Seismogram



★ : source , ▲receiver

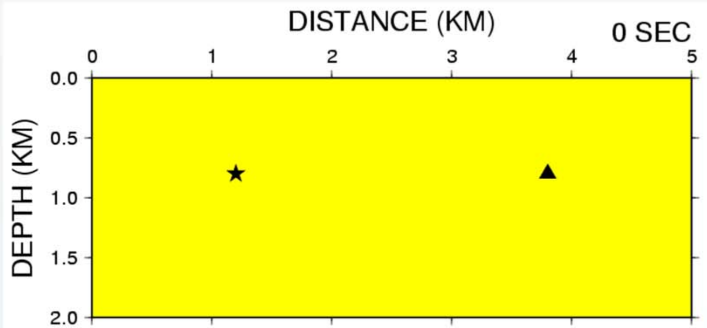
Forward

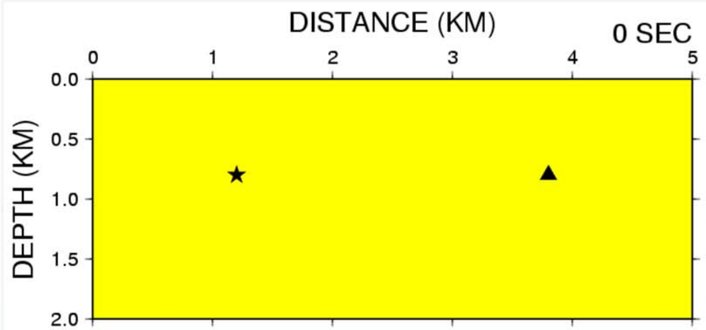


Direct wave

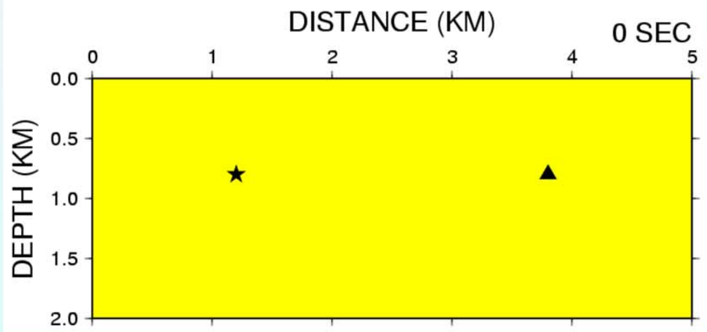
Reflect wave

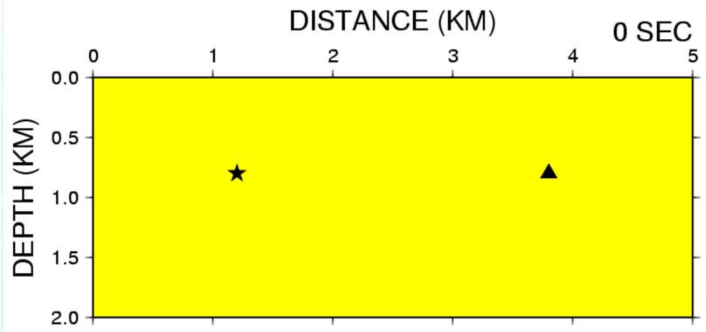
Backward



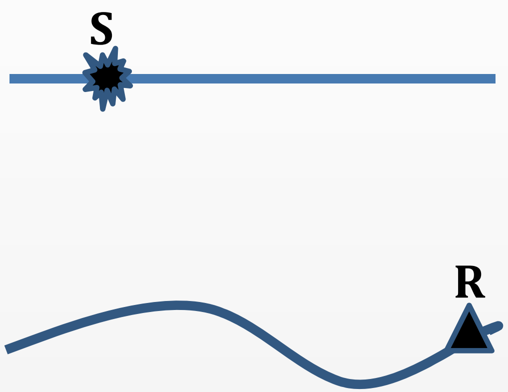


Kernel





Reciprocity Principal and Self-adjoint Validation



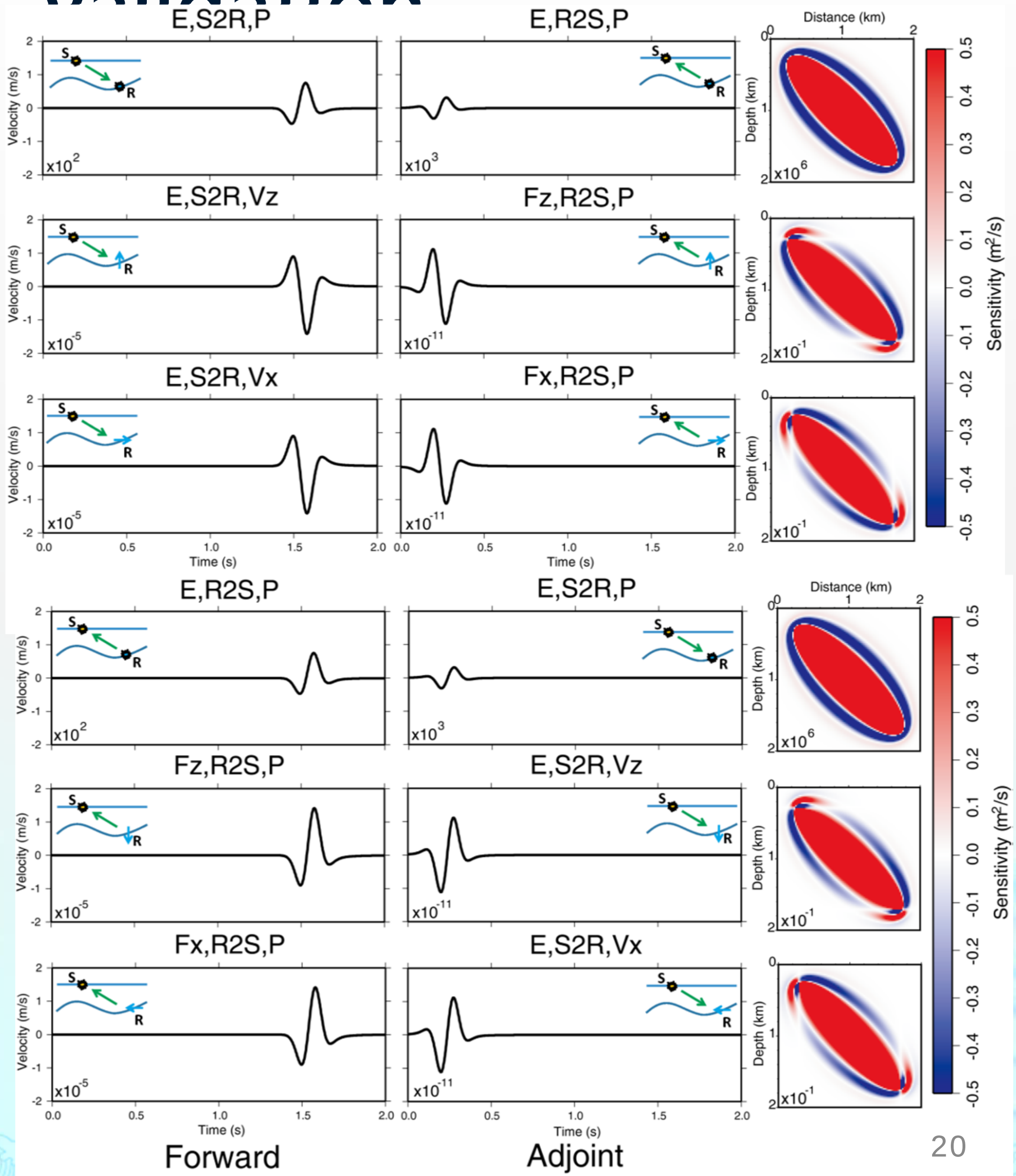
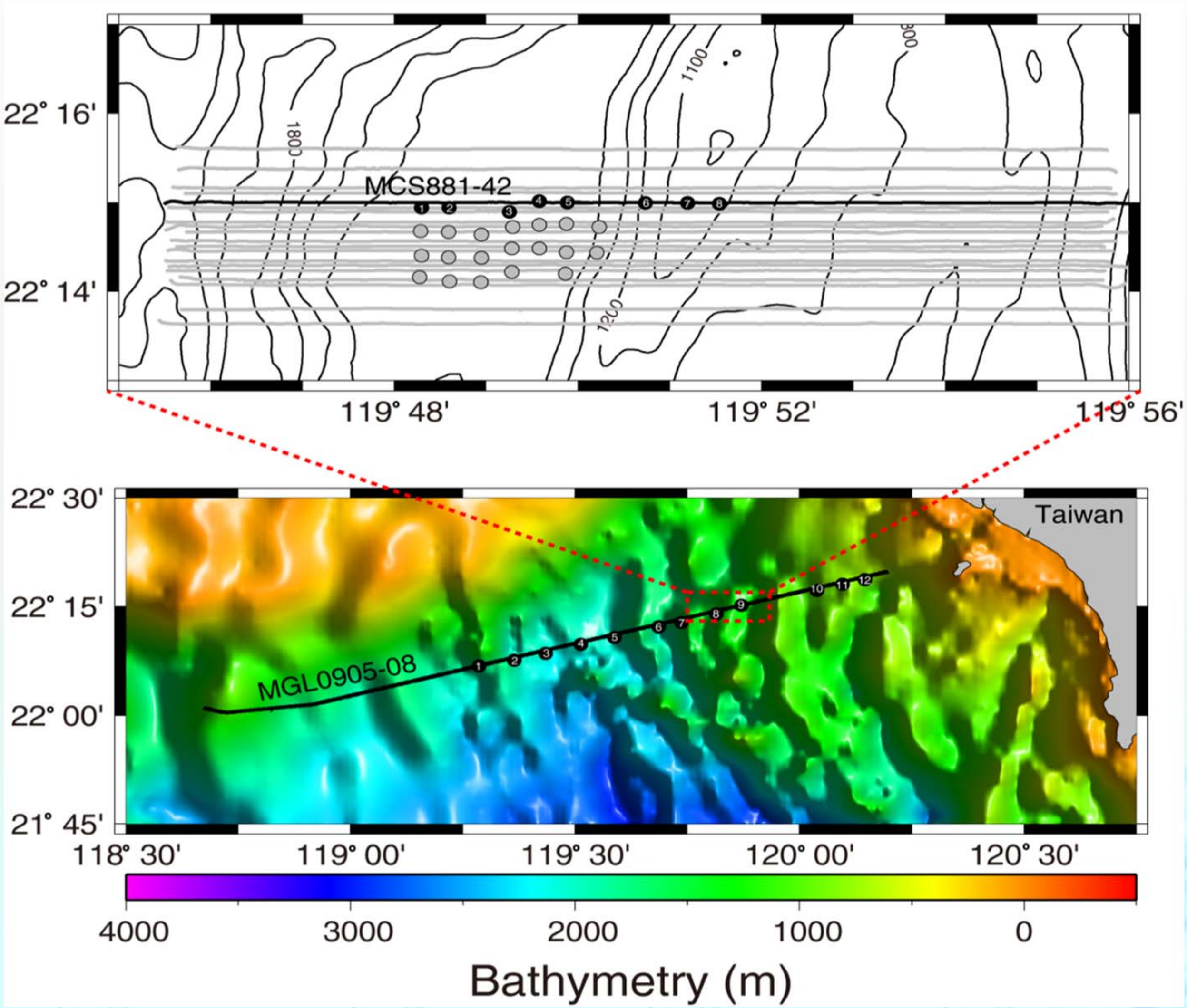


Figure 1c

Shot:
E: Explosive
Fx, Fz: Hori. and Vert. Forces
Receiver:
P: Pressure
Vx, Vz: Hori. and Vert. Velocities

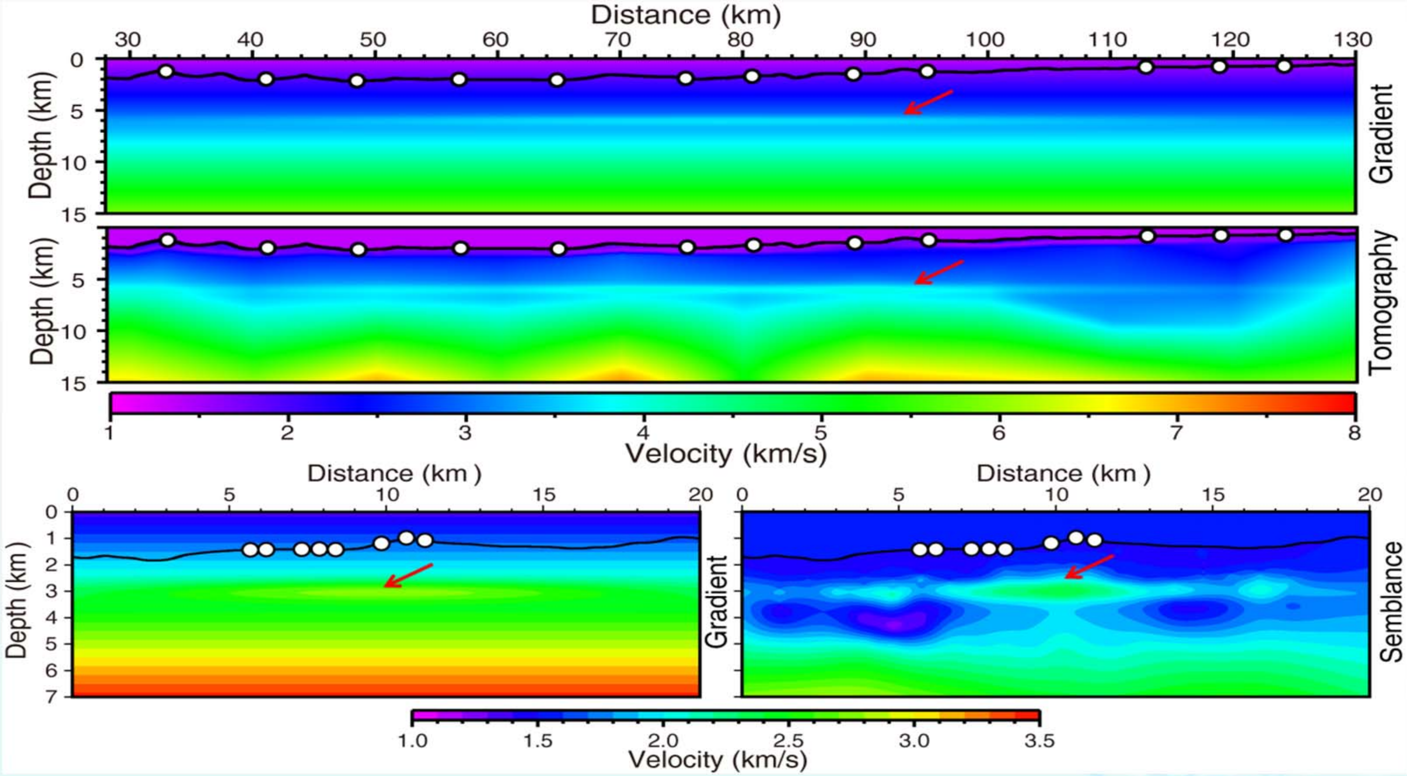
Illumination and Resolution Analyses For Marine Seismic Data Acquisition



Velocity Model + HVZ

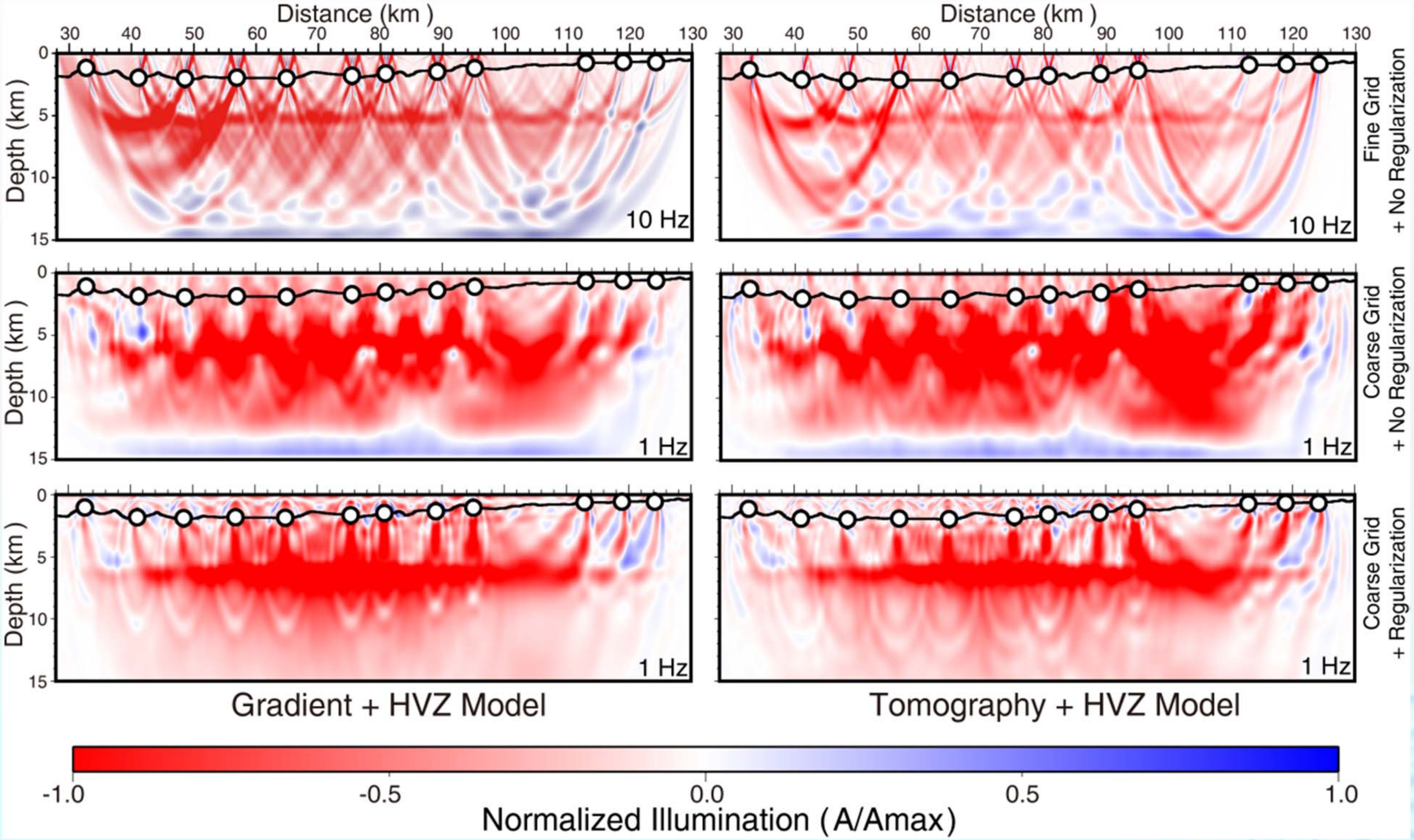
MGL0905-08

Mcs881-42

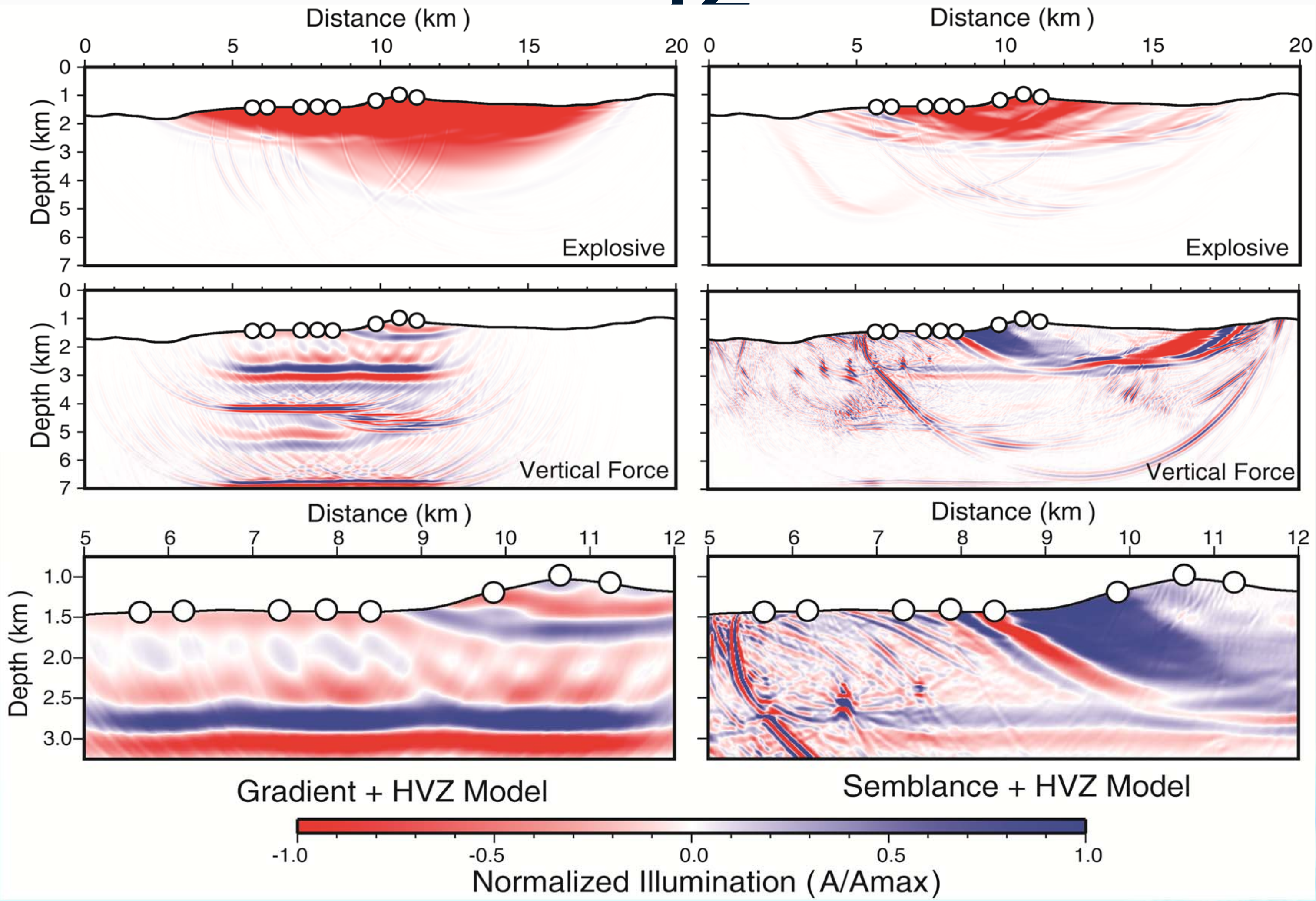


Red Arrow: HVZ, 500 m/s Anomaly

Sensitivity Kernel of MGL0905-08



Sensitivity Kernel of MCS881-42



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- **Introduction and Motivation**
- **Theoretical Background and Evaluation**
- **Preprocessing of Marine Seismic Data**
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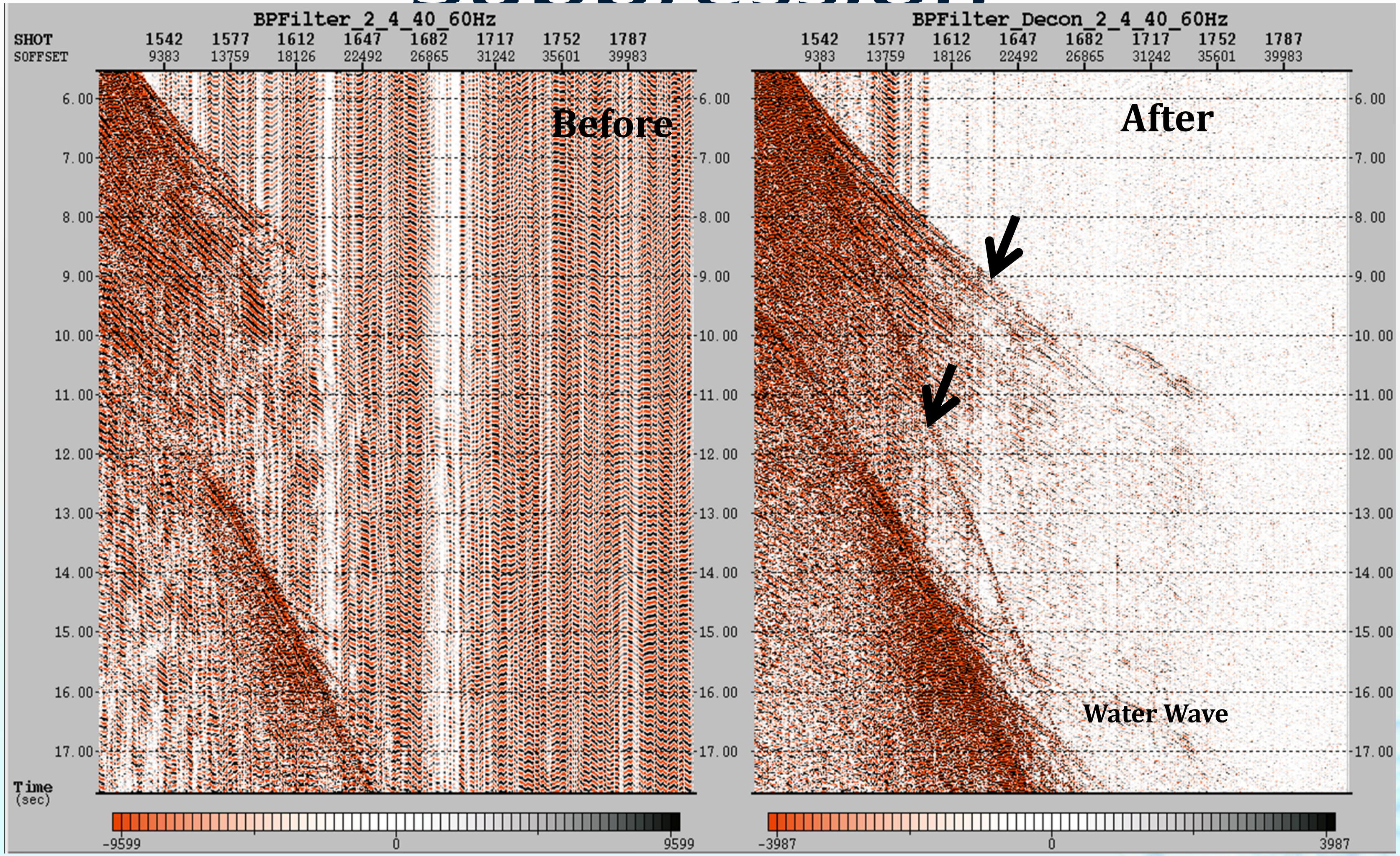
- **Conclusions and Discussions**

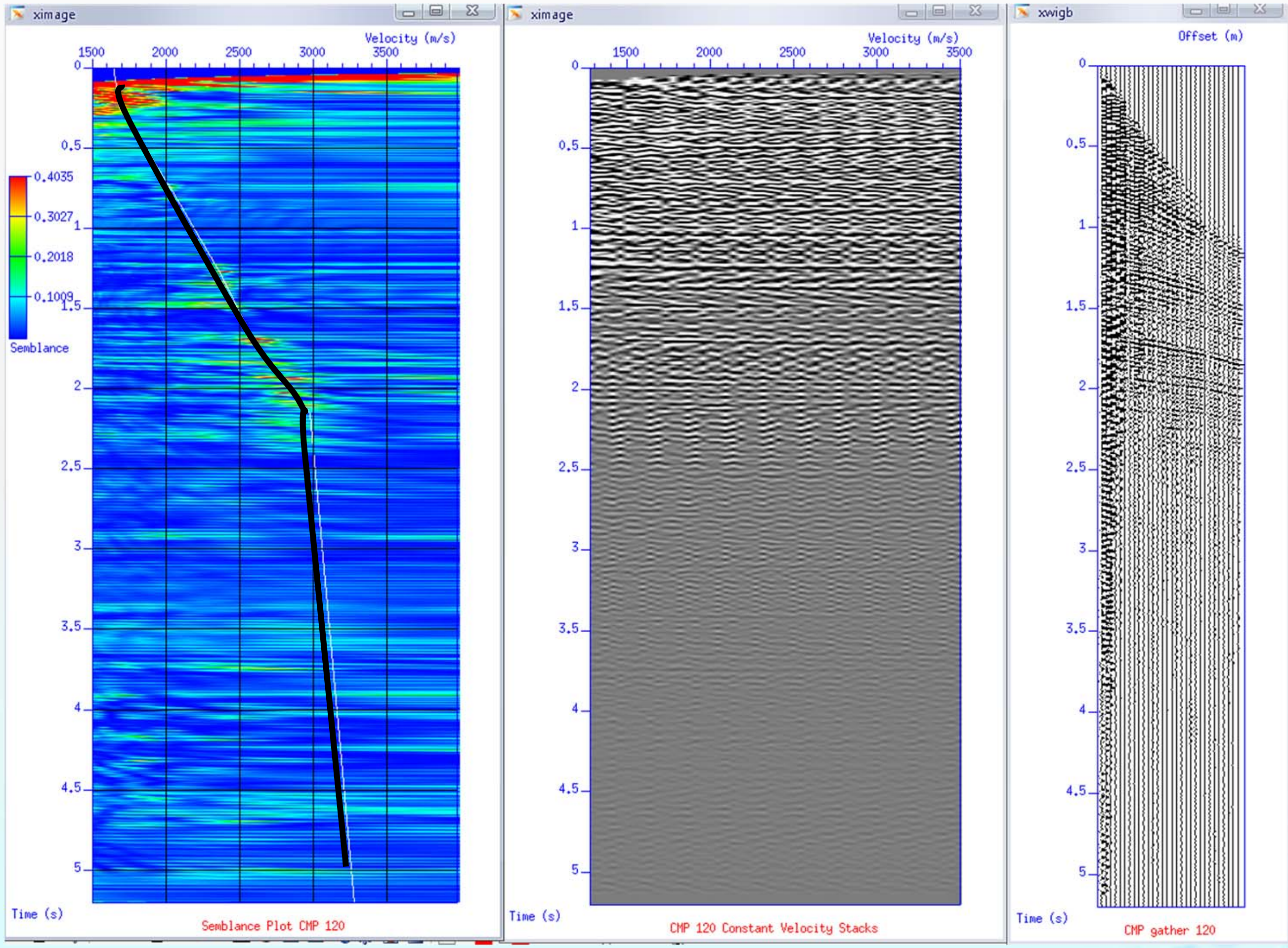
Pre-processing for FWI

- **Trace Editing**
- **Resample**
- **Frequency Analysis**
- **Band-pass Filter on Frequency Domain**
- **Spiking Decon.**
- **Mute Direct Wave**
- **Build Initial Model**

Noise Filtering and Suppression



Stacking Velocity Analysis: Semblance



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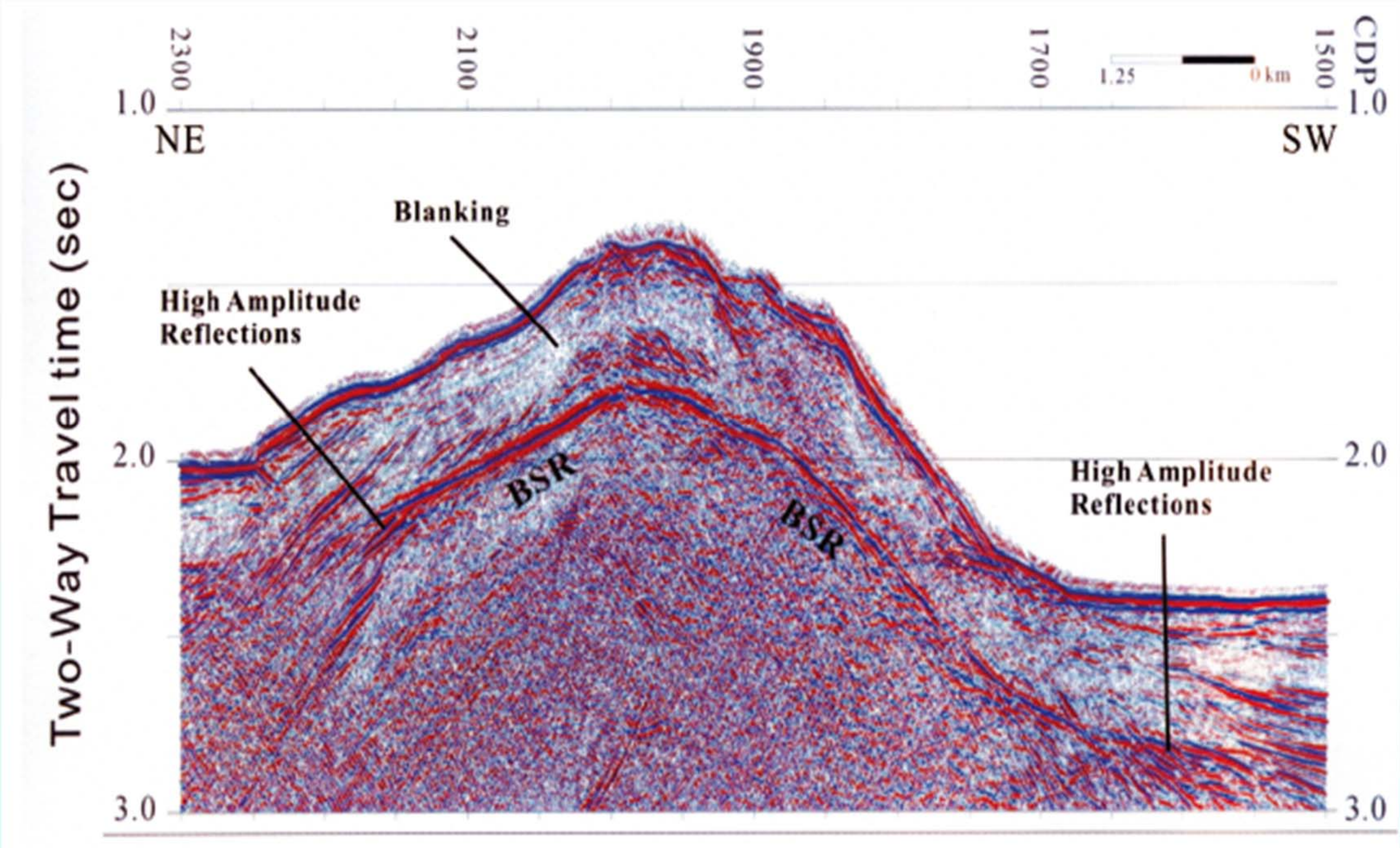
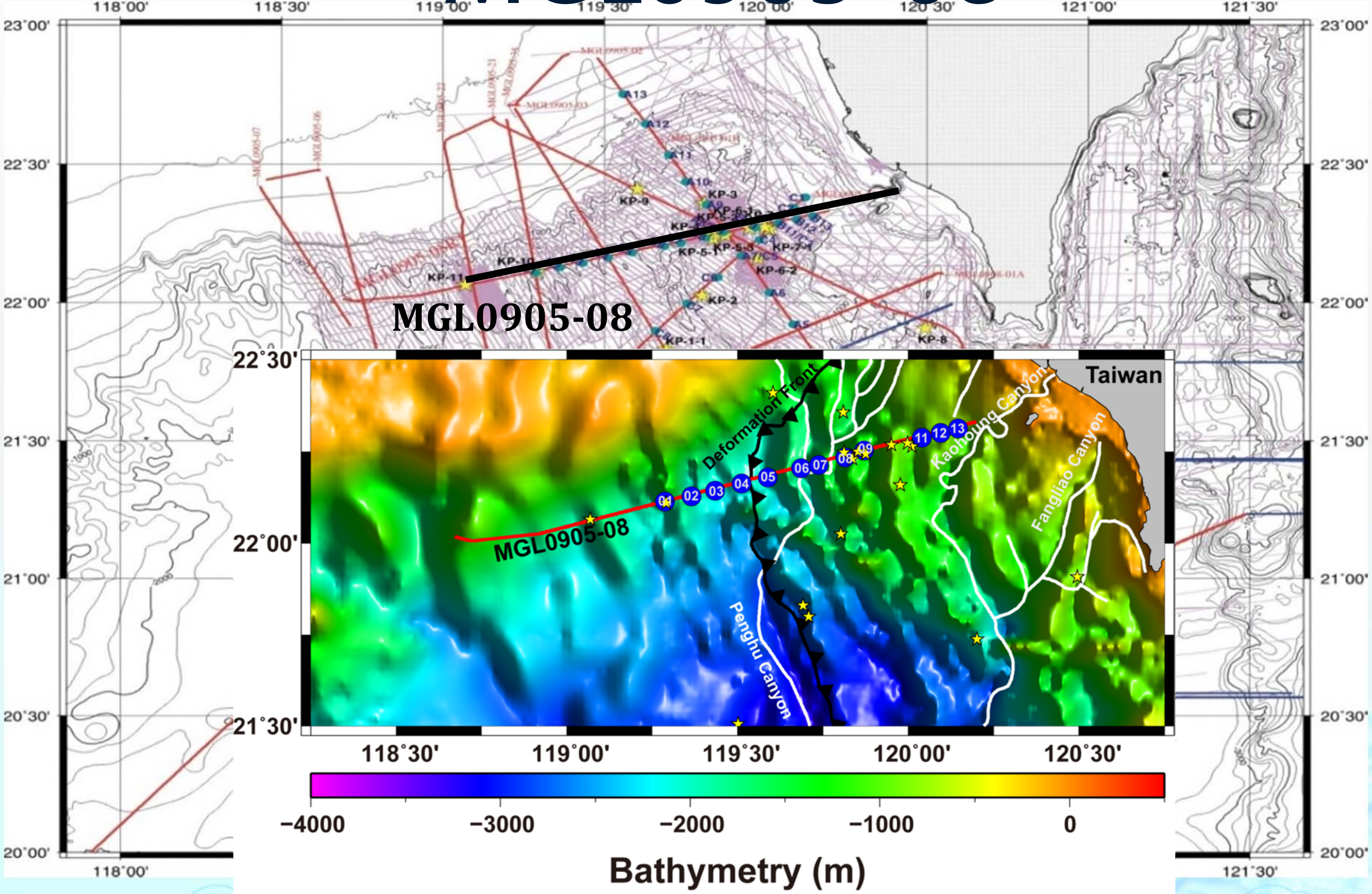
Bottom Simulating Reflector (BSR)



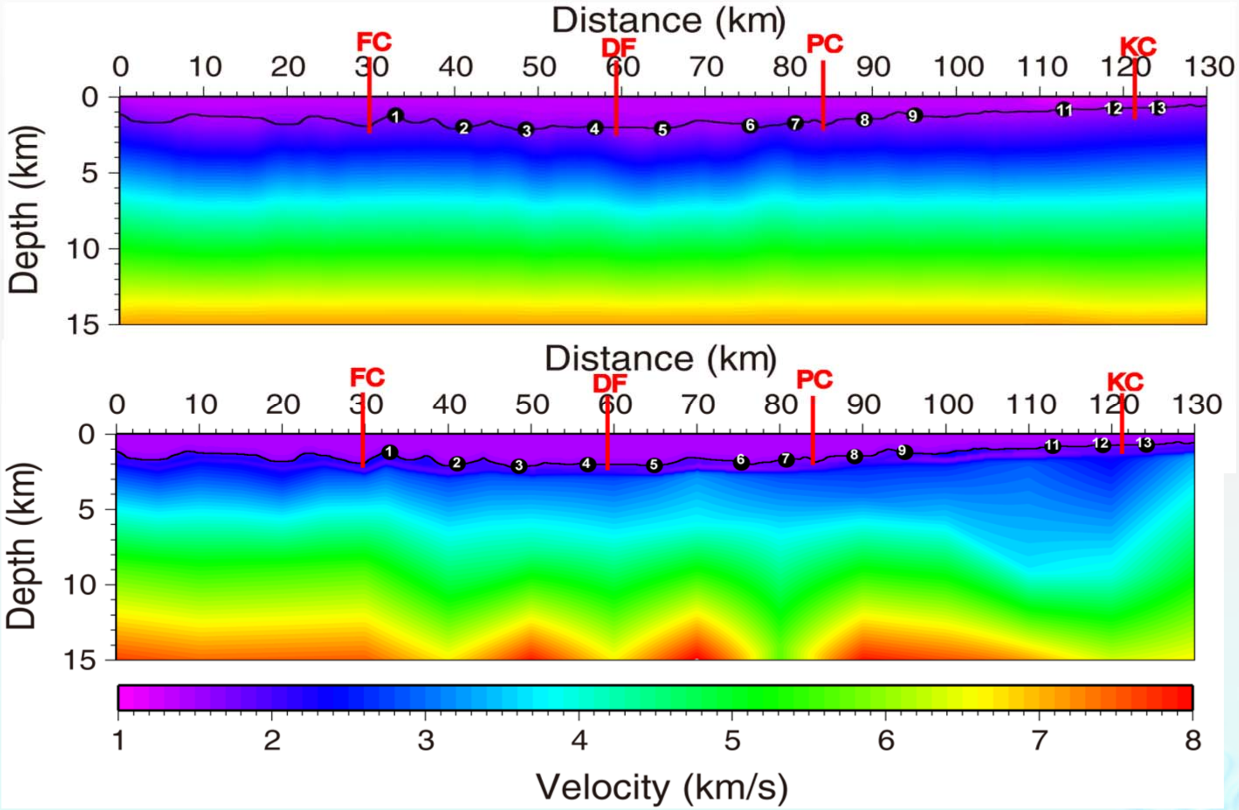
2009, Large-Offset MCS and OBSs, MGL0905-08



Two Initial Velocity Models

Semblance

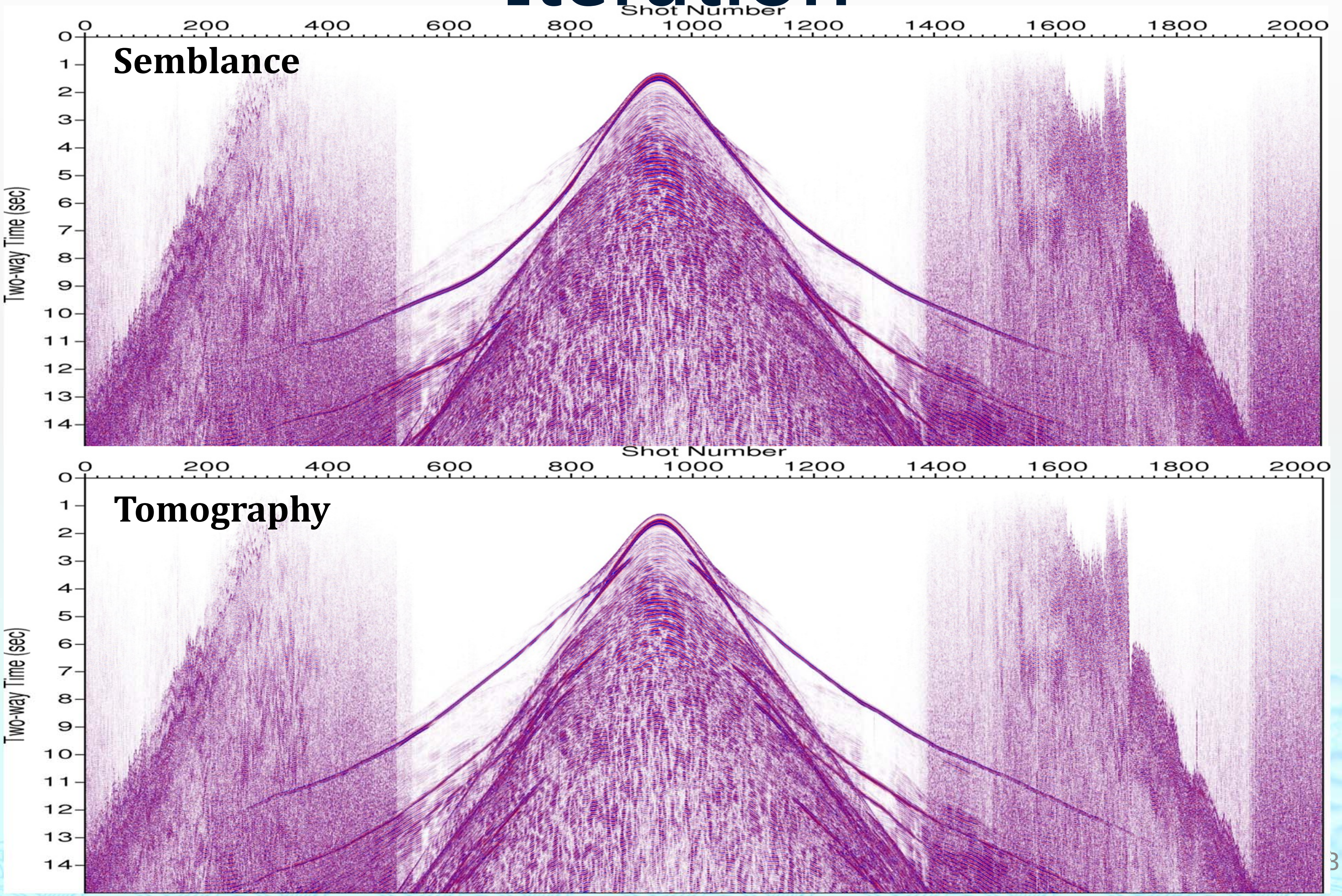
Tomography



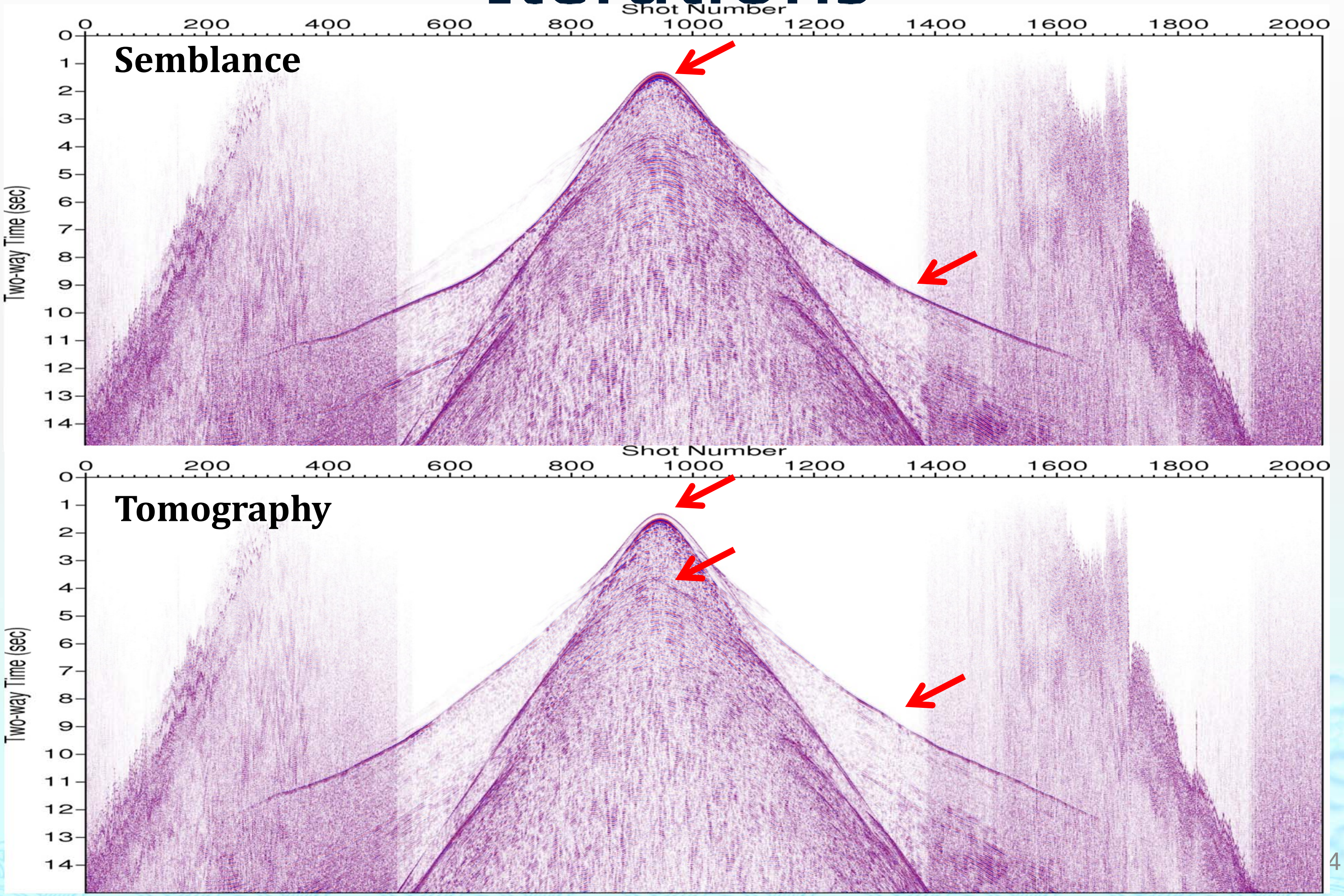
FC: Formosa Canyon; DF: Deformation Front; PC: Penghu Canyon; KC: Kaoping Canyon

Dominant Frequency: 7 Hz

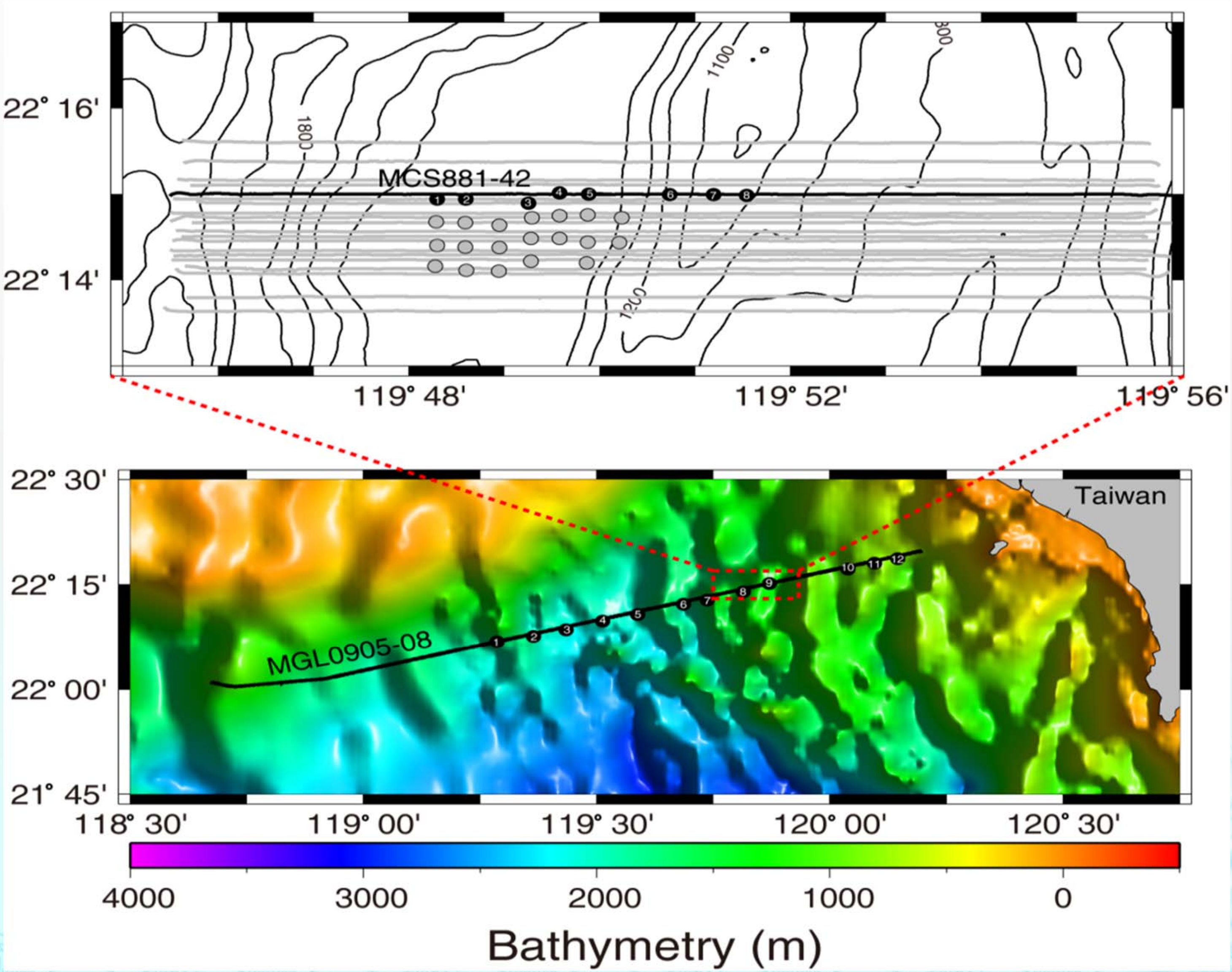
Residual Seismograms: First Iteration



Residual Seismograms: 20 Iterations

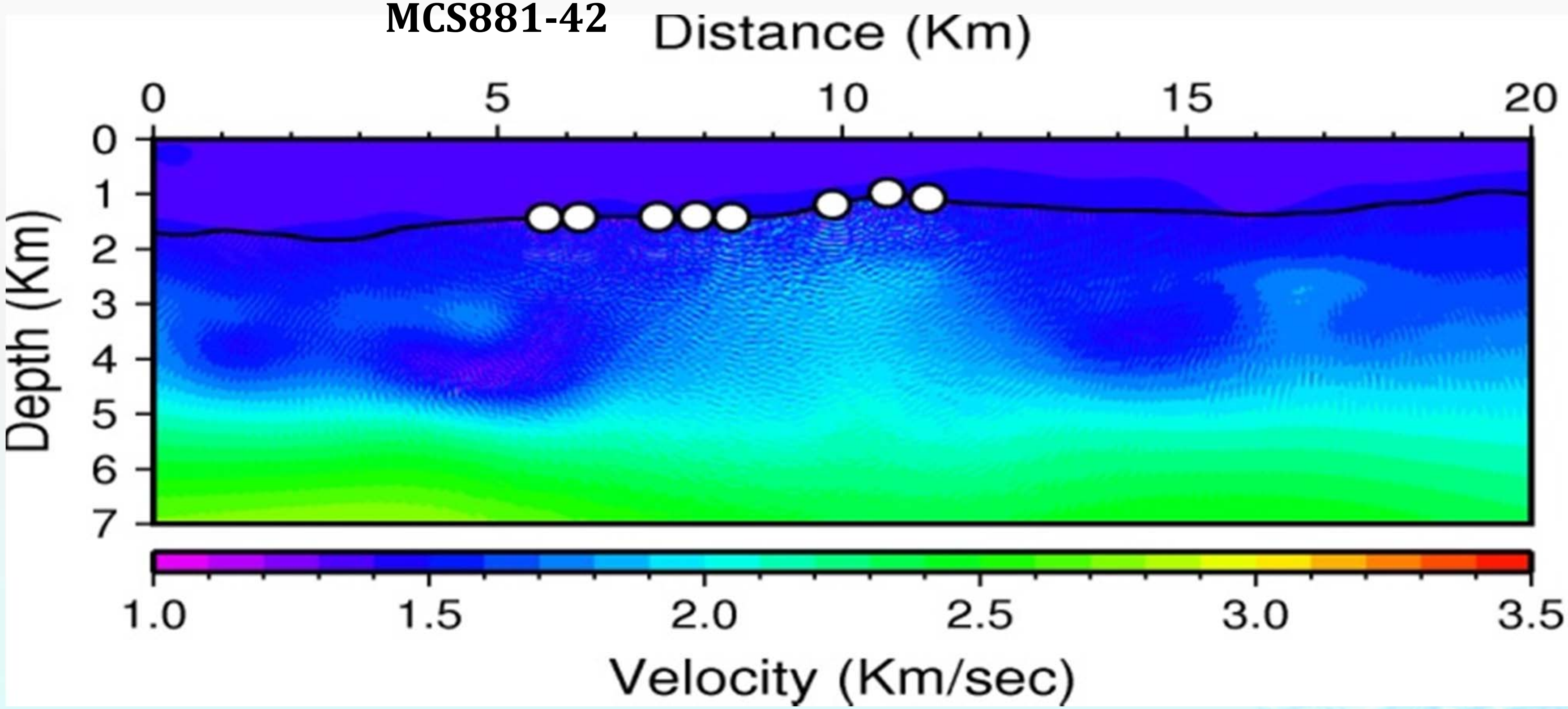


2009 3D OBS Survey, MCS881-42



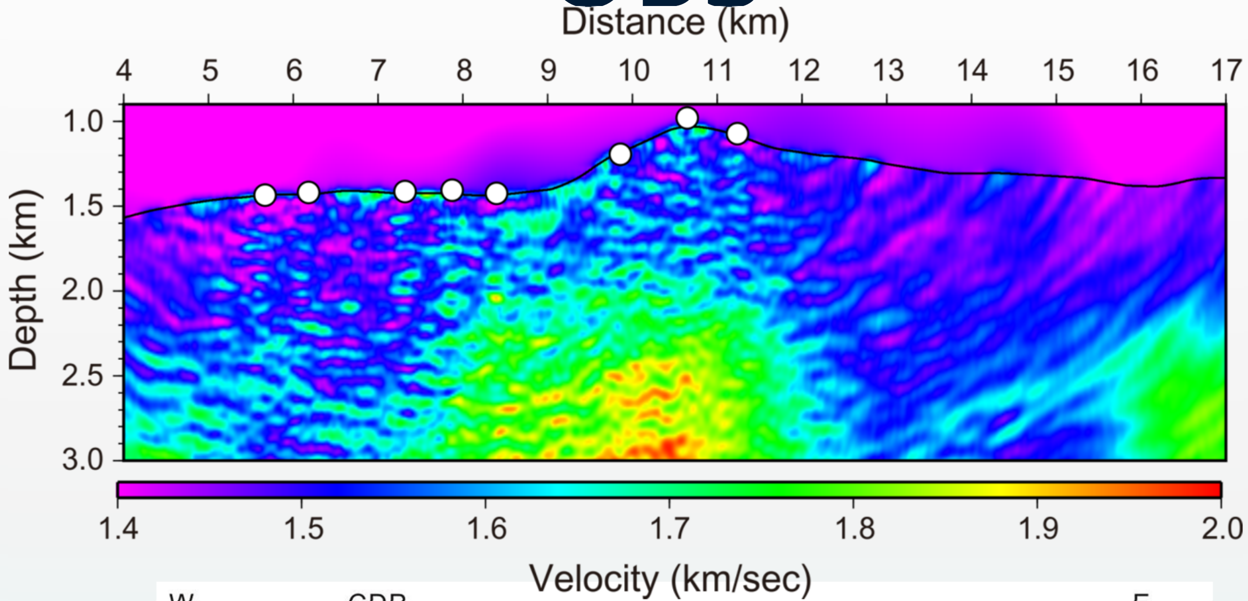
Results by Full Waveform Inversion: Multi-frequency, Vz Component

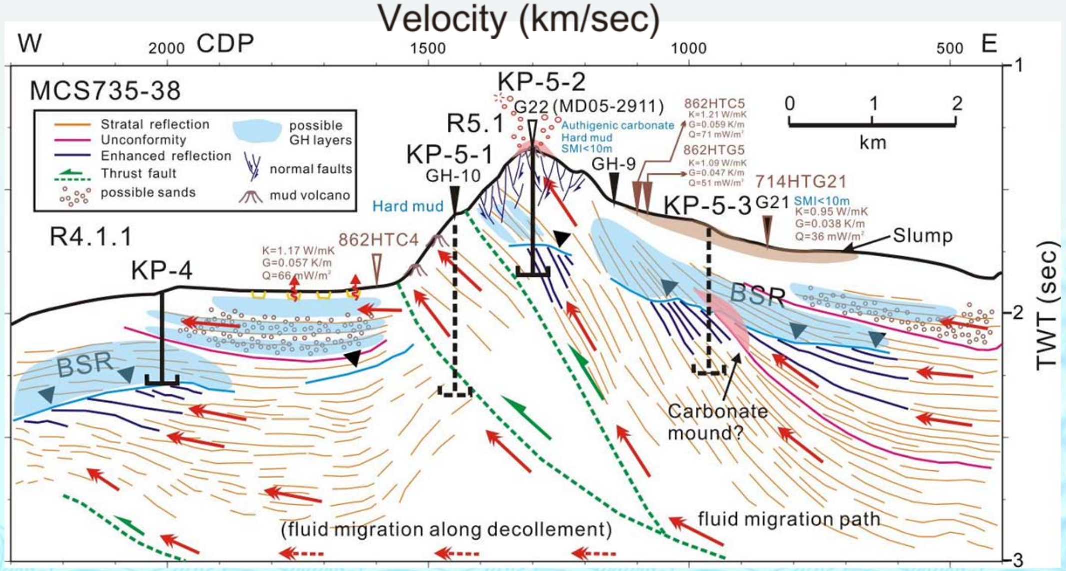
MCS881-42



Dominant Frequency: 3-12 Hz

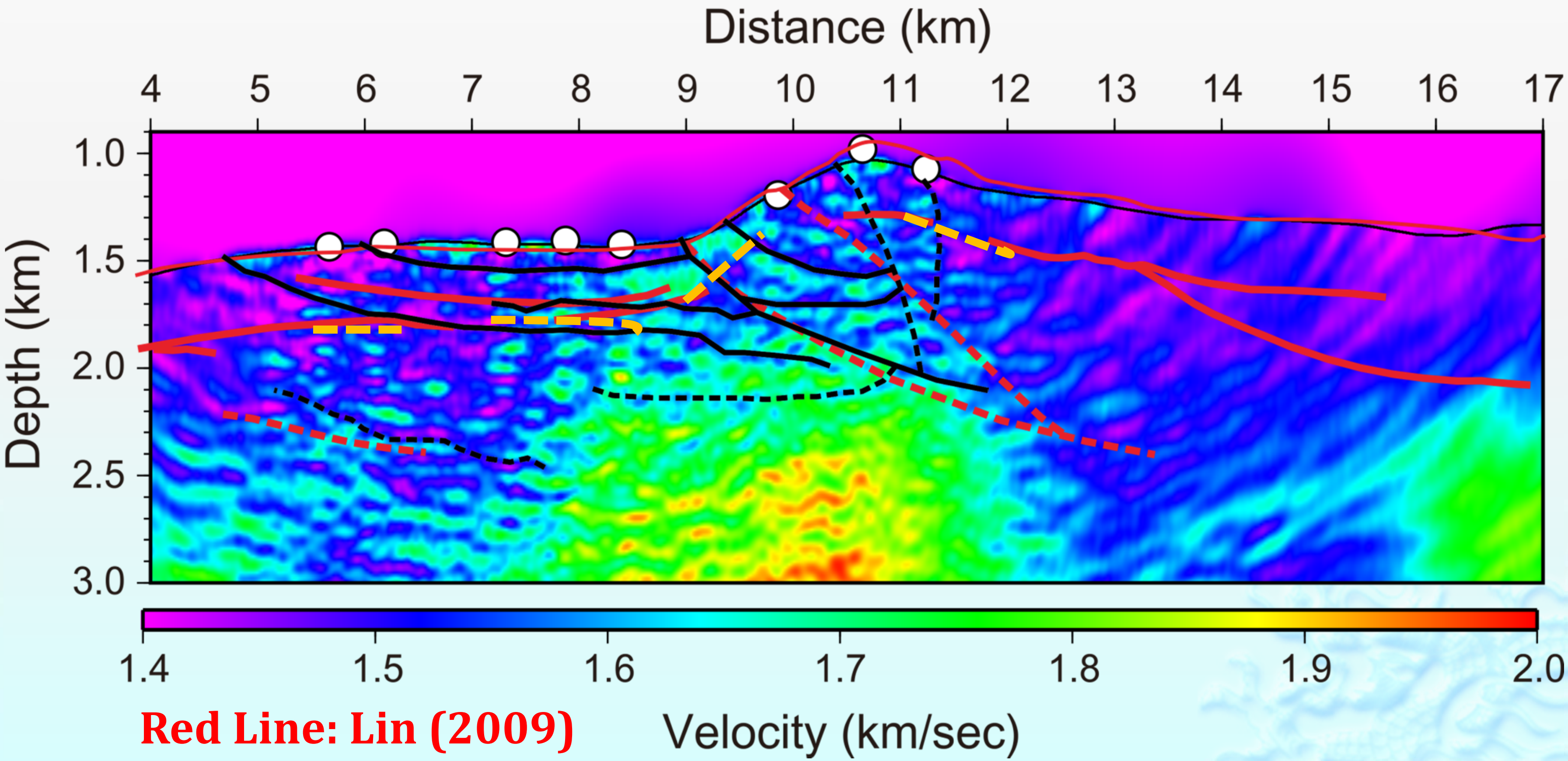
MCS881-42, FWI Result from OBS





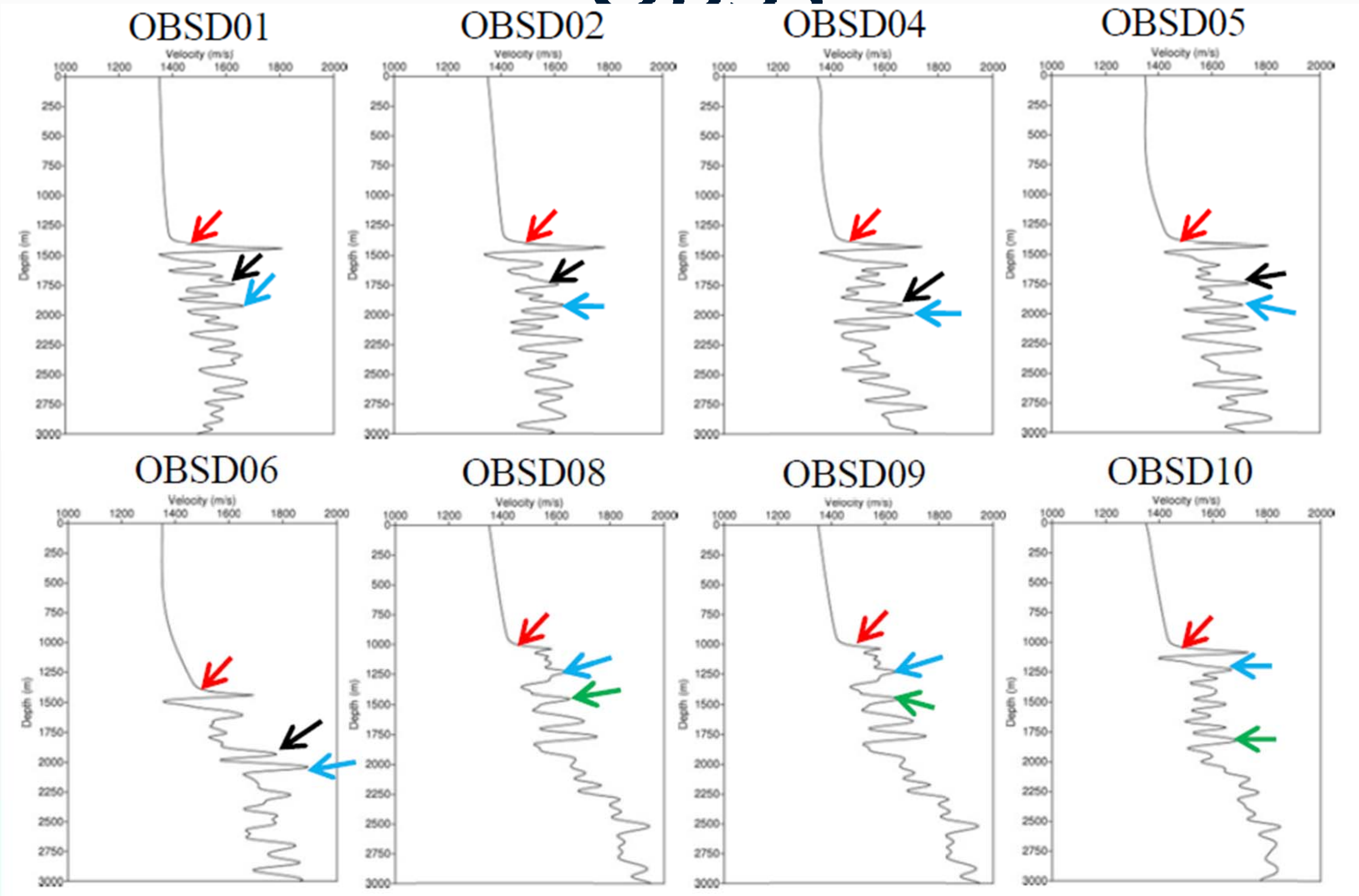
Lin (2009)

MCS881-42 FWI and Interpretation



Red Line: Lin (2009)

Velocity Functions Beneath Each OBSs



Velocity of BSR: 1.7 km/s; FG:1.4 km/s

Red: seafloor; Black: unconformity; Blue: BSR; Green: Fault

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Computation Cost for FWI

- **MS881-42 Velocity Model**
  - **Dimension: 20 km * 7 km(561 grid * 1601 grid)**
  - **dx=dz=12.5 m**
- **TDFWI**
  - **Number of time samples: 5000; dt=0.002 sec**
  - **8 OBSs, Need Total Memory of 126.4 GB**
  - **8 Cores with 15.8 GB/core**
  - **Need Disk Storage of 4.9 TB**
  - **3.77 hr/iter**
- **FDFWI**
  - **10 Frequencies (3~12 Hz)**
  - **8 OBSs, Need Total Memory of 37.57 GB**
  - **16 Cores with 2.35 GB/core**
  - **Need Disk Storage of 10 GB**
  - **0.67 hr/iter**

Conclusions and Discussions

- **Theoretical Development , Validation and Implementation for Field Data are Presented**
- **FWI is successfully applied to synthetic and practical examples.**
- **The Inversion is Well Suited for Parallel Inversion over Cluster Computing Environment.**
- **The image of Frechét kernels provide a unique opportunity in understanding the characteristics and limitations of reverse-time inversion and imaging strategy.**
- **The illumination analysis in terms of resolution for the targeted zone becomes important even during the survey planning stage.**
- **We apply spatial reciprocity relationship between vertical particle velocity wavefields generated by explosions (vertical geophone of an OBS) and pressure wavefields generated by a vertical force (air gun) for inversion strategy.**

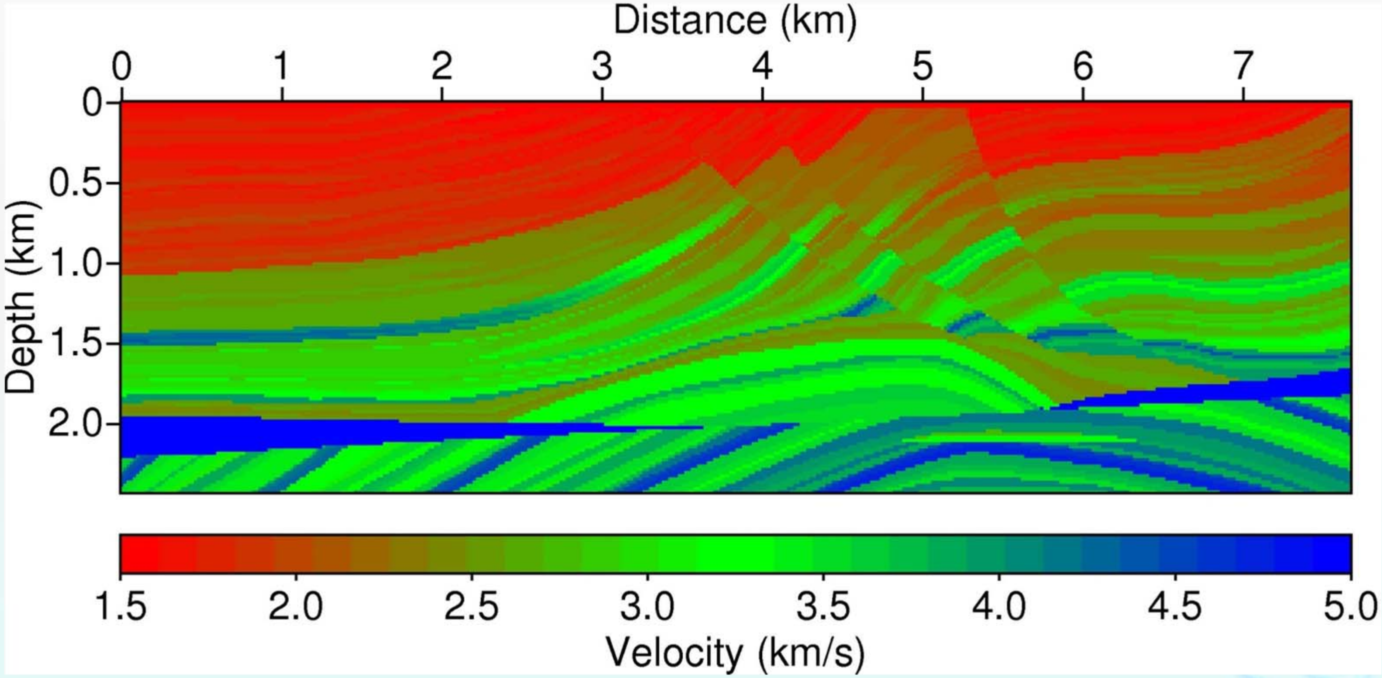
Conclusions and Discussions

- Multi-frequency or Multi-scale Strategy can Provide Better Resolution and Result with FWI
- FWI: Mitigation of Secondary Minima through Data Manipulation
  - Frequency hierarchy: from low to high frequencies (decimation)
  - Time windowing: from first-arrival phases to later phases
  - Space windowing: from low wavenumbers to high wavenumbers
- Practical Application of FWI to Seismic Line mcs881-42
  - Velocity of BSR: 1700 m/s
  - Depth of BSR: 200-500 m
  - Velocity of FG: 1400 m/s
  - Resolution: 58-333 m(Velocity Range:1400-2000 m/s)
- Geology and Tectonic Interpretation of mcs881-42
  - Depth of BSR, Formation Boundary and Unconformity
  - Low/High Velocity Zones for Gas-hydrate
  - Identification of Faults and Sediments
- Effectively identify velocity and location of BSR and FG
- Resolution of FWI Depends on the Source Wavelet, Dominant Frequency, Bandwidth and Shot/Receiver Interval

Split-step Plane Wave Waveform Inversion

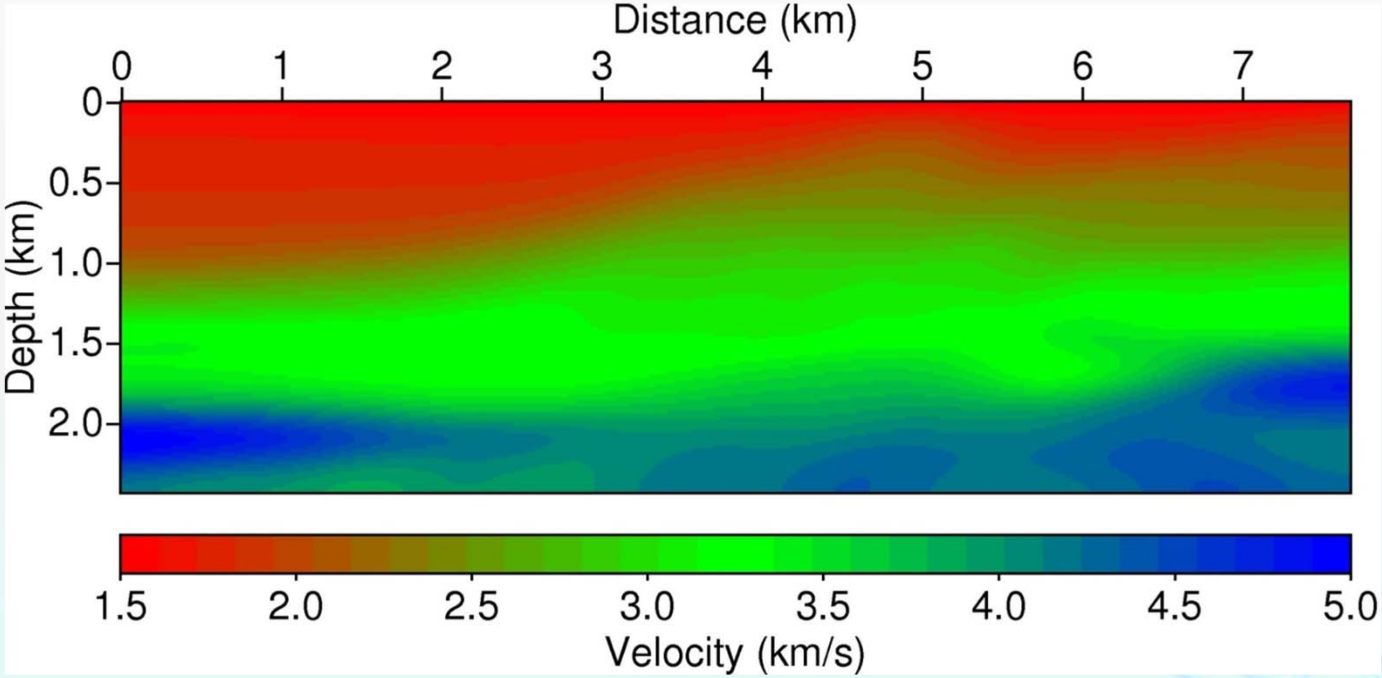
Kun-Sung Li, How-Wei Chen and Paul Stoffa

Marmousi Velocity Model



nx=384, nz=122, dx=dz=0.02 km, dt=0.004, nt=800

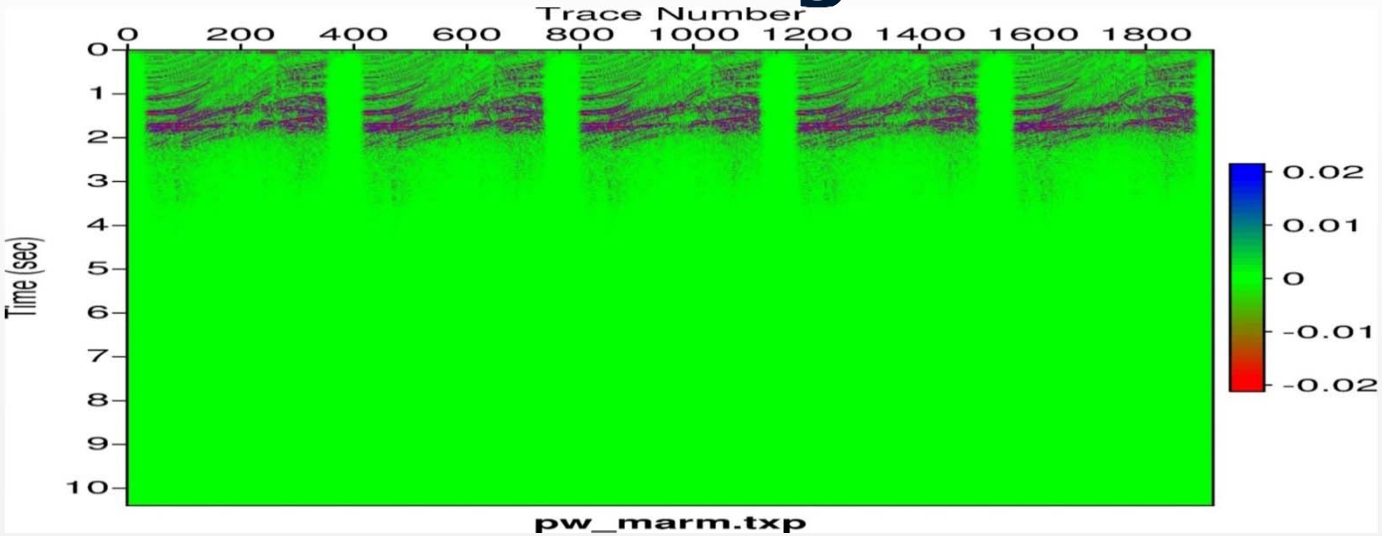
Initial Velocity Model



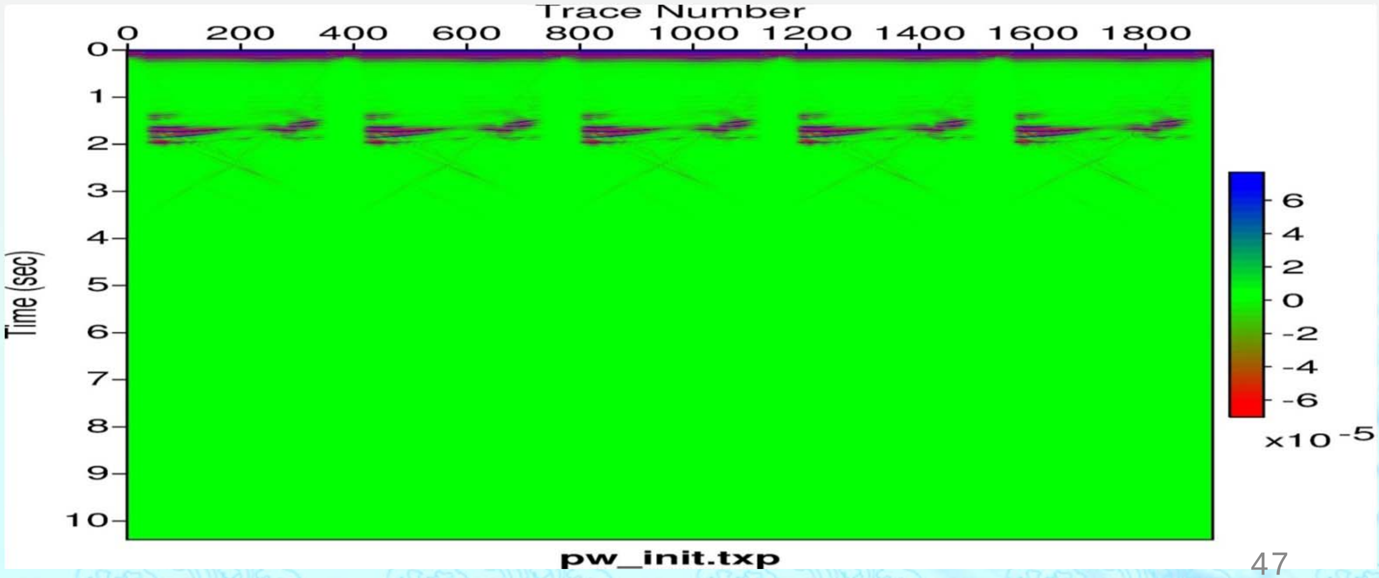
nx=384, nz=122, dx=dz=0.02 km, dt=0.004, nt=800

Marmousi (5 Ray Parameters) and Initial Models' Seismograms

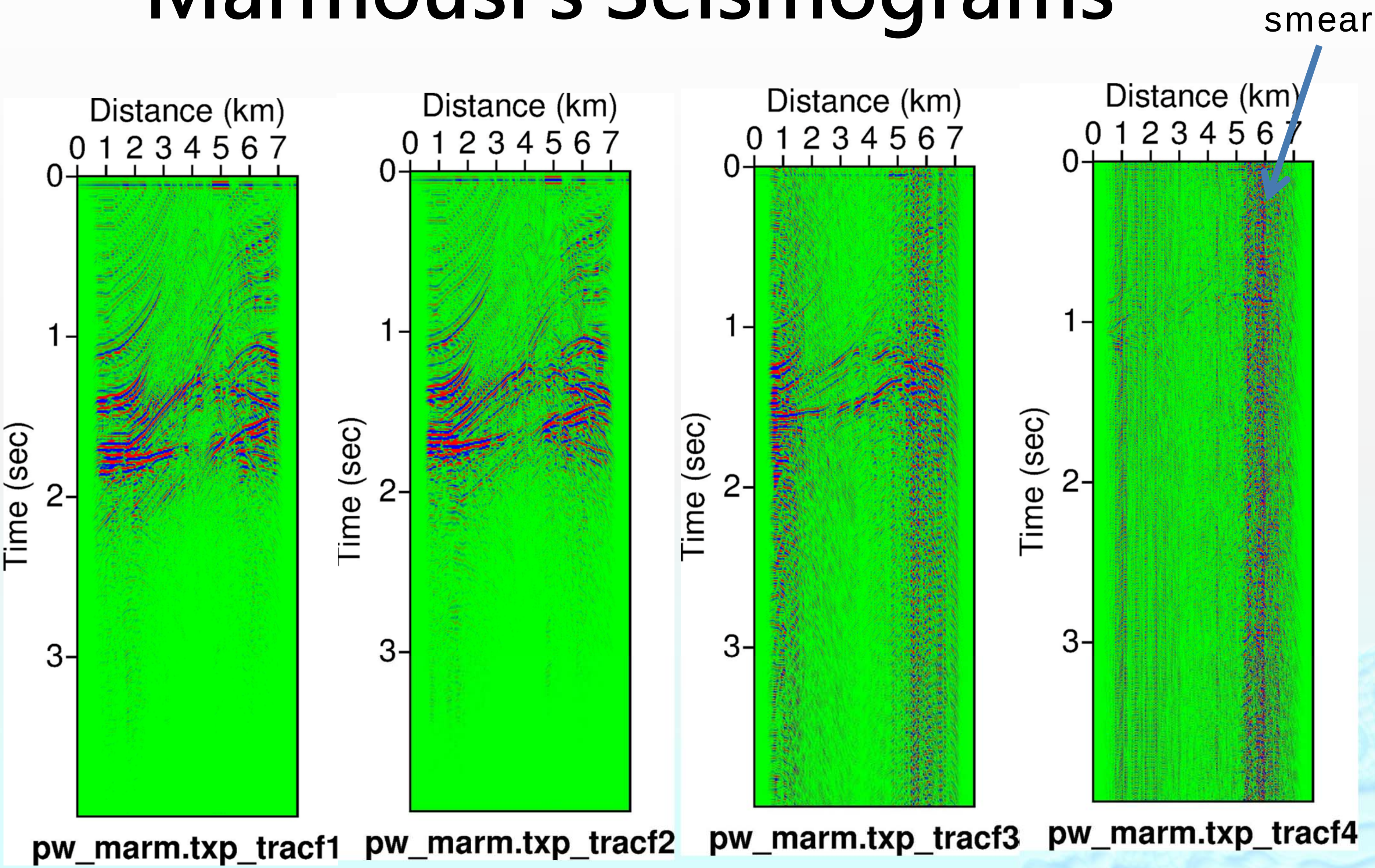
Marmousi



Initial



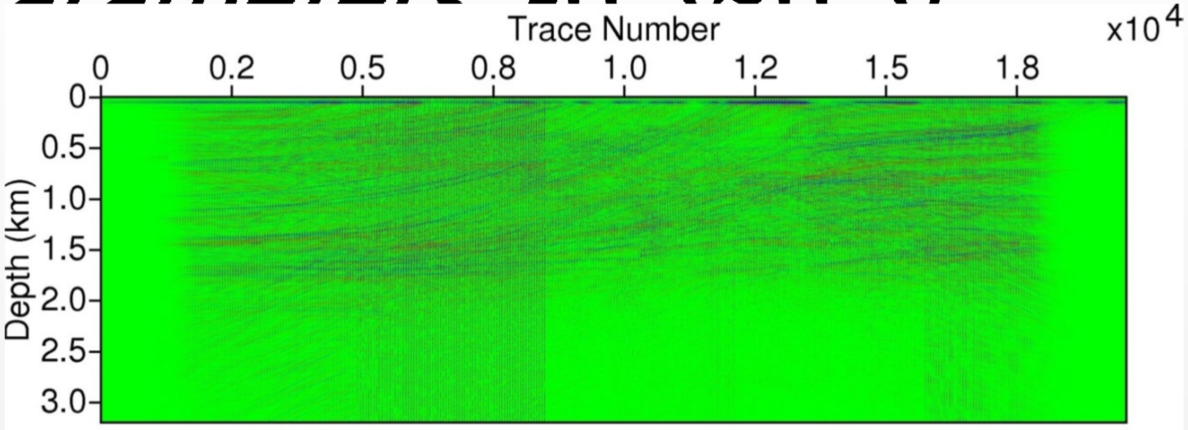
Marmousi's Seismograms



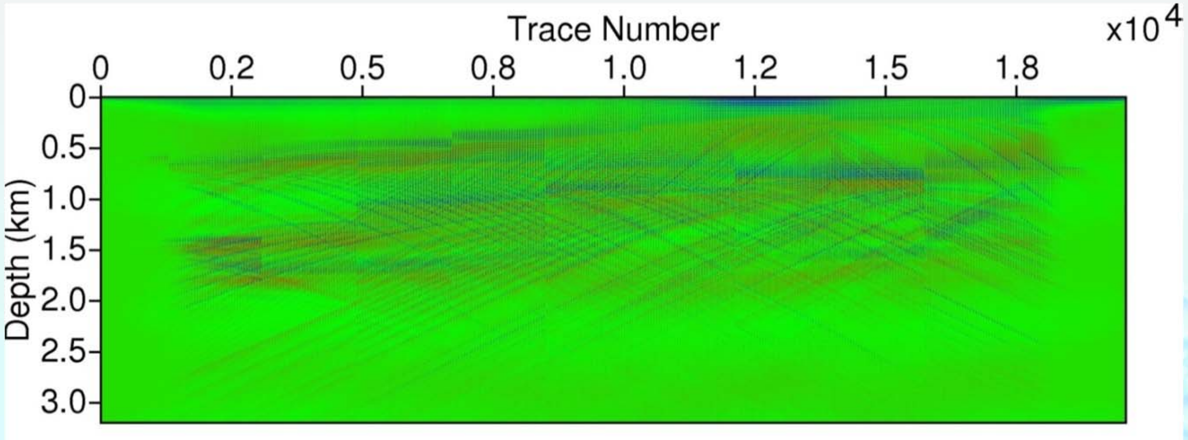
p=0.0 **p=0.1** **p=0.2** **p=0.3**

Marmousi and Initial Models' Seismograms (Ray Parameters: -0.5~0.5)

Marmousi

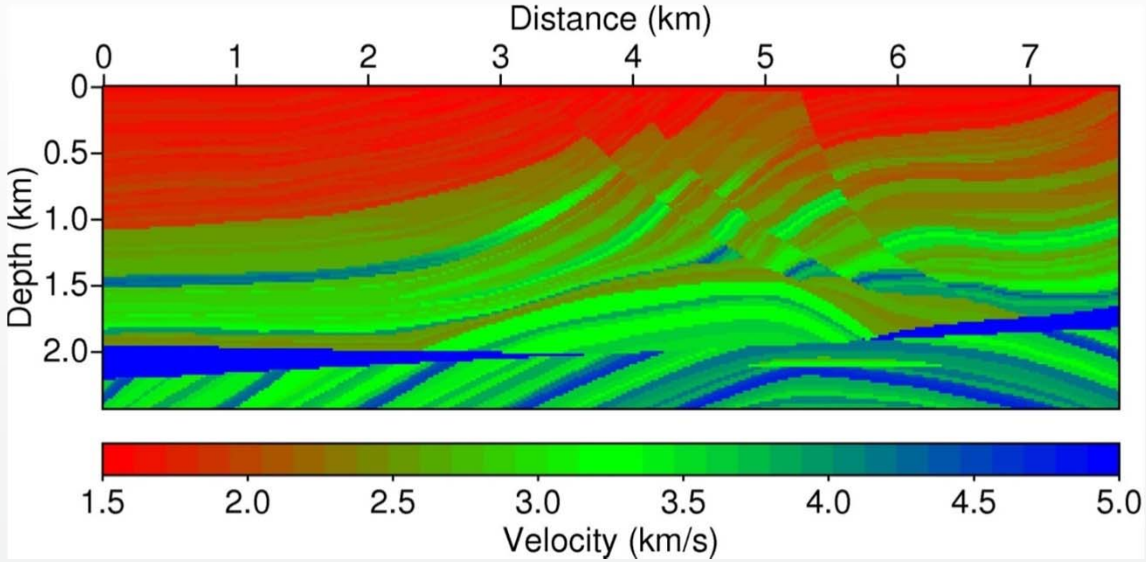


Initial

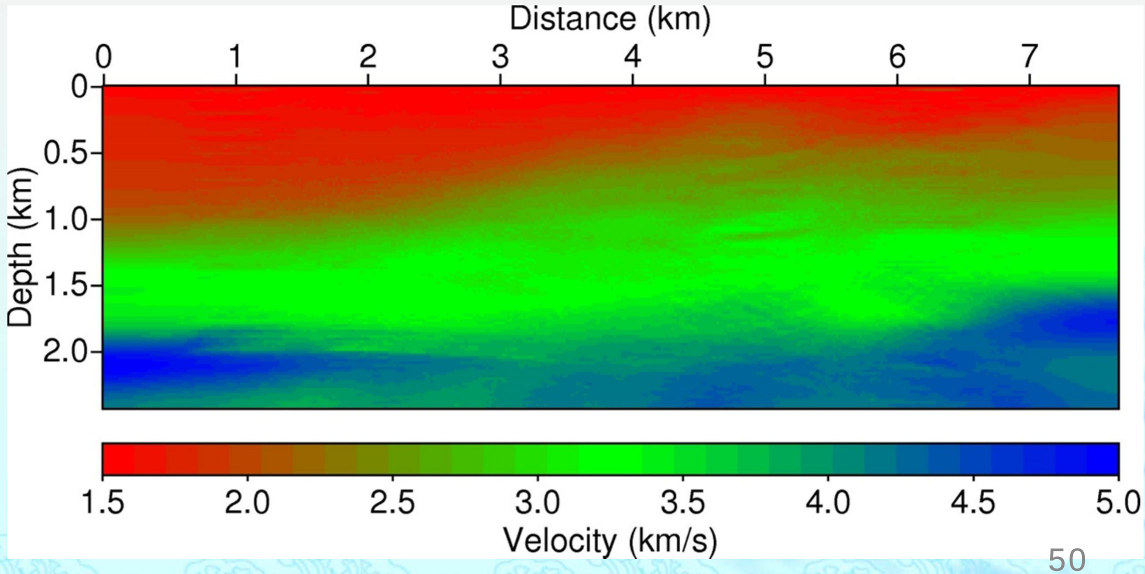


Marmousi Model vs Updated Model

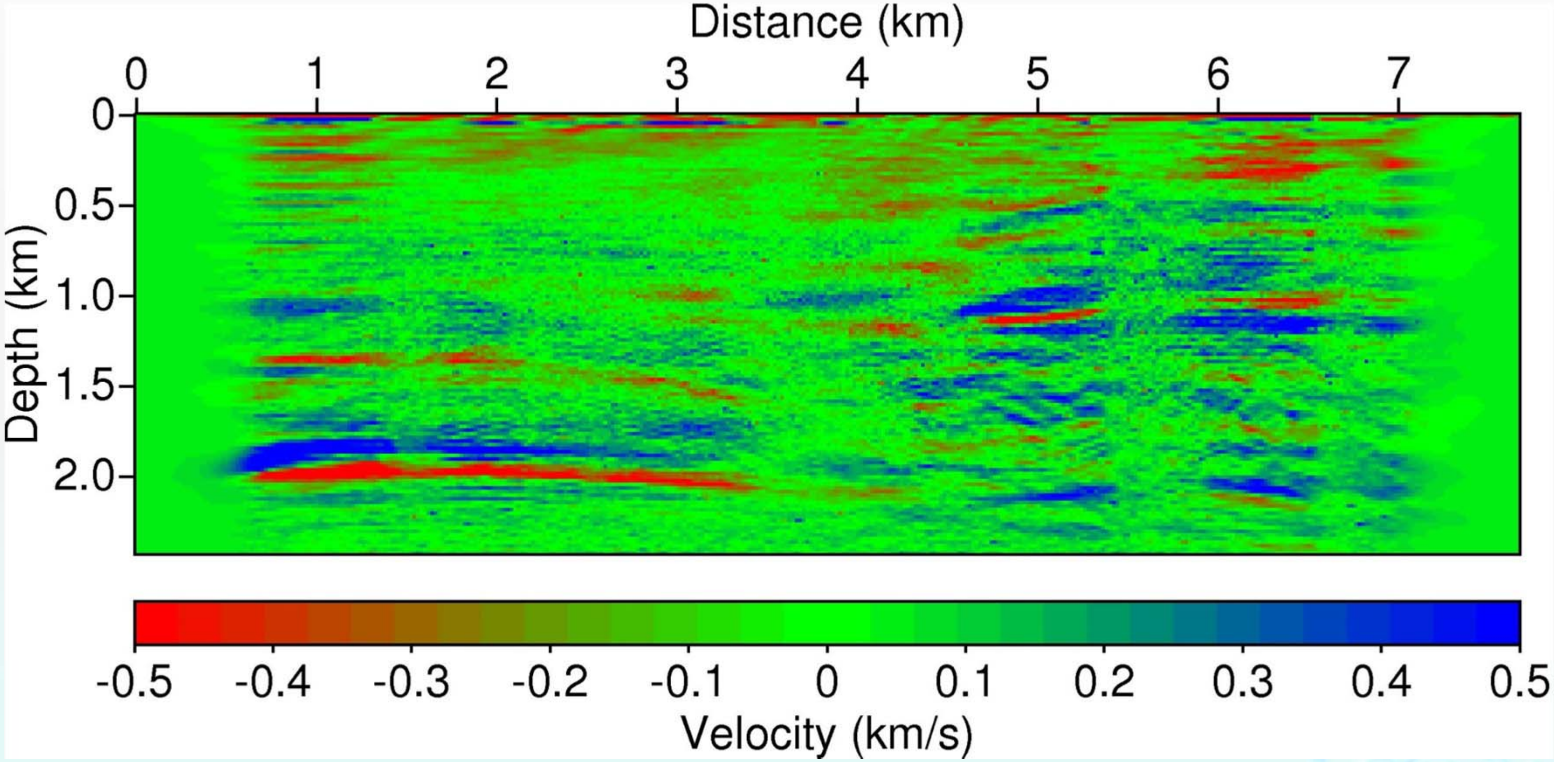
Real



Inverted



Velocity Difference



75 Iterations, 3 Hours, 2.4 min/iter

Thank You for Your Attention.

The Future Development of FWI

- Survey planning and Instrumentation
- Non-linear Algorithm and Optimization Methods
- Multi-component, Multi-attribute and Multi-parameter Full Wavefield Inversion

Acknowledgements

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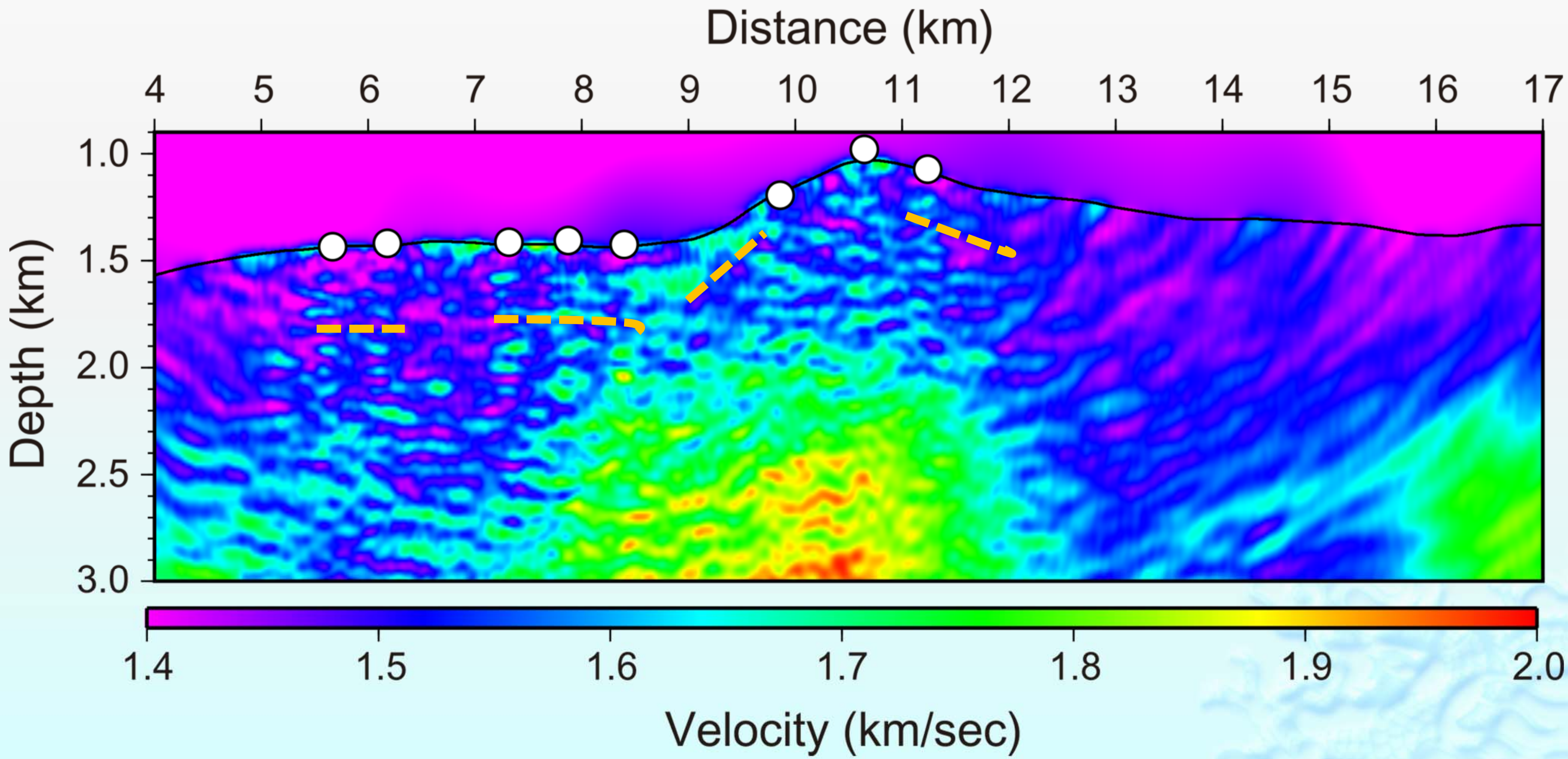
- Profs. C. S. Lee ,T. K. Wang and Technical Group for Providing Four-Component OBS Data


Distance (km)
4
5
6
7
8
9
10
11
12
13
14
15
16
17
1.0
1.5
2.0
2.5
3.0
Depth (km)
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Velocity (km/sec)