Wave Inversion Technology, Report No. 2, pages 269-276

Seismic Modeling of Complex Fault Zones

A. Goertz, M. Karrenbach[1]

keywords: *Finite Difference Modeling, Fault Zones*

ABSTRACT

In this project we apply and develop seismic exploration technology in a complex fault zone. We use tomographic velocity parameterizations to build a complex 3D model using the GOCAD software and merge a variety of models obtained on different seismic scales into one best fitting subsurface model. The model area is located along the San Andreas Fault (SAF) which is one of the global locations destined for drilling into an active fault zone. The proposed well through the SAF at Parkfield (Zoback et al. (1998)) will, together with a three dimensional image of the seismogenic zone, lead to insights into the physical and chemical properties of fracture zones. We use 3D finite difference techniques to compute full wave form responses of realistic extent in the model and simulate a variety of experiments, such as 3D surface seismics, VSP recordings, cross well recordings and downhole sources. Conclusions from our modeling will currently flow directly into the planning of seismic acquisitions proposed by Klemperer et al. (1998) in the target area. Potential processing algorithms can be tested on their ability to image complex structure. By modeling the physical properties of the fault zone itself, 4D seismic monitoring experiments can be simulated.

INTRODUCTION

The San Andreas Fault zone system in the Parkfield region has been investigated in various surveys in the past. Therefore this region is likely for the location of a fault zone drilling project. The aim is to acquire definite information about chemical and physical properties as well as petrological composition of fault zones. In order to derive a realistic model of the fault zone, several constraints were used and tested on their consistency together with results from various geophysical experiments. A smooth background velocity model was derived from two tomographic models of passive-source surveys that have been carried out in the past (Michelini and McEvilly (1991), Eberhardt-Phillips and Michael (1993)). The Fault Zone itself was constrained by seismicity and surface geology (Sims (1988)).

[1]**email:** agoertz@gpiwap5.physik.uni-karlsruhe.de, mkarren@ibm.net

3-D seismic wave propagation in fault zone structures is simulated using a finite difference method. This enables us to estimate the outcome of the real seismic experiment and to optimize the acquisition layout. Synthetic data is used to select appropriate processing sequences. The amplitude behavior of turning waves, which are critical for imaging the fault zone, can be simulated in various environments.

CONSTRUCTION OF A MODEL

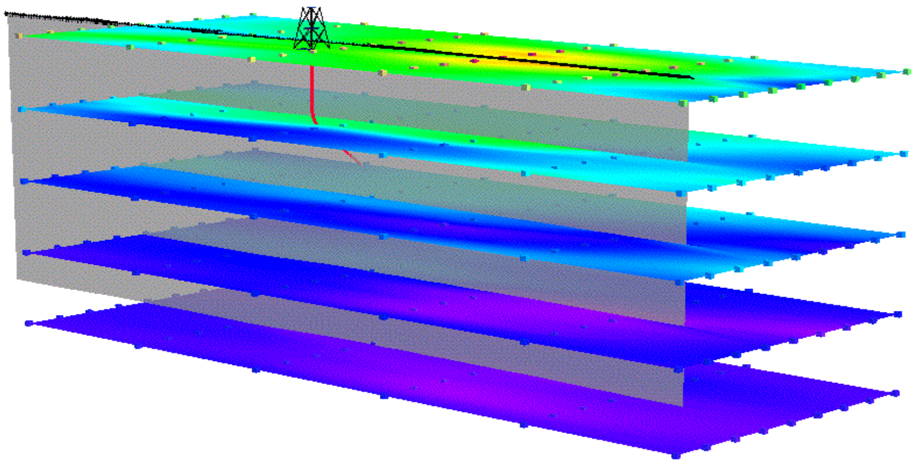

Figure 1: *Horizontal interpolation of the velocity grid to five depth layers show the main features of the velocity model. Thicker dots denote the initial tomographic grid. The vertical plane denotes the discontinuous fault.*

We tried to combine data from various geophysical disciplines focusing on different inherent properties in one model of the area around the proposed drill site. Two types of information were used in order to build a realistic model of the target area:

- Coarse-gridded velocity information from two tomographic models
- Constraints on the fault zone itself from seismicity and surface geology

Figure 1 shows the initial layers of a coarse-gridded velocity model obtained by tomographic inversion of local earthquake travel times (Michelini and McEvilly (1991)). Thicker dots within the layers denote the initial grid of velocity information. The fault plane is derived by vertically extending the surface trace of the SAF into depth. Interpolation was performed horizontally on either side of the fault thus leaving one faint discontinuity in the smooth velocity model: the fault itself. The location of the proposed drill site and the path of the well is denoted by the little derrick and the line

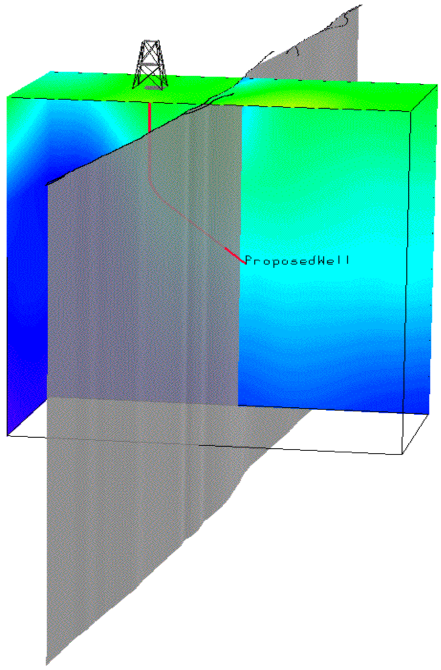

Figure 2: *Property model for the P-wave velocity together with the surface trace of the fault and the vertical fault plane. The model consists of 200 $*$ 200 $*$ 100 grid points which refers to a physical extension of 8 km $*$ 8 km $*$ 4 km, enclosing a volume of 256* km^3. *The derrick denotes the location of the proposed well. The proposed drilling will penetrate the fault zone in a depth of 4 km at an angle of* 45^o.

below.

In order to perform finite difference modeling, a densely and equally spaced ($\delta x = 40m$) velocity grid was created for a three dimensional volume around the proposed drill site. Vertical linear interpolation between the different depth layers leads to a smooth background velocity model. Due to the fact, that the interpolation was done independently on either side, the fault zone remains as a discontinuity. Fig. 2 shows the property model for the P-wave velocity. For elastic and isotropic seismic modeling, at least three physical parameters have to be given. With GOCAD as a powerful tool to create 3D models, other properties such as porosity or fluid saturation can be added easily.

FINITE DIFFERENCE MODELING

Finite difference simulations were carried out for an active experiment along the surface and within the borehole as well as for local shallow earthquakes. In a fine scale modeling scenario the subsurface model can be probed with a relatively high source frequency. A spatial sampling rate of the velocity grid of 40 m enables us to simulate waveforms with a dominant frequency of 20 Hz. The wavefield was recorded both at the surface with an aperture of 8 km and within the borehole for a VSP array. This will be the approximate acquisition parameters of the 3D survey (Klemperer et al. (1998)).

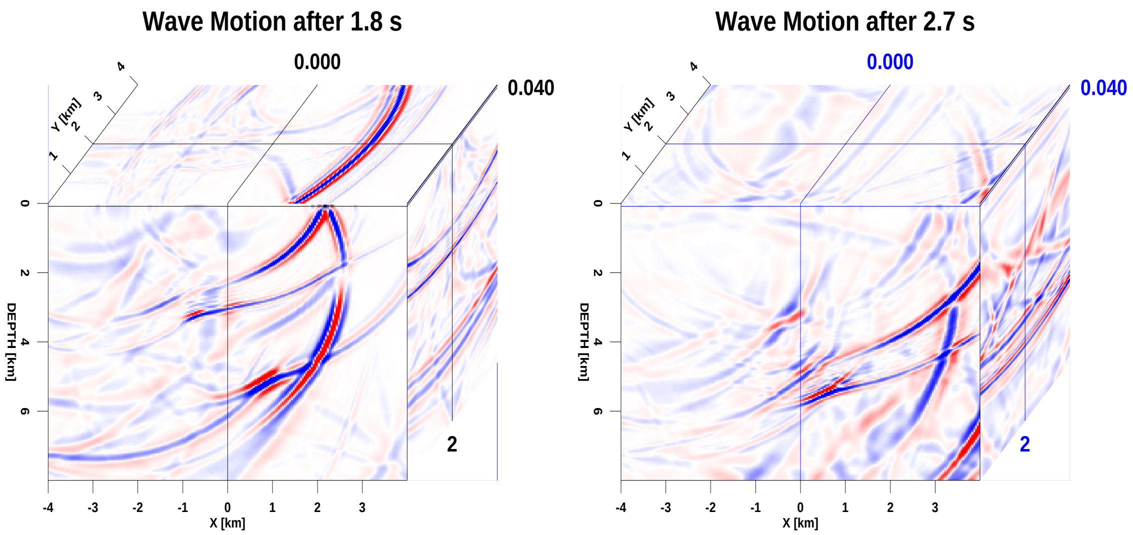

Figure 3: *Snapshots of the seismic wavefield after 1.8 s (left) and 2.7s (right). A caustic caused by a low-velocity body can be seen in both plots.*

Simulations were carried out on a parallelized Vector computer Fujitsu VPP300 at Karlsruhe University High Performance Computing Center.

Figure 3 shows snapshots of the seismic wavefield after 1.8 and 2.7 seconds produced by an isotropic compressional point source located on the left (southwestern) side of the fault. We observe a high resolution wave field that is produced by fine scale discontinuities, gradients and structures. Albeit the smooth background velocity, the wavefield becomes rather complex after a short time already. P, S and converted phases as well as reflections off the free surface make it difficult to trace individual phases from seismograms alone. Both snapshots show a caustic which develops at a low-velocity body near the fault at a depth of 5 km. Thin black lines denote the position of the frames which are displayed on the faces of the cube.

Seismograms for a line across the fault (along the x direction) in the middle of the cube (y = 0 km) are shown in Fig. 4. For this simulation, the source was located also on the left side of the fault, but in a depth of 2 km, thus presenting a small local earthquake or a source within the borehole. The fault, which is located at x = 0 km, produces turning waves in the recordings which can be seen clearly in both, horizontal and vertical components.

The left side of Fig. 5 shows a timeslice of the 3D synthetic prestack dataset at 1.2 s. The fault trace derived by surface geology is located around x = 0 km. Arrows denote turning P- and S-waves that evolve at the fault. Finally, a borehole seismogram of

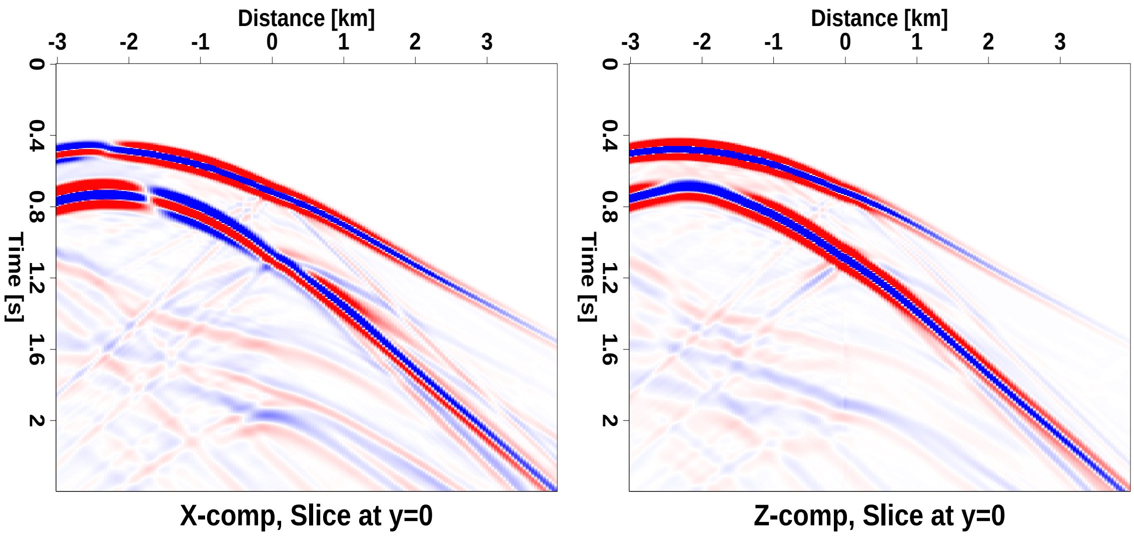

Figure 4: *Seismograms for a line across the fault. The source is located in a depth of 2 km. Turning waves evolve near 0 km, the location of the vertical fault.*

the proposed well is displayed on the right side of Fig. 5. The two turning waves that are visible in the timeslice on the left side can as well be seen in the VSP recordings and are again denoted by arrows.

CONCLUSION AND OUTREACH

We apply finite difference methods in three dimensions to get the full wave form seismic response of a complex fault zone. The model volume is similar to a proposed 3D survey in the Parkfield region. We model realistic wave field recording geometries, such as surface seismic surveys and Vertical Seismic Profiles, producing seismic recordings as could be expected in experiments.

It is planned to extend the finite difference code for modeling of fluid flows within the fault zone, thus enabling us to simulate 4D seismic monitoring experiments during the drilling and coring phase of the project. Insights into time dependence of rock properties will help in understanding the seismicity of active fault zones.

REFERENCES

Eberhardt-Phillips, D., and Michael, A. J., 1993, Three-dimensional Velocity Structure and Seismicity in the Parkfield Region, Southern California: JGR, **98**, 15737ff.

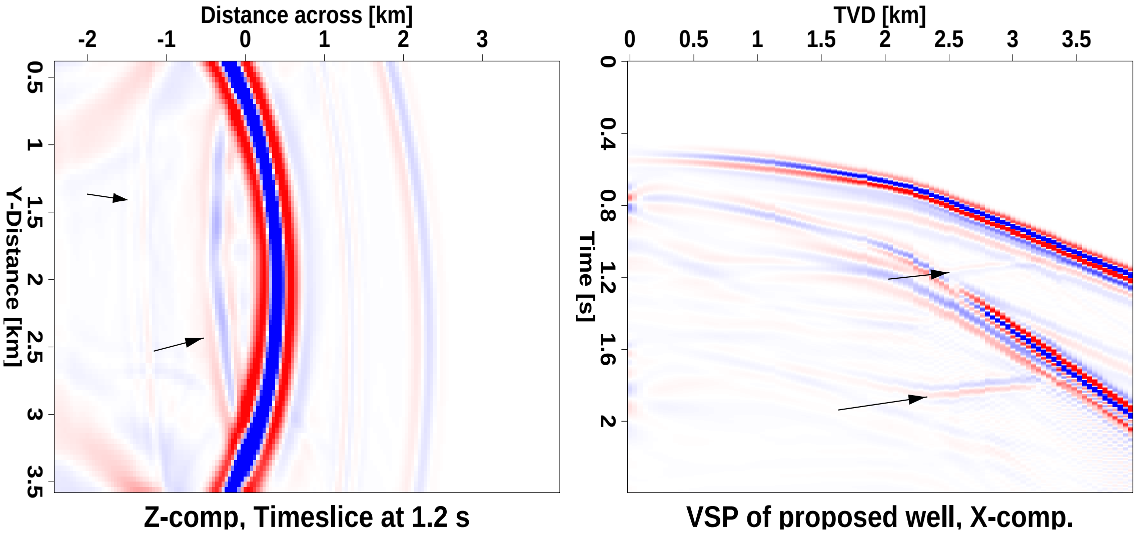

Figure 5: *Timeslice of the 3D prestack dataset at 1.2 s (left) and a VSP recording of the proposed well (right). Arrows denote turning P- and S-waves.*

Klemperer, S. D., Talwani, M., and Hole, J., 3D Seismic Reflection Experiment to extrapolate 1D Drilling into the 3D-heterogeneous Fault Zone:, A proposal submitted to NSF, 1998.

Michelini, A., and McEvilly, T. V., 1991, Seismological Studies at Parkfield I: Simultaneous Inversion for Velocity Structure and Hypocenters using Cubic B-Splines Parametrization: BSSA, **81**, no. 2, 524–552.

Sims, D., Geologic Map of the San Andreas Fault Zone in the Cholame Hills Quadrangles, San Luis Obispo and Monterey Counties, CA:, Misc. Field Studies Map MF-2115, USGS, 1988.

Zoback, M. D., Hickman, S. H., and Ellsworth, W. L., Scientific Drilling into the San Andreas Fault at Parkfield, CA: Project overview and operational plan:, A proposal submitted to NSF, 1998.

PUBLICATIONS

A. Goertz, M. Karrenbach and B. Traub: *Seismic Wave Field Modeling in the Parkfield Region*; AGU Fall Meeting proceedings, San Francisco, Dec. 1998

M. Scheidhauer, M. Karrenbach and T. Ryberg: *The Los Angeles Region Seismic Experiment (LARSE): Conventional Processing of Fault Zone Reflections*; AGU Fall

Meeting proceedings, San Francisco, Dec. 1998

T. Ryberg, M. Scheidhauer and M. Karrenbach: *The Los Angeles Region Seismic Experiment (LARSE): Seismic Mapping of Shallow Fault Zones*; KTB/ICDP Colloquium, Bochum, Germany, 1998

J. Mueller, M. Karrenbach, M. Scheidhauer, B. Traub and K.-U. Vieth: *Modeling of seismic wave propagation in Fault Zones*; AGU Fall Meeting proceedings, San Francisco, Dec. 1997