ANNUAL REPORT

Approaching Seismology in the Source -

Earthquake Source Studies at LVEW and SAFOD, Year II:

Parkfield and Mammoth studies from vertical seismic arrays

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Key Words:

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Investigations undertaken

In this project we continued studies of the near-source structure, surrounding rock and fluid properties, and source parameters of microearthquakes recorded on deep-well geophysical instruments at Parkfield and Long Valley. In July 2002 we placed a Vertical Seismic Profiling array of 3-component seismographs in the 2.1 km deep SAFOD Pilot Hole. In August 2003, in cooperation with the USGS and Carnegie Institute of Washington, we installed a smaller VSP array in the 2.6 km deep Long Valley Exploratory Well. Based on new data obtained in 2004 from the Parkfield array, we report here the observation of variable Vp/Vs ratios along the PH and along the SAF. We also report the completion of a PhD dissertation by J. Andres Chavarria on the Parkfield data under the support of this grant. Toward the end of our grant period we also made significant observation at both the SAFOD and LVEW sites, including the 9/28/04 Parkfield earthquake and the sequence of eastern California earthquakes that took place at the Adobe Hills, to the northeast of Long Valley.

The PH array has recorded both natural seismicity and surface shots, the latter being fired to help constrain the velocity models being used for earthquake location. During its first year of operation, the PH system detected 1210 microearthquakes in the SAFOD area, some with S-P times as little as 0.2 s. These seismograms have allowed us to analyze SAFOD site microearthquakes from a unique perspective. An example, an M _ 1.2 event located 10 km more-or-less directly below the array, is shown in Figure 1. These data have much higher signal-to-noise ratios than observations made on the surface [e.g., Abercrombie, 1997] and hence give very accurate measurements of travel times and incidence angles with depth along the array. Combined, these data by themselves have helped constrain the locations of ‘‘target earthquakes’’ for the SAFOD drilling effort [Oye et al., 2004], including two M _ 2 events in October 2003 that are currently under intense investigation for just this purpose. Data from surface networks and PH recordings have been used for event location and determination of the3-D velocity structure at the SAFOD site [Thurber et al., 2004; Roecker et al., 2004]. Because of its length, close sensor spacing, and sensitivity to all 3-components of seismic motion, the array of Omni seismometers can give direct measurements of ray parameters, local attenuation, and separation of wave types.

For instance primary P and S wave phases can be easily identified by their moveouts (P waves faster than the S; Figure 1). In the following section we discuss measurements of this sort and their relationship to the PH area geology and physical properties of the SAF.

Our study of their moveouts has allowed us to distinguish a number of secondary phases besides the direct P- and S-waves. For example, the event in Figure 1 contains a number of secondary phases between the P and S waves and also after the S wave. Such arrivals are common features of both deep and shallower earthquakes and they have been the focus of other studies we have published [Chavarria et al., 2003]. We have identified them as different types of converted waves associated with secondary faults adjacent to the SAF.

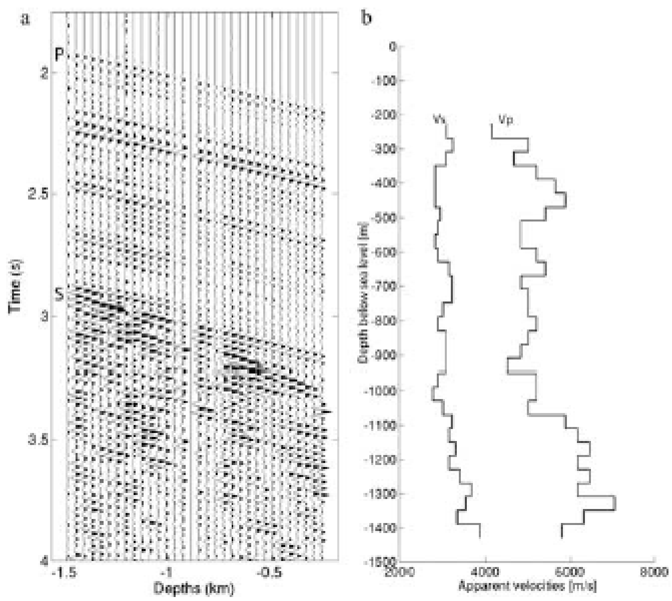

Figure 1. (a) A variable density wiggle plot of the vertical component of a magnitude 1.2 earthquake recorded on the SAFOD Pilot Hole array. Depths are in meters below sea level. The depth of the event hypocenter was 10 km. The secondary phases seen between the P- and S-waves were analyzed by *Chavarria et al.* [2003] and interpreted as signals reflected and scattered from nearby faults. (b) The depth dependent apparent P-and S-velocities of this event as measured on the 32 levels of 3-component sensor along the 1240 m long array.

We have also been able to identify converted waves from the SAF itself. These particular secondary signals appear to be P-S conversions. They appear to originate in areas that have been suggested to contain either fractured rock with fluids and/or materials like clays [Unsworth et al., 1997], or buried sedimentary rocks with fluids [Park and Roberts, 2003].

Results.

Surface-explosion and microearthquake seismograms recorded by the array give valuable insights into the structure of the SAFOD site. The ratios of P- and S-wave velocities (Vp/Vs) along the array suggest the presence of two faults intersecting the PH. The Vp/Vs ratios also depend on source location, with high values to the NW, and lower ones to the SE, correlating with high and low creep rates along the SAF, respectively: See Figure 2. Since higher ratios can be produced by increasing fluid saturation, we suggest that this effect might account for both our observations and their correlation with the creep distribution.

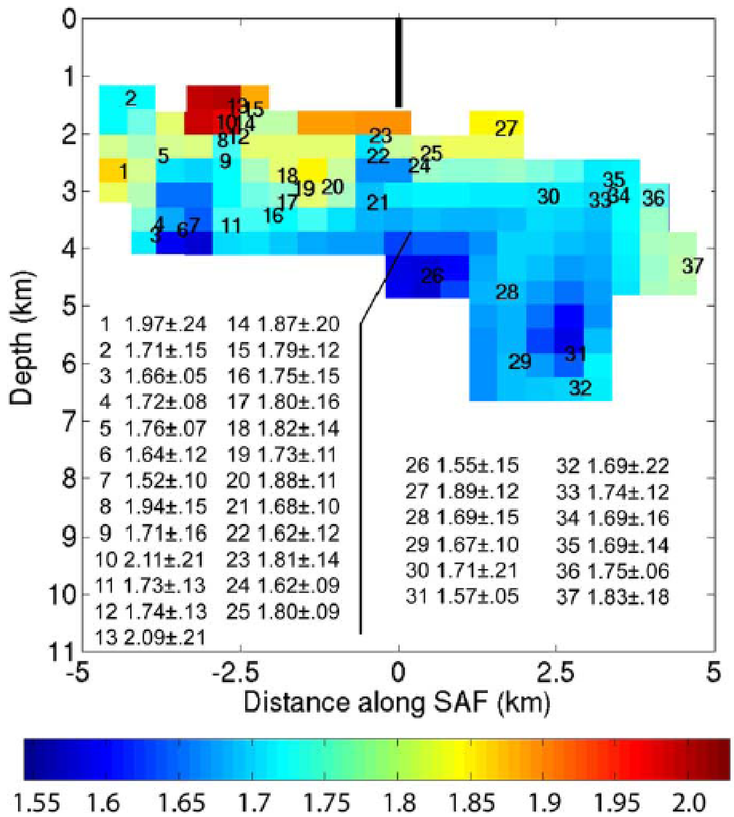

Figure 2. Cross section along the SAF with Vp/Vs ratios. This cross section shows earthquake hypocenter locations (the numbers corresponding to the list of Vp/Vs values below the cross section), the location of the SAFOD PH array (the solid line at the coordinate origin), and the values of their associated Vp/Vs ratios. The depths are given in kilometers below sea level. The thin solid line separates events along the NW creeping segment of the fault, with higher Vp/Vs ratios, from events along the more locked SE segment, with lower Vp/Vs ratios.

The array 32 3-component seismometers in the SAFOD Pilot Hole has allowed us to observe microearthquake waves from the SAF in unique ways. Earthquake data recorded on these instruments carries the benefit of high signal-to-noise ratios even for small events. The PH data alone can be used to find their locations [Oye et al., 2004]. Further, the multiple levels and overall lengths of the array provide important information about the velocity structure both in the vicinity of the PH and along the SAF.

In the area of the PH, we have interpreted two zones of high Vp/Vs ratios as indicating the presence of significant faults, one of which lies near the base of the PH. This structure should be encountered during the drilling of the SAFOD borehole in the summer of 2004. Further away, along the SAF, we have found that Vp/Vs ratios are lower to the SE of the PH, correlating with the decrease in creep rate. Based on our interpretation that lower Vp/Vs ratios represent regions of lower fracture density and lower fluid saturation and pressure, we suggest that our results support the hypothesis that the fault begins to lock to the SE because of a lack of such features. If so, then it is these features that lubricate the fault and allow it to creep, a hypothesis that the SAFOD borehole will at long last test.

Non-technical Summary

The San Andreas Fault Observatory at Depth (SAFOD) has the goal of understanding earthquake processes at hypocentral depths. In July 2002 Duke University installed a vertical array of seismometers in the SAFOD Pilot Hole (PH). Seismograms recorded by the array give insights into the structure of the SAFOD site. The array data suggest the presence of two faults intersecting the PH. The data also depend on source location, correlating with high and low creep rates along the SAF. Since our observations can be produced by increasing fluid saturation, this effect could be guiding the seismicity and creep along this segment.

Reports published

Chavarria, J. A., P. E. Malin, and E. Shalev (2004), The SAFOD Pilot Hole seismic array: Wave propagation effects as a function of sensor depth and source location, Geophys. Res. Lett., 31, L12S07, doi:10.1029/2003GL019382.

Availability of seismic, geodetic, or processed data

All the data discussed in this Annual Report are available through 3 sources: 1. The Northern California Integrated Seismic Network Data Center: http://www.cisn.org/; 2. The United States Geological Survey, Menlo Park; and 3. The PI of this project:

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