# Upper Crustal Shear Structure of NE Wyoming Inverted by Regional Surface Waves From Mining Explosions---Comparison of Niching Genetic Algorithms and Least-Squares Inversion

Rongmao ZHOU and Brian W. STUMP, *Dept. of Geological Sciences, Southern Methodist University, Dallas, TX 75275-0395.* E-mail: zhou@passion.isem.smu.edu, stump@passion.isem.smu.edu


## Abstract

Surface-wave dispersion analysis of regional seismograms from mining explosion is used to extract shallow subsurface structural models. Seismograms along a number of azimuths were recorded at near-regional distances from mining explosions in Northeast Wyoming. The group velocities of fundamental mode Rayleigh wave were determined by using the Multiple Filter Analysis (MFA) and refined by Phase Matched Filtering (PMF) technique. The surface wave dispersion curves covered the period range of 1 to 12 sec and the group-velocities range from 1.1 to 2.9 km/sec. Besides least-squares inversion, a niching genetic algorithm (NGA) was introduced for crustal shear-wave velocity inversion. Niching methods are techniques specifically to maintain diversity and promote the formation and maintenance of stable sub-populations in the tradition genetic algorithm. This methodology identifies multiple candidate solutions when applied to both multimodal optimization and classification problems. Considering the non-uniqueness of inversion problem, the capacity of NGA is explored to retrieve classes of S-wave velocity structural profiles from the dispersion curves. Synthetic tests illustrate the range of non-uniqueness in linear surface wave inversion problems. Application of this new technique to regional surface wave observations from the Powder River Basin provides classes of models from which the one that is most consistent with geologic constraints can be chosen.


## Study Goals

- Extract regional mid-period fundamental Rayleigh waves (1~12 sec) from mining explosion seismograms
- Invert dispersion curves for crustal shear-wave velocity structure of NE Wyoming
- Compare inversion results from linear least-squares method with those from niching genetic algorithms

## Geological Setting of Study Area

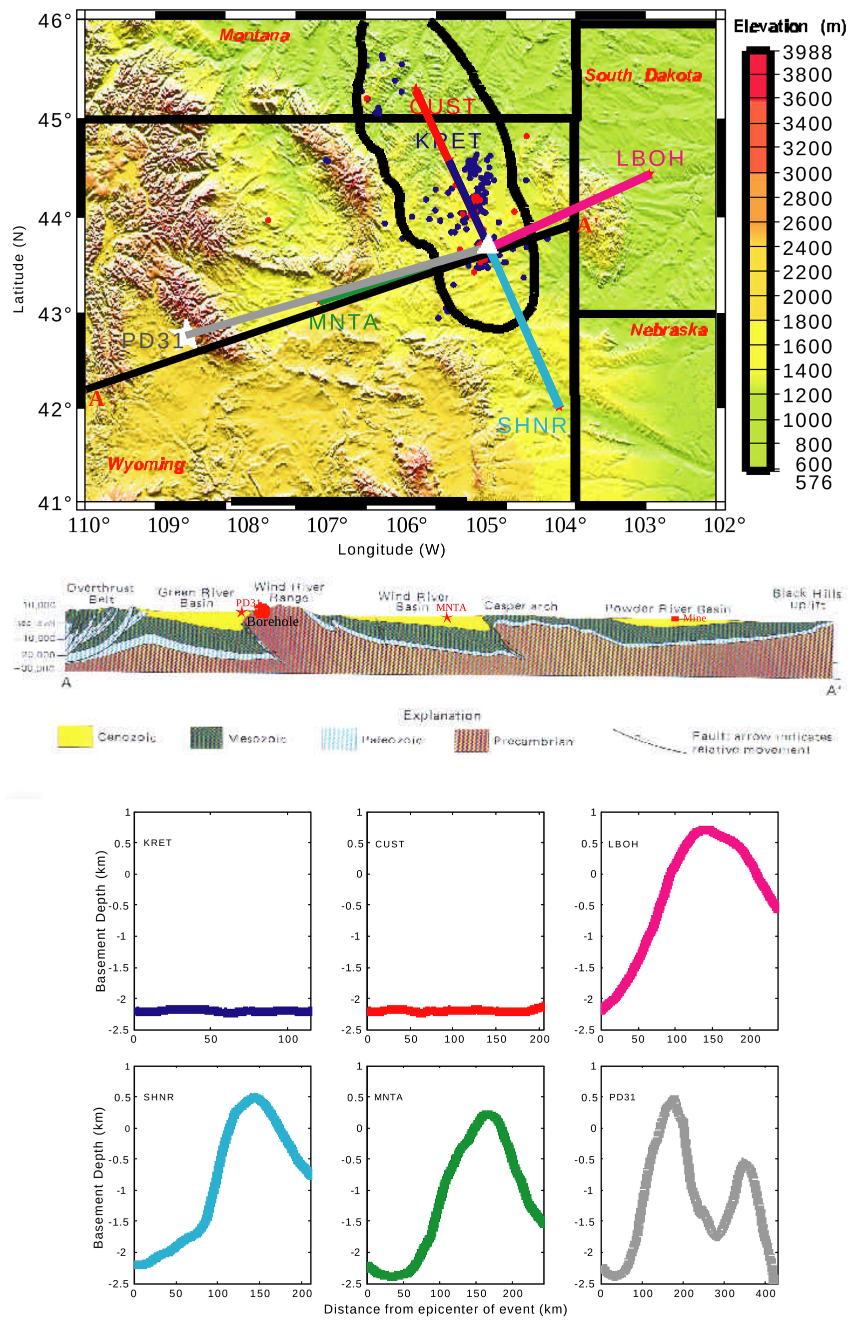

Figure 1.Upper: Topographic map of study area with the distribution of temporary stations (Red Stars) and permanent station (White Star). White triangle is the event studied. Elevation scale is presented at right.

Middle: Structural cross section from NE to SW across Wyoming (line of section AA' shown at upper panel).

Lower: Crustal cross sections of basement thickness from epicenter (white triangle at upper panel) to stations (data generated from Geoscience Interactive Databases of the Institute for the Study of the Continents (INSTOC) and the Department of Geological Sciences at Cornell University).

## Data

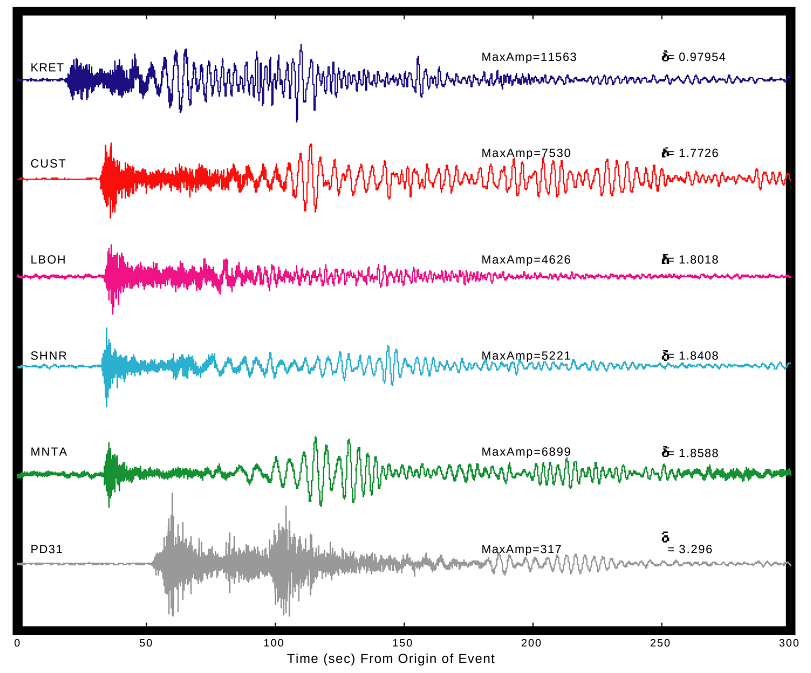

Figure 2. Observed vertical component seismograms of event (white triangle in upper panel of Figure 1) at all stations. (Seismometer for PD31 is KS54000. Other stations use STS-2)

Group velocities of fundamental mode Rayleigh wave are determined from observations by using the Multiple Filter Analysis (MFA) (Dziewonski et al., 1969) and refined by Phase-matched filtering (Herrin and Goforth, 1977) to remove effects of multi-pathing and extract fundamental mode Rayleigh surface wave.

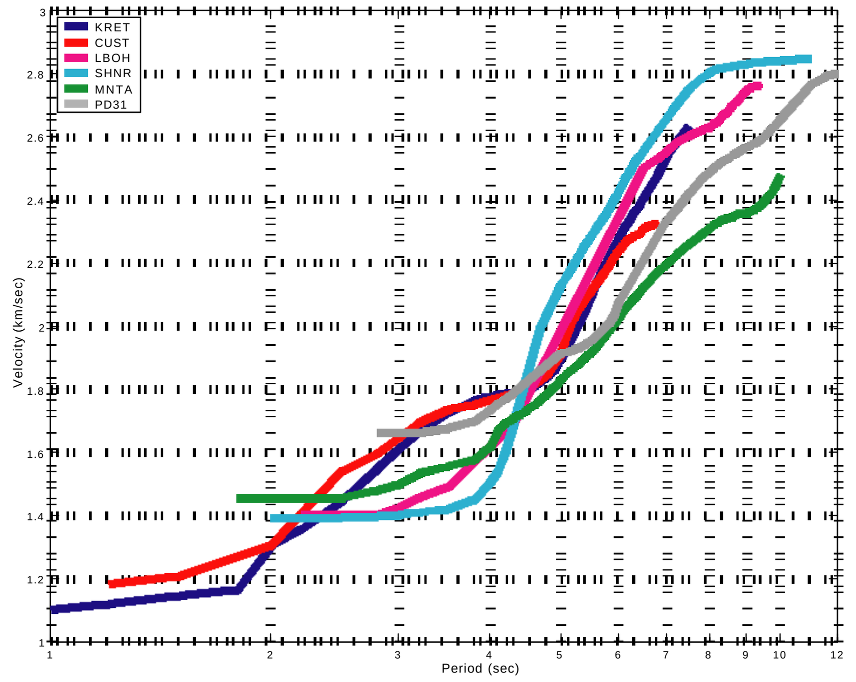

Figure 3. Fundamental Rayleigh-wave dispersion curves of event

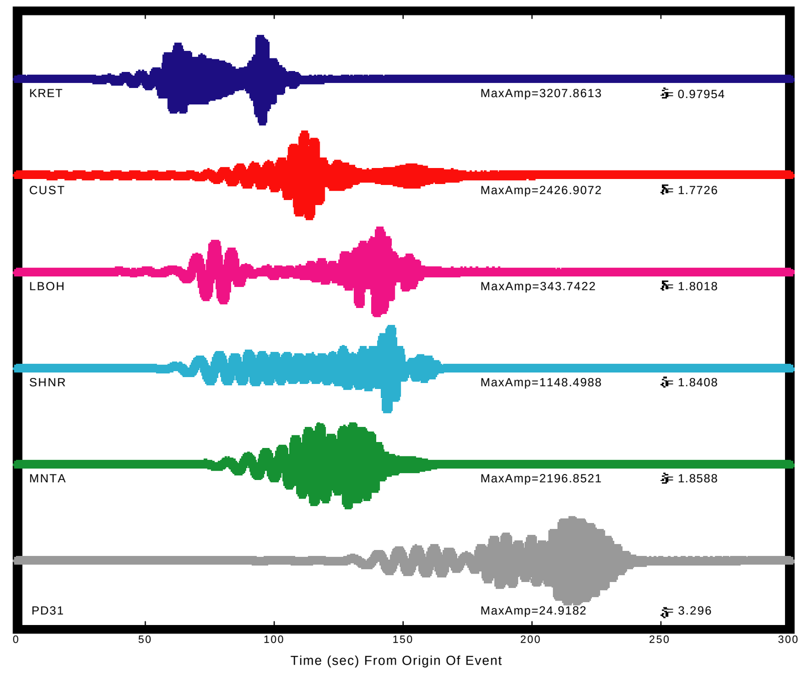

Figure 4. The fundamental mode Rayleigh waves are extracted using Phase-matching Filter (PMF)

### Data Characteristics

- Mining explosions generate surface waves
- Fundamental Rayleigh waves exhibit normal dispersion
- Group velocities range from 1.1 to 2.9 km/sec over period 1 to 12 sec
- Apparent azimuthal and range effects

## Inversion Methods

### Least-squares Inversion

Surface-wave dispersion analysis is one method used to extract a subsurface structural model from records of earthquakes and in our case mining explosions. Surface-waves dispersion curves are nonlinear functions with respect to the physical properties of layers within the Earth, including shear and compressional wave velocities, the densities of the media and the thickness of the layers. The shear-wave velocities provide the primary influence on the dispersion curves. So we can linearize the problem by neglecting higher-order terms in the Taylor series expansion and considering shear wave velocities as the sole unknown parameter. An iterative least-squares solution is determined such that changes in model parameters are chosen to minimize the difference between the observed and the predicted data. In an iterative, least-squares inversion for linearization the nonlinear problem, the resulting model is highly dependent on the initial estimate of the crustal velocity structure and may not represent a unique velocity model.

### Niching Genetic Algorithms Inversion

An inversion approach can be viewed as an optimization process in which a model is sought that best explains the observations. Genetic algorithms (GAs) are global optimization methodologies for non-linear problems and they are based upon principles from biological genetics and operate analogous to evolution. Using an analogy to population genetics (i.e. selection, crossover and mutation), these algorithms can simultaneously search both globally and locally for an optimal solution by using several models. In GAs, an initial population of models is selected at random and GAs seek to improve the fitness (which is a measure of goodness of fit between data and synthetic for the model) of the population generation after generation within a specified search range. Niching genetic algorithms (NGA) are a variation of GAs which are capable of locating multiple, optimal solutions within a single population. One scheme for NGA is crowding which is inspired by a corresponding ecological phenomenon --- the competition, among similar members of a natural population for limited resources. Deterministic crowding (DC) was designed specifically to maintain diversity and exhibits extensive niching capabilities when applied to both multimodal optimization problems and classification problems. Fitness based upon the inverse of the squares of the absolute value of difference between prediction and model is used in the application of these techniques.

## Synthetic Test

### Least-squares Inversion

We run a synthetic test by using both inversion methods. The test model consists of 8 thin layers in the upper 9.8 km of the crust overlying a half space. The model and its dispersion curve are presented at Figure 5 in blue. The linear least-squares inversions were run using two different starting models (thin red and green lines at Figure 5). The two inversion results (thick lines in same figure and in same colors corresponding with starting models) produce quite different models. The example illustrates the non-uniqueness of least-square inversion.

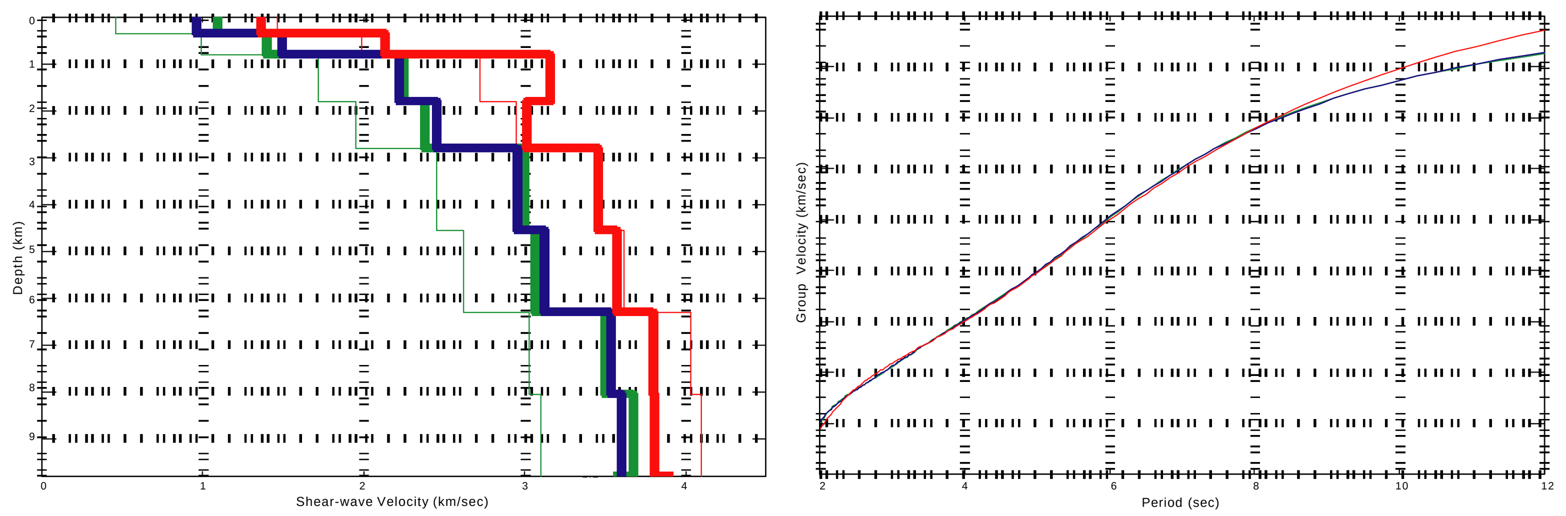

Figure 5. Left: Model for synthetic test and the inversion results from linear least-squares. Blue line represents the input model for synthetic test. Thin green and red line are starting models for linear least-squares inversion and their inversion results are thick lines in same color, respectively.

Right: Fundamental Rayleigh-wave dispersion curves of input model and inversion models in same color corresponding with models.

### Niching Genetic Algorithms Inversion

Eight models resulting from NGA and their fundamental Rayleigh-wave dispersion curves are presented in Figure 6. Without any prior information, NGA finds models fit the dispersion curve including a model almost the same as the input model. This illustrates that NGA is robust and effective and can be used to interpret surface wave dispersions.

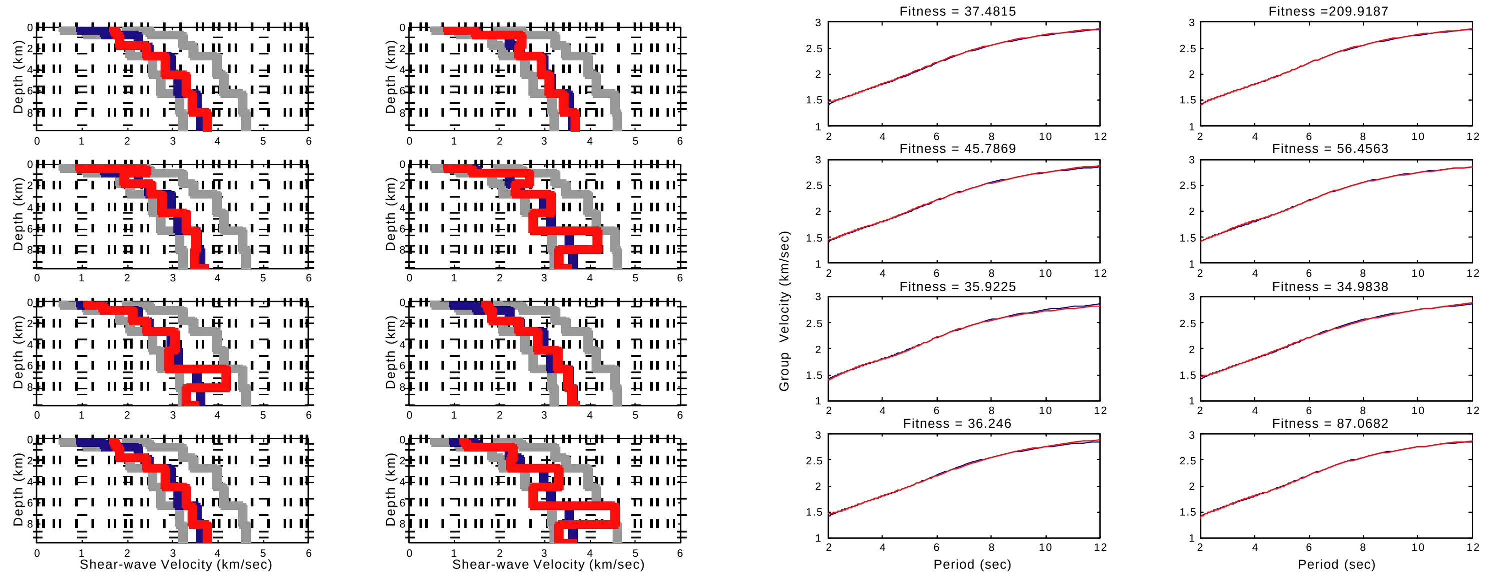

Figure 6. Left: Models for synthetic test and the inversion results from Niching Genetic Algorithms (NGA). Blue lines represent the input model for synthetic test. Gray lines at each sub-panel are search range and the red line are eight inverted models with best fitness function value.

Right: Fundamental Rayleigh-wave dispersion curves of input model (blue) and inversion models (red).

## Results

### Least-squares Inversion

A representative one-dimensional velocity model for eastern Wyoming is chosen as the initial model for iterative, least-squares inversion. The inversion results for the six stations of the event are shown in left panel of Figure 7 with starting model in black line. The right panel of Figure 7 compares the observed and inverted dispersion curves (solid line with start).

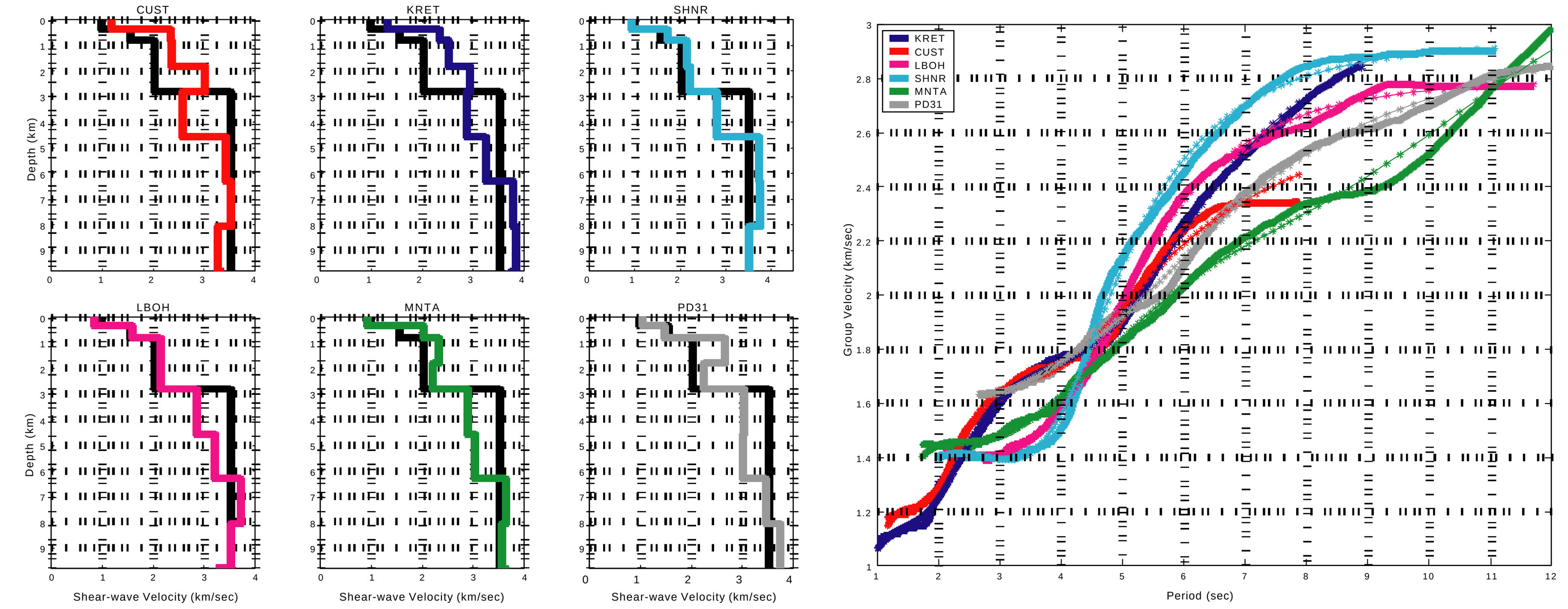

Figure 7. Left: The results of crustal velocity model inverted from dispersion curves of all stations (black for starting model).

Right: The comparison of dispersion curves of observation (solid line) and calculations from inverted models (solid line with star) within a period range 1 ~12 sec.

### Niching Genetic algorithms inversion

Niching Genetic Algorithms with the deterministic crowding method are run on the observation data (Figure 8). The left panel for each station presents the resulting crustal models and the right panel are the corresponding dispersion curves. The 6 models with best fitness function are presented for all stations. All resulting models have better resolution at shallow layers than deep layers as represented by the increased variation in the models at deep depth. Similar crustal models are obtained from CUST and KRET, both in the Powder River Basin. The results from MNTA and PD31 show similarity with increased shallow velocities (0-2.8 km) for PD31. The results from LBOH and SHNR give higher velocity than others from 2.8 km until 6.3 km which is consistent with geology (Figure 1).

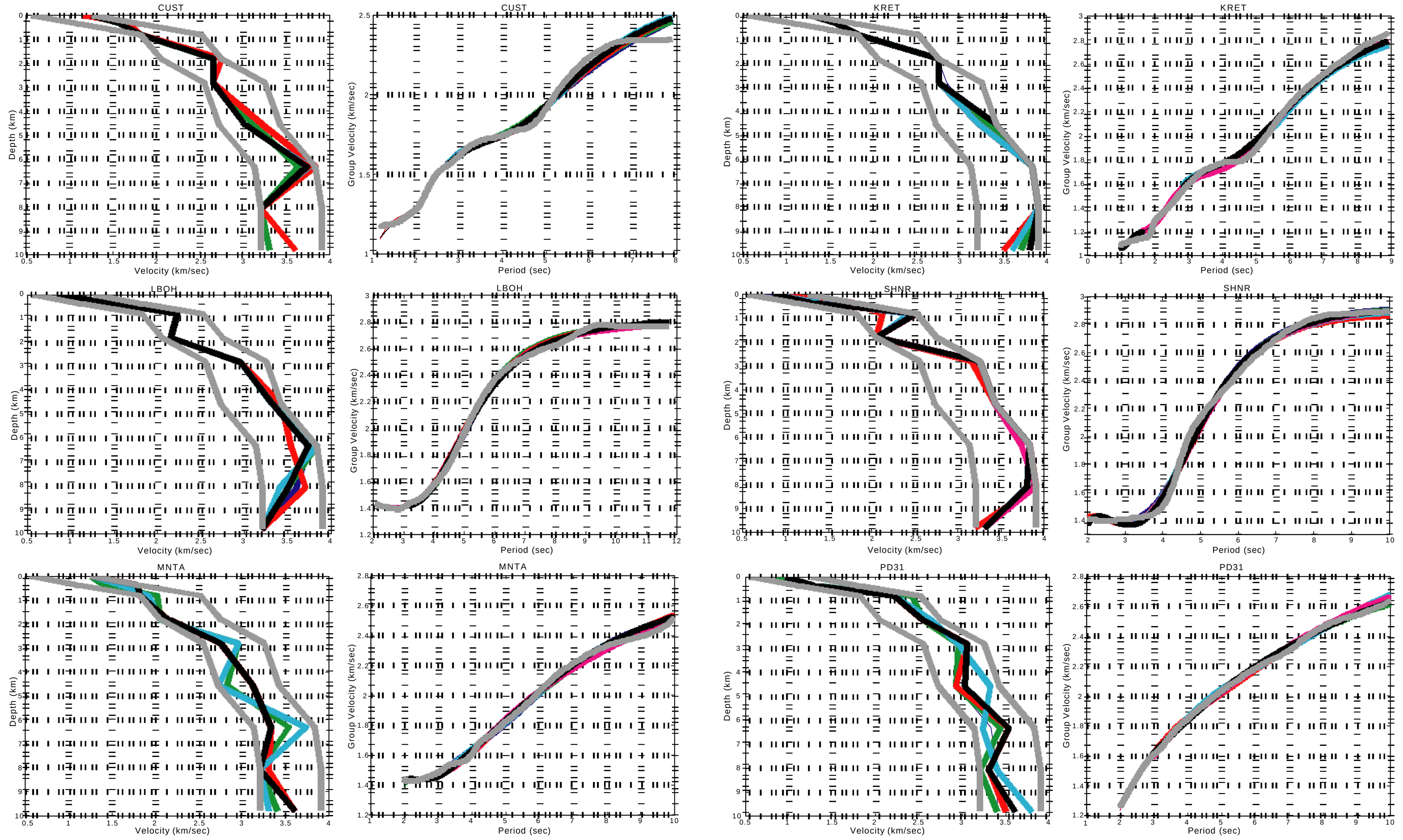

Figure 8. Inversion results from observation data by niching genetic algorithms with deterministic crowding method. Each station has two sub-panels under the same station code.

Left panels: crustal shear-wave models. Gray lines are search range and the 6 inverted models in different colors

Right panel: observed dispersion curve (gray) and theoretical dispersion curves from inversion models in same color with their models.

## Conclusion

Millisecond time delay mining blasts can generate mid-period (1~12 sec) surface wave which provide us a great opportunity to study upper crustal shear-wave velocity structure. Synthetic test and inversion from observation data show the niching genetic algorithms can be used to interpret surface wave dispersion data for inverting crustal shear-wave structure without any *a priori* information. Mid-period (1~12 sec) dispersion data from eastern Wyoming illustrate the strong effect of two and three dimensional shallow crustal structure in the 0~9.8 km depth range.