

High Resolution Imaging of Fault Zone Properties

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Summary

Our last year studies focused on two efforts aiming to establish a reliable method for extracting quantitative information from observed seismic fault zone (FZ) trapped waves. Both works use a generalized version of the 2D analytical solution of Ben-Zion and Aki [1990, BSSA] for a scalar wavefield in a structure consisting of two uniform FZ layers between two uniform quarter spaces (Figure 1a). In the first study, forward calculations involving variations of model parameters one at a time were used to examine the dependency of seismic FZ trapped waves on basic media properties and source-receiver geometry. The analysis indicates that the waves are highly sensitive to a large number of parameters, and that the wavefield is far more complex than has been assumed in observational studies using these waves. The results also show that the zone connecting sources generating seismic FZ waves and observation points with appreciable wave amplitude can be over an order of magnitude larger than the FZ width, in contrast to assertions made in other works on the subject. In the second study, we developed together with Andy Michael (USGS, Menlo-Park) grid-search and genetic algorithm inversions based on correlation coefficients between observed and synthetic waveforms. The inversion algorithms allow us to test a very large number (e.g., several tens of thousands) of models in a systematic and objective manner, and to establish confidence bounds on the best result by treating jointly volumes in the governing (about 10D) parameter space. As expected from the forward modeling study, the inversion results show that good fits to observed waveforms can be obtained for a wide range of values in any one parameter by varying the other parameters (Figure 2). The results also reveal that the correlation coefficient between synthetic and observed data is a complex function of the fault zone parameters. This creates problems for traditional optimization techniques, which we will attempt to overcome in the continuing studies.

Forward Model Calculations

To provide a basic quantitative understanding of seismic FZ waves, we used a generalized version of the 2D analytical solution of Ben-Zion and Aki [1990] to study the dependency of the waves on media velocities, media attenuation coefficients, layers widths, and source-receiver geometry. In general, the interference patterns controlling seismic FZ waves change with the number of internal reflections in the low velocity structure. This number increases with propagation distance along the structure and it decreases with fault zone width. Thus the primary length scale governing the waves is the ratio of propagation distance along the structure divided by fault zone width. The critical angle of reflection within a low velocity layer increases with the impedance contrast between the layer and the bounding media. Hence the number of internal fault zone reflections increases (for given length scales) with the velocity contrast. The relative lateral position of the source within the low velocity layer modifies the length scales associated with internal reflections and influences the resulting interference pattern. Low values of Q affect

considerably the dominant period and overall duration of the waves. Thus there are significant trade-offs between propagation distance along the structure, fault zone width, velocity contrast, source location within the fault zone, and Q . The lateral and depth receiver coordinates determine the particular point where the interference pattern is sampled and observed motion is a strong function of both coordinates. These effects are discussed in detail and illustrated by Ben-Zion [1998]. As pointed out in previous works on the subject, the generation and observation of seismic FZ waves require sources and receivers to be in the vicinity of the low velocity structure. In contrast to previous works, however, the simulations of Ben-Zion [1998] indicate that the zone connecting sources generating the waves and receiver positions with appreciable wave amplitudes can be over an order of magnitude larger than the FZ width. Initial extension of our basic parameter space to 3D cases of P , SV and SH waves in FZ models with irregular geometries and non uniform material properties are given by Igel, Ben-Zion and Leary [1997]. Additional 3D simulations for laterally heterogeneous fault zone with depth-varying properties will be done in the continuing work. Our study of parameter trade-offs indicates that a proper quantitative analysis of observed seismic FZ waves requires an inversion procedure which can map volumes in parameter space that have equivalent effects, within some error limits, on the waves. Work on this subject is discussed below.

Inversion of Fault Zone Trapped Waves

Various groups identified candidate seismic FZ waves in observed data, and modeled them with synthetic waveform calculations [e.g., Fukao et al., 1983; Li et al., 1990; 1994; Leary and Ben-Zion, 1992; Hough et al., 1994]. These studies, however, have only used forward modeling which is problematic due to strong parameters trade-offs as discussed above. In order to overcome these difficulties, we are developing a rigorous inverse approach to extract high resolution structural information from the waveforms along with realistic confidence bounds.

One manifestation of the problem with forward modeling is that small changes in single parameters can make large changes in the synthetic waveforms. For instance, Figure 1c shows the effect of changing the shear wave velocity in the fault zone by only 0.1 km/s. This seemingly small change destroys the previously good fit between observed and synthetic seismograms. This could naively suggest that these waves can resolve the FZ shear velocity to within 0.1 km/s. However, a large parameter space study (Figure 2) shows that it is impossible to obtain good fits to the observed waveform with larger variations of this parameter, if other parameters also change in an appropriate compensatory manner. Finding these complex compensatory changes in multiple parameters requires a systematic search of the parameter space by using an objective inverse method. Using an inverse method will also provide confidence bounds on the best result.

To establish an inverse method we first quantify the fit function as the correlation coefficient between the observed data and synthetic waveforms base on the solution of Ben-Zion and Aki [1990] and Ben-Zion [1998]. We then use iteratively the correlation coefficient in grid search and genetic algorithm inversions [Michael and Ben-Zion, 1998a-c; ms. in preparation]. As an initial application, we apply the inversion procedures to model FZ trapped waves (Figure 1b) generated by a cluster of earthquakes in the Parkfield segment of the SAF. The events were recorded by the borehole station Middle Mountain and were located about 5 km deep and 5 km to the SE from the station. The range of best fitting parameters suggest that the segment of the SAF between the generating earthquakes and Middle Mountain can be characterized by a single FZ layer with a width of about 250 m, S wave velocity reduction with respect to the surrounding rock of about 30%, and a Q value of about 50. As shown in Figure 2, however, good fits can be obtained for a wide range of parameter values.

While a grid search is a very systematic exploration of the parameter space, genetic algorithms are more computationally efficient because less time is spent on models with poor fits (Figure 2a). Grid searches are also inefficient if many values of each parameters are tested. With genetic

algorithms there is smaller cost for using a fine step size. The genetic algorithm also maintains a population of models and thus provides information about a large set of acceptable models that can be used to infer the confidence bounds on the best model. The results (Figure 2b-d) show that most parameters are poorly constrained, although wide search ranges provide limits on FZ width and shear wave velocity. The continuing studies will focus on narrowing the range of acceptable model parameters by large-scale inversion of many waveforms (if they are available) and incorporation of constraints based on tomography and other related data

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- Michael, A. and Y. Ben-Zion, Inverting Fault Zone Trapped Waves with Genetic Algorithm, *EOS Trans. Amer. Geophys. Union*, 79, F584, 1998b.
- Michael, A. and Y. Ben-Zion, Modeling Fault Zone Trapped Waves with Inversion Algorithms, extended abstract for the *International Workshop on Frontiers in Monitoring Science and Technology for Earthquake Environments*, Japan, 1998c.

Publications Supported by this Proposal

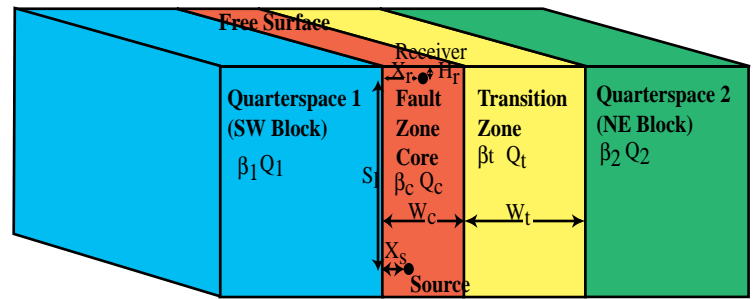
Papers:

- Ben-Zion, Y., Properties of seismic fault zone waves and their utility for imaging low velocity structures, *J. Geophys. Res.*, **103**, 12567-12585, 1998.
- Michael, A. and Y. Ben-Zion, Inverting Fault Zone Trapped Waves with Grid-Search and Genetic Algorithms, in preparation for JGR.

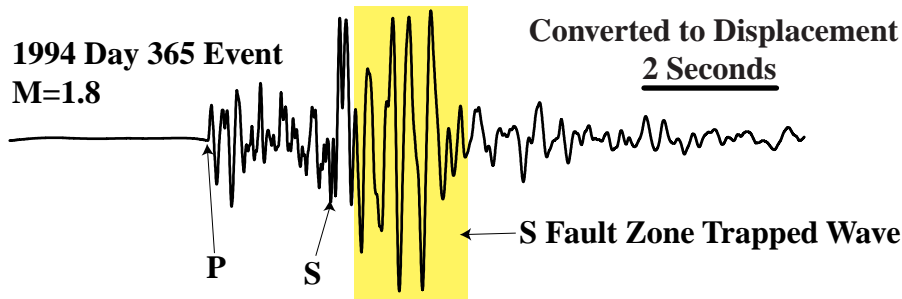
Abstracts:

- Michael, A. J. and Y. Ben-Zion, Challenges in Inverting Fault Zone Trapped Waves to Determine Structural Properties, *EOS Trans. Amer. Geophys. Union*, 79, S231, 1998.
- Michael, A. and Y. Ben-Zion, Inverting Fault Zone Trapped Waves with Genetic Algorithms, *EOS Trans. Amer. Geophys. Union*, 79, F584, 1998.
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a) A model of two quarterspaces separated by two vertical layers used to generate synthetic seismic fault zone waves with the solution of Ben-Zion and Aki (1990). Shear wave velocity, attenuation parameter and layer width are denoted by β , Q , and W . The source and receiver offsets from the edge of the fault zone core are marked by X . The receiver depth is H_r and the source distance from the receiver in the plane of the fault is S_1 .



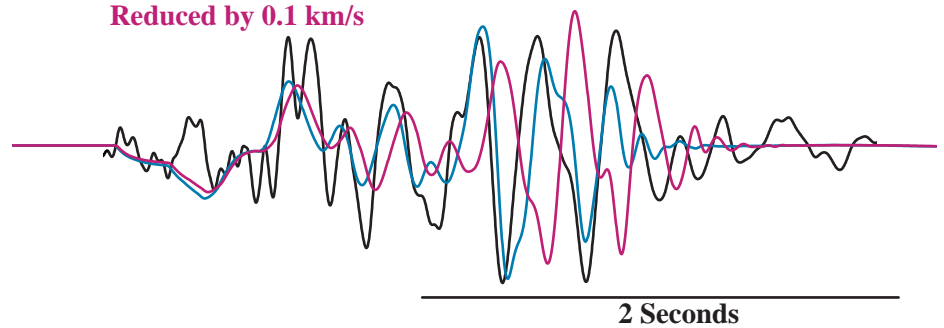
For the grid search and genetic algorithm inversions the fault zone core and transition zone are collapsed into a single layer and the quarterspace Q 's were fixed at 200. This was based on the results of the forward modeling.



b) Dispersive waves observed on a downhole velocity sensor in the San Andreas fault zone at Parkfield, California, are interpreted as fault zone trapped waves.

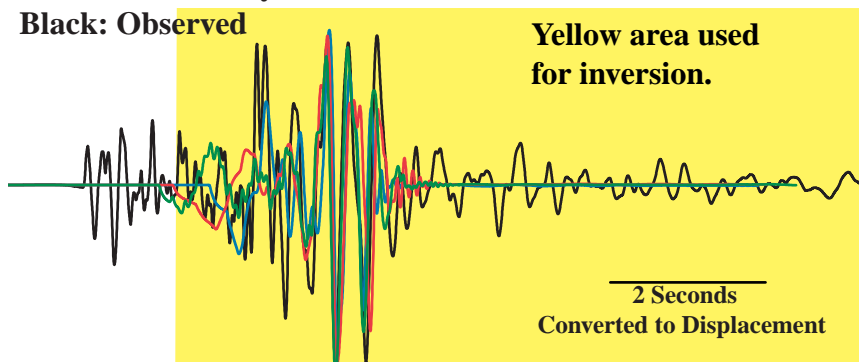
c) Small variations in a single parameter can result in large changes in the fit between observed and synthetic seismograms. Here only the fault zone shear wave velocity is varied while all other parameters are held fixed.

Black: Observed
 Blue: Synthetic From Forward Model
 Purple: Synthetic with Fault Zone Velocity Reduced by 0.1 km/s



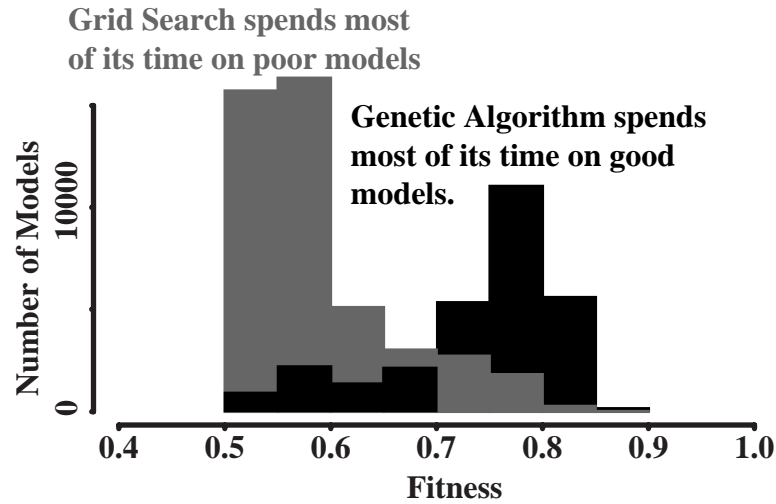
| Method | #Models Tested | Best Fitness |
|-------------------|----------------|--------------|
| Forward Modeling | ~100 | 0.85 |
| Grid Search | 45,000 | 0.87 |
| Genetic Algorithm | 18,600 | 0.87 |

Colors: Best Fit Synthetics
 Black: Observed

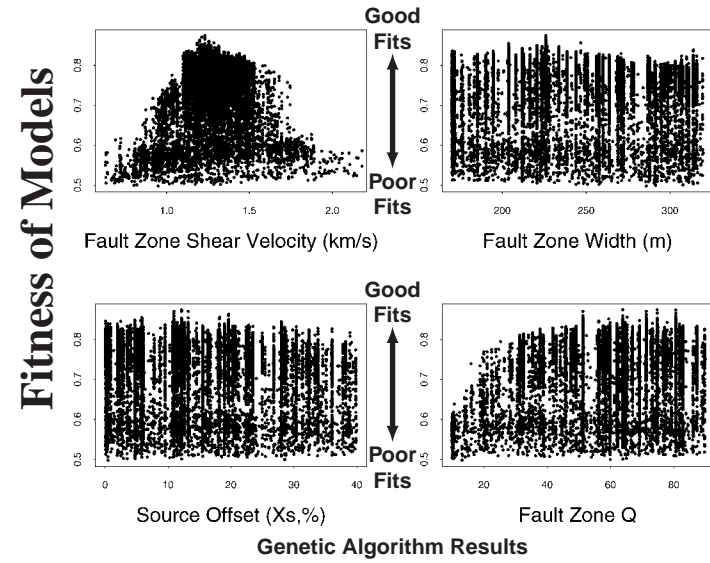


d) All search methods are capable of finding a model with a good fit between the observed and synthetic seismograms. The Fitness value is an objective measure of this fit $= (1+C)/2$, where C =cross correlation between the observed and synthetic seismograms. This transforms the cross correlation onto the range 0 to 1 for convenience when using the genetic algorithm inverse method.

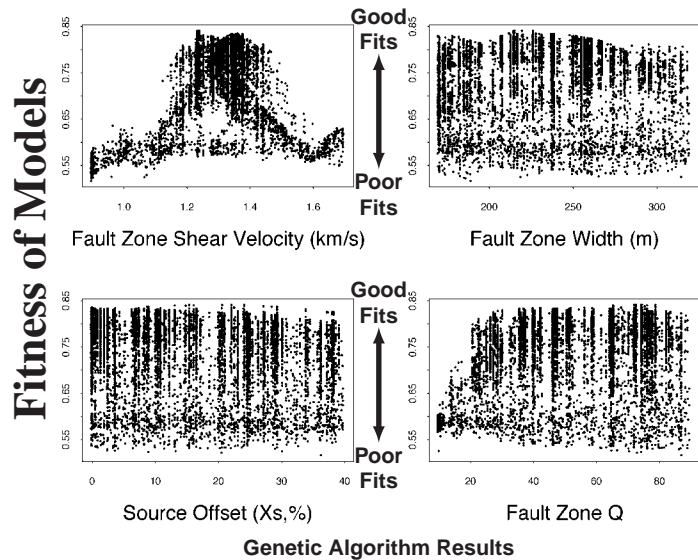
Figure 1



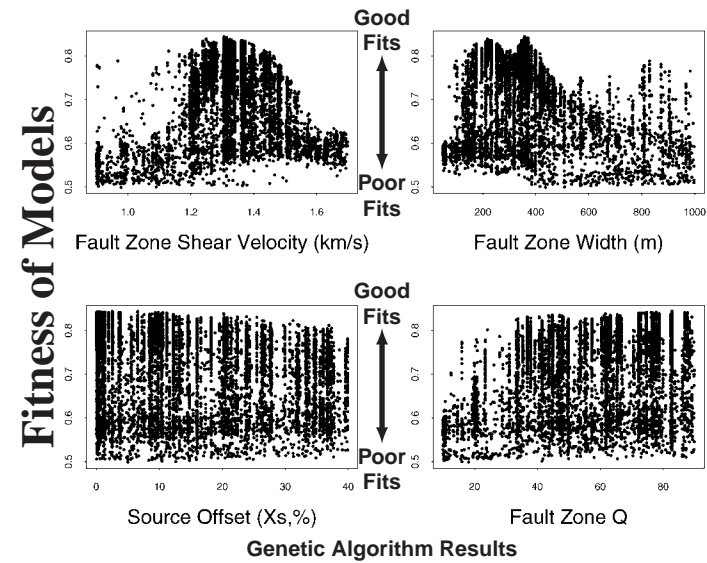
a) Histogram of the fitness of models tested by the grid search and genetic algorithm inversions demonstrate that the genetic algorithm is more efficient at exploring the part of the parameter space which contains high fitness models.



b) Scatter plots contain one point for each of the 18,600 models tested during the genetic algorithm inversion. Only the fault zone shear wave velocity and the fault zone Q show some resolution. The fault zone width, source offset and the quarterspace shear velocities (not shown) and the source to receiver distance (not shown) are not resolved at all.



c) Holding the quarterspace shear velocities and the source to receiver distance fixed does not appear to significantly improve the resolution of the other parameters.



d) A wider search range for the fault zone width shows some resolution for this parameter. Such a large search range would have been impractical with the grid search inversion method.

Figure 2