WAVEFORM TOMOGRAPHY AND ITS APPLICATION TO MARINE SEISMIC REFRACTION DATA

Sreeja Nag[1,2], J.P. Canales[2]

sreejanag@gmail.com

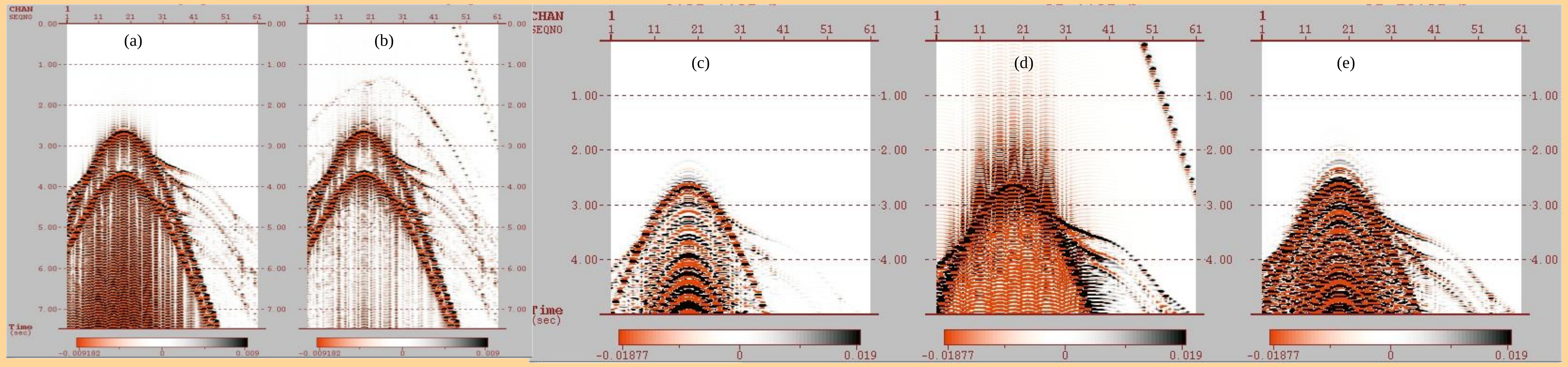
[1]Indian Institute of Technology, Kharagpur, India, [2]Woods Hole Oceanographic Institution, Massachusetts, U.S.A.

INTRODUCTION

We explore the applicability of two-dimensional seismic waveform tomography to conventional deep-water, long-offset (10s of kilometers) seismic refraction experiments in which ocean-bottom receivers and sea-surface sources are usually spaced several kilometers and a few 100s of meters apart, respectively. In particular, we test the application of waveform tomography to ocean-bottom seismometer (hydrophone) data collected along the rift valley of the Mid-Atlantic Ridge near 26°N in the vicinity of the active TAG hydrothermal system, which is thought to be located on the hanging wall of an active oceanic detachment. If successful, waveform tomography could provide detailed velocity information related to fluid flow and alternation along the fault zone that cannot be obtained from traveltime tomography analyses. We use the frequency-domain, elastic-wave equation approach of R.G. Pratt. Source and velocity inversion is done at selected frequencies using "efficient waveform inversion" to minimize the misfit of data residuals via the gradient method.

FORWARD MODELING

Boundary conditions = All absorbing with Sponge
Maximum Frequency : 15 Hz
Minimum velocity (water) = 1500 m/s
Min. Wavelength = 100m
Grid interval = 100/4 = 25m
Total grid size = 961 by 321 for area of 24km by 8km
Total time = 7.5s
Frequency interval = 0.133Hz
Number of frequencies = 112
Time domain sampling = 10ms
Time domain damping = 0.4X7.5 = 3s
Source signature = Keuper wavelet,dominant freq = 40Hz
Velocity model = From Travel time Tomography
Density Model = Carlson Model 1*(Carlson&Ruskin 1984)*
Attenuation Model : Q=50 for V<6.5km/s, Q=120 forV>6.5km/s
Base Frequency = 0.04Hz



OBS 55 :(a) Synthetic forward modeled seismograms using damping parameter = 0.5s, Tmax = 7.5s and 112 frequencies. Top surface has free surface condition. (b) Damping constant is 3s, other parameters same as (a). (c) Synthetic seismograms with a full absorbing boundary, damping constant 0.5s, maximum modeled time of 7.5s and 112 frequencies. Unrealistically high amounts of energy arriving at later times render this model undependable (d) Damping constant = 3s, all other parameters same as (c). A distinct wraparound of energy arriving till 3s after the maximum modeled time of 7.5s is seen. (e) Max. Time = 10.5s, 157 frequencies, damping=3s. Modeling more frequencies and longer times decreases aliasing to a great extent too. A suitable value of damping and modeled time reduces wraparound *and* yields realistic synthetics. No attenuation model included.

The 2D, frequency domain acoustic wave equation is given by [e.g. Aki and Richards, 1980] :-

$$\omega^2 \frac{P(x,z)}{K(x,z)} + \frac{\partial}{\partial x}\left[\frac{1}{\rho(x,z)}\frac{\partial P(x,z)}{\partial x}\right] + \frac{\partial}{\partial z}\left[\frac{1}{\rho(x,z)}\frac{\partial P(x,z)}{\partial z}\right] = -S(x,z) \quad \text{...Equation (1)}$$

where P = Pressure, ρ=density, K=bulk modulus, S=Source. (via OMEGA)

The inverse problem (via software FULLWV) would minimize the objective function given by Equation (2).

If we expand, by Taylor's series, the resultant change in the misfit/objectivefunction is given by Equation (3).

$$E(m) = \frac{1}{2}\delta d^t \delta d^* \quad \text{...Equation (2)} \qquad E(m+\delta m) = E(m) + \delta m^t \nabla_m E(m) + \frac{1}{2}\delta m^t H \delta m + O(\|\delta m\| \quad \text{...Equation (3)}$$

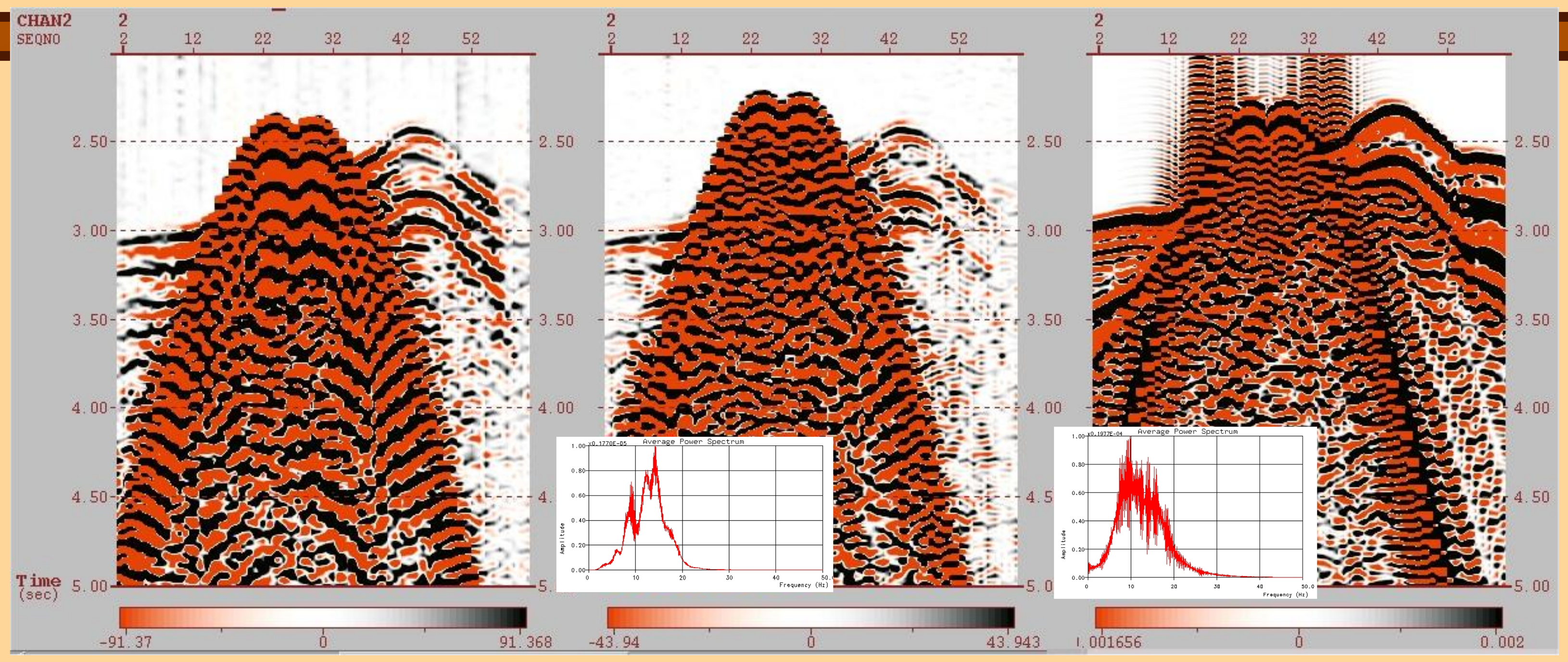
Using the concept of virtual sources and assuming source-receiver reciprocity to hold

$$\nabla_m E(m) = J^T \delta d = F^T \left[S^{-1}\right]^T \delta d \qquad \nabla_m E(m) = F^T v \qquad v = [S^{-1}]^T \delta d = [S^{-1}]^* \delta d \quad \text{...Equation (4)}$$

v can be called a "backpropagated wave"or a forward model with sources placed at receiver locations having magnitudes equal to data residuals at those receivers.

DATA PROCESSING

- Multiples beyond an arrival time of 7.5s were muted. Time reduced seismogram for velocity = 6km/s was used.
- Spherical Divergence was corrected for using time-dependent correction , V_o depends on the value of V=1500m at t=0.
- Seismogram was wavelet-shaped as response to a minimum-phase Butterworth wavelet (length 300ms, df= 2Hz to 45Hz)
- Predictive deconvolution operators were designed individually for each of the OBS gathers using a window of 1s around the first arrival far-offset, seismic refraction energy. Specifications: Operator length = 90 points, predictive delay = 50 samples, bandwidth = 2Hz to 45Hz and 0.1% spectral whitening.
- Low-pass filtered using a Butterworth filter (length 51 points, lower order =3, higher order=6 , bandpass = 2Hz to 15Hz)
- Front-end noise, mostly instrument related, before the first arrivals are muted for reduced time earlier than 1.75s.
- The direct water wave is muted so that the inversion procedure specifically uses the large-offset, crustal refracted energy to fit the model.
- Maximum modelled time =10.5s for an input into inversion.
- Offset-dependent amplitude scaling is done on the observed data in appropriate ratio with the forward modelled data on the Traveltime model.



OBS 16, 61 shots. (a) Undeconvolved but processed data. (b) Processed, deconvolved data (c) Forward modeled data. The bubble pulse which interferes with the second arrival in the Observed seismogram is considerably removed by deconvolution. This second arrival now correlates with the second arrival of the synthetic seismogram. Deconvolution makes the arrivals more distinct. Inset shows the amplitude spectrum of the seismograms, and the removal of the notch at 10Hz due to deconvolution.

REFERENCES

A.J. Brenders and R.G. Pratt, Full waveform tomography for lithospheric imaging : results from a blind test in a realistic crustal model, *Geophys.J. Int.*, 168, 133-151, 2007.

J.P. Canales et al., Crustal structure of the Trans-Atlantic Geotraverse (TAG) segment (Mid-Atlantic Ridge, 26° 10'N): Implications for the nature of hydrothermal circulation and detachment faulting at slow spreading ridges, *Geochem. Geophys. Geosyst.*, doi:10.1029/2007GC001629

R.G. Pratt et. al. Gauss Newton and full methods in frequency-space seismic waveform inversion, *Geophys.J. Int.*, 133, 341-362, 1998.

L. Sirgue and R.G. Pratt, Efficient waveform inversion and imaging : a strategy for selecting temporal frequencies, *Geophysics*, 69, 231-248, 2004.

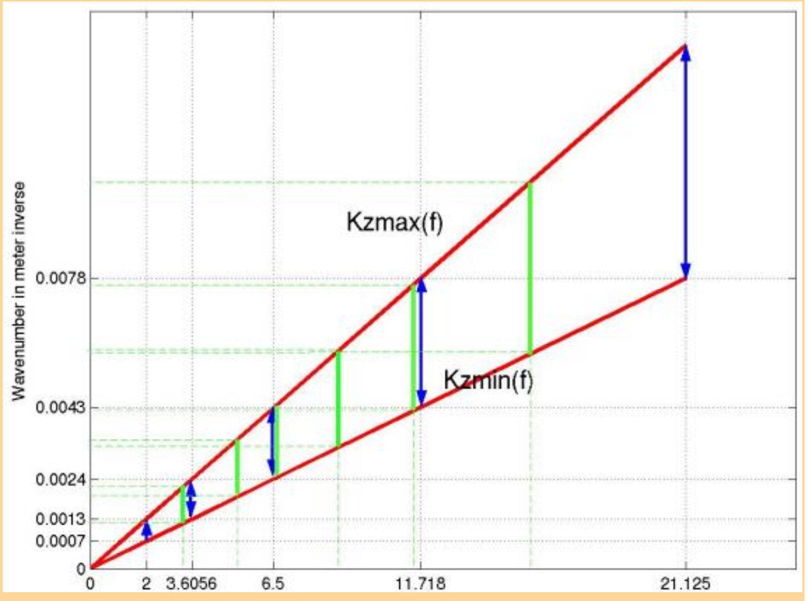
S. Operto et. al., Crustal seismic imaging from multifold ocean bottom seismometer data by frequency domain full waveform tomography : Application to the eastern Nankai trough, *Journal of Geophysical Research*, Vol. 111, B09306, 10.1029/2005JB003835, 2006.

W.S.D. Wilcock et. al., Seismic attenuation structure of the East Pacific Rise near 9°30'N, Journal *of Geophysical Research*, 100, B12, 24147-24165, 1995.

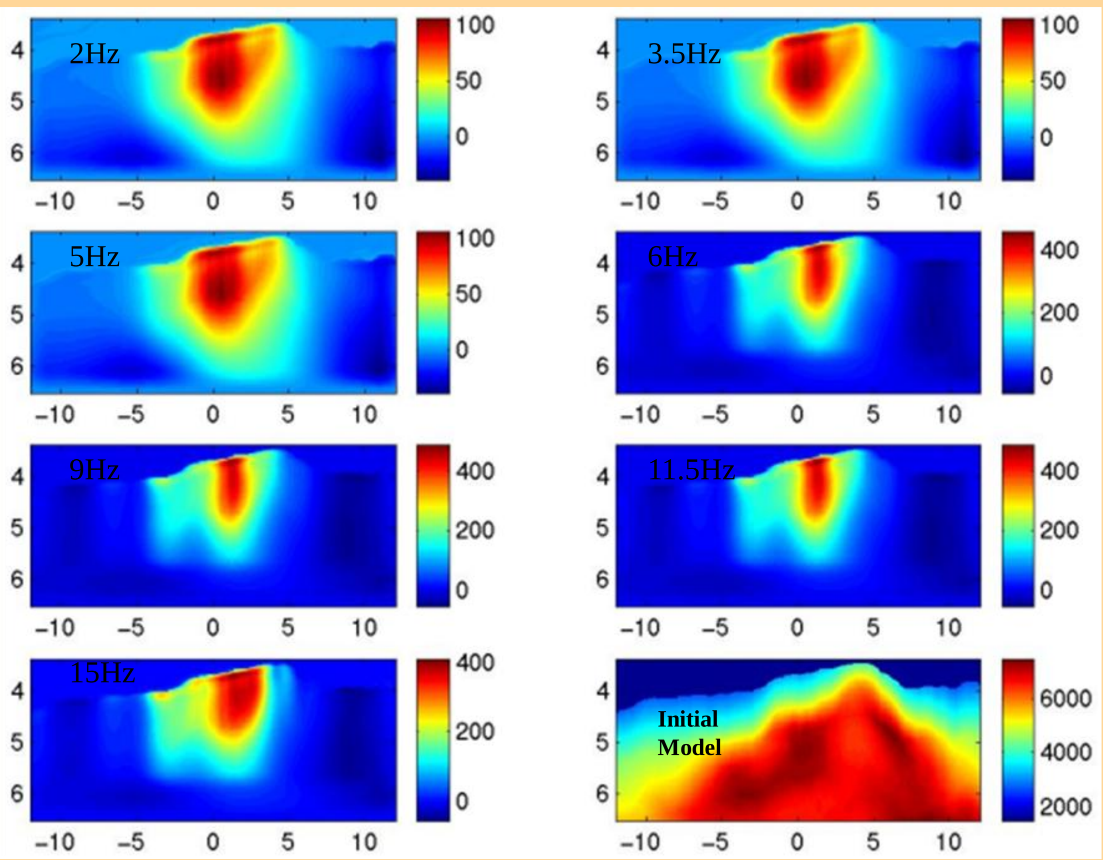
INVERSION

- Source inversion done and amplitude and phase Inverted source is used.
- For 7 sequential frequencies, the monochromatic component from the direct water wave, muted Observed Data is extracted.
- A background velocity model of 4km/s with appropriately calculated rho, Q is used to form forward data that is subtracted from each run of the forward model before calc. residuals. This concentrates residuals to the high k components + removes direct wave
- Gradient method of inversion, Conjugate gradient for Hessian approx.
- 20 loops per frequency OR minima of Misfit function
- Offset weight = 7km-8km-20km-30km
- Depth weighting = 0-0-6km-6.5km. Gradient is tapered outside of this.
- Gradient Masking :Gradient value above the sea-floor topography forced null.
- Gradient Filtering : Starting with λ(min_x)=5km, λ(min_z)=500m for 2Hz, band of k-filter increased to λ(min_x)=1km, λ(min_z)=20m for 15Hz.

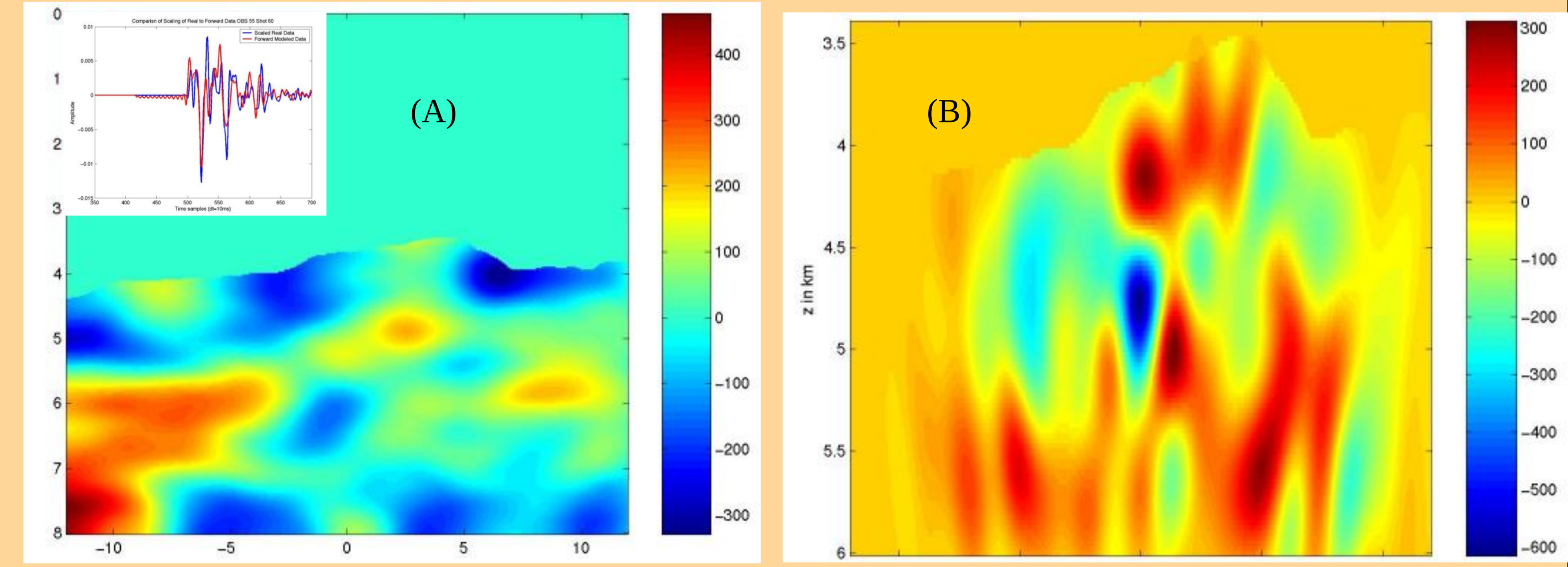
A stochastic model based on *Pullammanappallil 1997* was made to check inversion results. Data leakage seems to be occuring. Considerable work would have to be done to re-model inversion parameters and tested on this synthetic model to counter the effect of spatial under-sampling at the acquisition stage



The wavenumber-frequency space for the geometry of experiment. The enclosed space within red lines indicate the of wavenumber coverage for each frequency. The vertical blue lines are the k-coverage for each of the minimum number of frequencies that should be inverted and the vertical green lines are the k-coverage of the frequencies actually inverted for. Data redundancy on the k-space increases the stability of inversion.



The velocity model at each frequency minus the starting model, to show the updates with respect to the original at each sequential stage. As expected, the maximum update occurred at 6.5Hz as the first spurt of seismic energy on the spectrum arrives. All colors indicate velocity in m/s. Axes are marked in km.



(A) Stochastic Velocity perturbation on the traveltime tomography model, perturbations above the sea-floor topography are masked. All colors indicate velocity marked in m/s and x-z axis indicate distance in km. INSET: OBS 55, Shot 60 -The blue curve shows the forward modeled seismogram recorded using the stochastically computed velocity model (observed synthetic seismogram) and the red curve shows the same trace using the traveltime tomography velocity model. Since the first arrival travel-time pick matches within a period, the velocity model is accurate as a starting model for Waveform Tomography using synthetically generated observed data. It hould give accurate results provided the acquisition sampling and associated parameters are correct.

(B) Final velocity model (after inversion of 7 sequential frequencies using the traveltime tomography model as the starting model and a synthetic seismograms computed on the stochastic model as the observed data) minus the staring model. All wavelengths above 2Km (z) and 5km (x) were inverted for. This figure should ideally match (A) if the inversion process is accurate.

Thus, although initial results indicate that the inversion is stable and converges; however leakage of velocity updates leads to the speculation about the adequacy of the source-receiver spacing at the data-acquisition stage.