SAFOD-SITE CRUSTAL PROPERTY, FAULT GUIDED WAVE, & TREMOR STUDIES USING EXISTING SURFACE ARRAY & BOREHOLE SEISMIC DATA

Award Number 07HQGR0010

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Abstract. San Andreas Fault Observatory at Depth (SAFOD) surface array and borehole seismic data were investigated to study the SAFOD-site fault structure and properties. The data for this study come from both surface- and borehole-based earthquake monitoring experiments at the SAFOD site. The objectives of the study was to establish how the fault and crustal properties encountered during SAFOD drilling in 2004 and 05 relate to surface observations and SAFOD-site seismicity. These objectives supported the Priority Topics in Earthquake Physics and Occurrence by using SAFOD data to understand the environment in which local earthquakes occur.

The data used in this project include recordings from: (a) several ~2.7 deep 3-component seismometer deployments ~0.4 km from the SAF in the SAFOD Main Hole (MH), (b) a 1.4 km long, 46 vertical + 24 3-component geophone array, running at ground-level from the SAFOD site to ~0.4 km of the SAF, and (c) both single and multilevel borehole seismometers in the 2.1 km deep SAFOD Pilot Hole (PH). The 2.7 km deep MH data include observations taken within 50 m of where fault creep appears to be deforming this borehole.

Because of the increased seismicity surrounding the September 2004 Parkfield M~6, the data sets included hundreds of seismograms with features such as fault guided waves (Fg) from well located earthquakes. A subset of the MH seismograms – ones from earthquakes that are more than 4 km below the SAFOD site – contain what appears to be a new type of Fg wave: a dispersive "leaky mode" trapped wave that arrives in between the direct P and S waves. recorded with it have not be studied for their relationship to this earthquake. These data were analyzed and modeled to (1) map the connections and properties of SAFOD-site fault slivers and segments, (2) determine the manner in which these features trap and focus earthquake energy, and (3) establish how the faults observed in the SAFOD MH and those mapped on the surface are related. The active slivers and connected segments of SAF at the SAFOD site were be determined by comparing the locations of events with and without guided waves. The frequency contents and amplitudes of the fault guided waves will be measured and modeled to determine the lateral and vertical velocity structures and thickness of their associated faults.

Results

In our study, the constraints from well logs and seismic tomography have been used to reduce the trade-offs among model parameters. Our grid-search modeling tested various values of fault zone width, velocity, attenuation, wall-rock velocities, layer depth, and source location as we conducted in our previous study of fault-zone trapped waves at Parkfield SAF and other active faults [e.g. *Li et al.*, 1997, 2004a]. The result is a downward tapered, two-layer, low-velocity fault zone sandwiched between different east and west sides of the SAF (Fig. 2a.). The model parameters are listed in Table 1.

The widths and velocities of the fault core and jacket model at ~3-km depths are consistent with the SAFOD borehole logs. The waveform fits corresponding to this velocity model are shown in Fig. 1. The synthetic seismograms fit the guided wave amplitude behaviours and travel times recorded at both the borehole seismograph and surface array stations. Tin these examples, the cross-correlation coefficients between synthetic and observed waveforms for fault-guided waves are better than 0.8. They also fit the depth dependant duration characteristics of both the on-fault and off-fault events between at depths between ~2.5 km and ~11.5 km (Fig. 2).

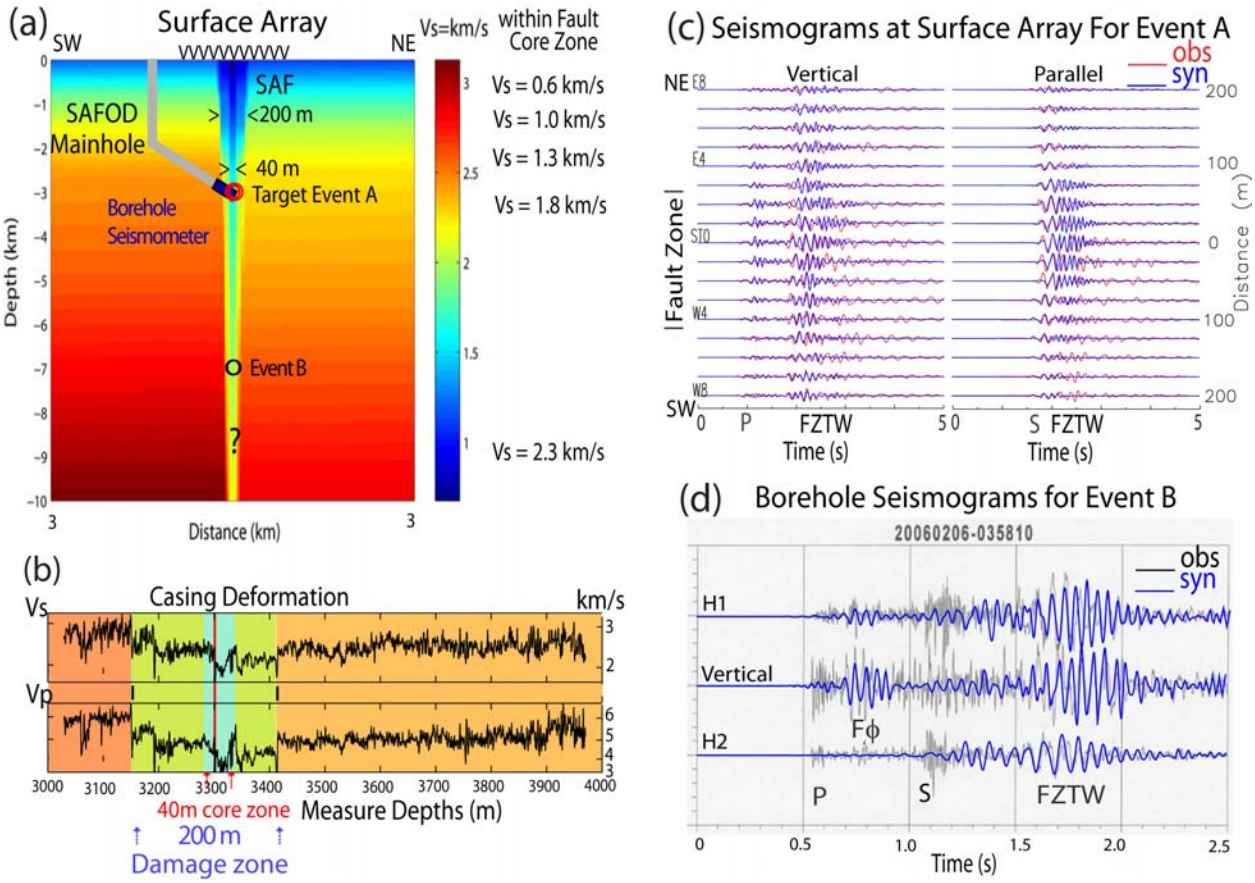

Figure 1 (a) Cross section near the SAFOD site showing the *S*-wave velocity model used in this study to compute synthetic fault-guided waves for the surface and borehole observations. Earthquakes A and B illustrate the type of fault guided waves used in this study. (b) Seismic velocities from SAFOD well logs showing a 40-m fault core and a 200 m low velocity "jacket" zones. The red line indicates the location where fault creep is currently deforming the borehole casing. The depths shown in figure are measured distances from the wellhead along the drilling pipe. (c) Observed (red) and computed (blue) vertical- and parallel-component seismograms at the surface array for event A. The seismograms were low-pass filtered below 8 Hz and are plotted using a single global scale. (d) Observed and computed 3-component borehole seismograms recorded for event B. The synthetic seismograms have been band-pass (12-18 Hz) filtered. The large signal between the P- and S- waves labeled $\mathbf{F_\phi}$ has been recently identified as a fault guided P-wave [*Ellsworth and Malin*, 2006].

In order to examine the affect of fault-zone depth on fault-guided waves, we tested the truncated fault zone models, the fault zone width going to zero at different depths between 2 km to 12 km. None of the models with a fault truncated at shallow depths fit the data. For example, Fig. 2 shows synthetic seismograms for 11 on-fault events using a fault zone truncated at 4 km with its width and velocities at ~3 km constrained by the well logs. Synthetic guided waves for this shallow fault-zone model show nearly constant duration guided waves for the events below 4 km and much shorter than observed wavetrains.

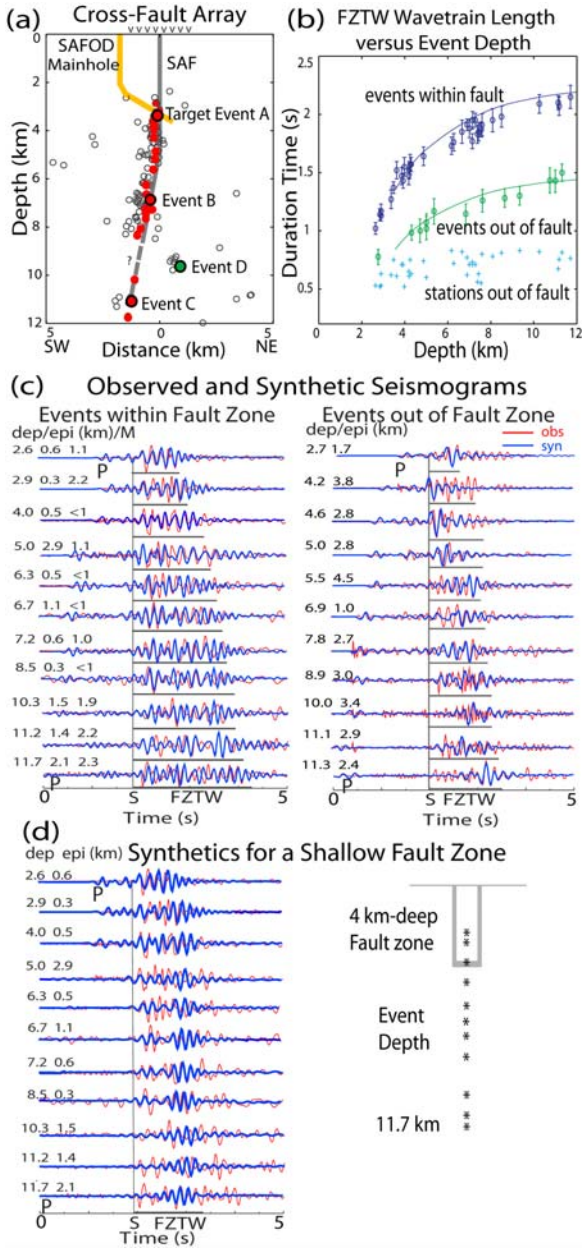

Figure 2 (a) Cross section through the SAF (grey line) at the SAFOD site showing locations of the microearthquakes (circles). Red circles mark the 33 events showing strong fault-guided waves. The locations of events A to D are also shown. (b) The measured time durations (denoted by blue circles) of guided waves at stations within the fault zone versus event depth. Compared these to ones measured at the same stations for off-fault earthquakes (green circles) and ones at stations away from the fault zone for on- and off-fault events (blue circles). Each data point is the average of 4 on- or off-fault stations. The error bars are standard deviations and the curves are polynomial fits to the data. (c) Observed and synthetic vertical-component seismograms at station ST0 for 11 on-fault and 11 off-fault earthquakes with magnitudes of *M*0.5-2.3 at different depths. The *S*-arrivals for these events are aligned at the same time. The focal depth and epicentral distance from ST0 are plotted for each event. The finite-difference synthetic seismograms were computed using the model in Fig. 1a. Seismograms have been low-pass filtered below 8 Hz and are plotted in trace-normalized. Bars denote the post-*S* wave durations, in which amplitude envelopes of guided waves are above twice the level of the background noise coda. (d) Synthetic seismograms at ST0 for 11 on-fault events using a 4-km-deep fault zone for comparison with observations.

Evidently, the SAFOD fault-guided waves can be explained in terms of a tapered, 30-40 m wide fault core of ~40% reduced velocity inside of a wider, 100-200 m jacket of ~25% reduced velocity. The relatively intact wall rocks surrounding this composite damage zone have different velocities east and west of the SAF. Further, based on matching of the duration characteristics of the guided waves as a function of event depth, it would appear that at least the low velocity jacket, and probably its interior core, extends downward to no less than ~7 km (Fig. 2c). This is the depth inferred by the most clearly resolved and best fit guided waves seen in the SAFOD borehole seismograms modeled here (Fig. 2d). The structural model presented in Figure 2a is a simple and plausible one that explains much of the data. But it is almost certain that the true structure is considerably more complicated.

Reports Published:

Citation: Li, Y.-G. and P. Malin (2007), San Andreas Fault damage at SAFOD viewed with fault-guided waves, *Geophys. Res. Lett.*, 35, Doi:35/2007GL.

Availability of Data:

All the data used in this study are available from the North California Earthquake Data Center, web site: http://www.ncedc.org/