Earthquake locations and three-dimensional fault zone structure along the creeping section of the San Andreas fault near Parkfield, CA: Preparing for SAFOD

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1Introduction

The basic plan of the San Andreas fault-zone drilling project, known as SAFOD (San Andreas Fault Observatory at Depth), is to penetrate the fault near Parkfield, CA, at seismogenic depths. In a second phase, satellite core holes will be drilled off the main hole to sample the fault at several points, including in the vicinity of the rupture patch of a magnitude ~2 repeating earthquake. In order to facilitate the drilling plans, we are using data from local earthquakes recorded on a dense array of surface and borehole seismometers to image the kilometer-scale three-dimensional (3D) structure of the region around the drill site and provide well-constrained location estimates for potential drilling target earthquakes.

2Data and Analysis

A temporary seismic array, known as PASO (Parkfield Area Seismic Observatory), was installed around Parkfield, CA, in stages starting in July 2000 (Figure 1). Initially, 15 recording instruments from the Incorporated Research Institutions for Seismology (IRIS) Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL) were deployed, all with 3-component short-period (1 Hz) sensors. In June and July of 2001, the 15-station array was augmented by the installation of 44 additional PASSCAL 3-component telemetry stations within the aperture of the original array, and 2 of the original stations were moved. 36 of the new sites were installed with broadband sensors, and the remainder with short-period (1 Hz) sensors.

Approximately 35,000 arrival times for first P and S waves (60% P, 40% S) from 6 explosions and 453 local earthquakes were included in a joint inversion for earthquake locations and 3D Vp and Vp/Vs structure, using the iterative damped least squares algorithm simull2000 [Thurber and Eberhart-Phillips, 1999]. All but 9 of the events included in the inversion (6 earthquakes and 3 explosions) were recorded by stations of the PASO array. We obtained data from the UC-Berkeley High Resolution Seismic Network (HRSN) and from the USGS Central California Seismic Network for about 350 earthquakes and 3 of the explosions, and from USGS temporary stations for 3 earthquakes and 3 of the explosions. The sample rates for the PASO and the USGS stations are 100 sps, whereas it is 250 sps for the HRSN. Node spacing for the model ranged from 1 to 3 km in the direction normal to the SAF, 2 to 3 km parallel to the SAF (Figure 1), and 1 to 3 km in depth. The coordinate origin is at 35°58.20′N, 120°31.35′ at a point on the SAF trace (M. Rymer, personal communication), and the coordinate system is rotated 40°.

Based on prior studies and our preliminary results with a smaller dataset, the initial velocity model included a contrast in Vp across the fault (southwest side ranging from 0.3 to 0.6 km/s faster) from the surface to 5 km depth, in order to speed convergence. A trade-off analysis between damping values, solution size, and misfit was used to select appropriate damping levels, with different damping values...
used for Vp and Vp/Vs. Our final solution achieved a 72% reduction in data variance compared to the initial model, with a final overall RMS misfit of 0.05 s (0.03 s for P, 0.09 s for S). Calculated model uncertainties are 2 to 3% for Vp and about 1% for Vp/Vs in the regions with acceptable resolution (diagonal element >0.25). To test the robustness of our results, the model presented here was compared to that from an inversion using a different algorithm employing a finite-difference method for travel time calculations on a 200-m grid, and inversions were carried out with both shifted grids and finer grids, as well as with synthetic data based on the actual observations. The features we discuss are present and stable in all these tests, and well above the uncertainty level in the final model.

3. Results

The 3D structure around Parkfield is dominated by the velocity contrast across the SAF, as expected based on previous tomography studies [Lees and Malin, 1990; Michelini and McEvilly, 1991; Eberhart-Phillips and Michael, 1993]. Overall, P wave velocity variations along the fault strike are relatively modest. The P wave velocities on the SW side of the fault are typically 1 km/s (20–25%) faster than those to the NE in the depth range (relative to sea level) of about 2 to 7 km (Figures 2a–2c), a contrast that is typical of that found in many fault-zone studies [Mooney and Ginzburg, 1986; Eberhart-Phillips et al., 1995]. At shallow depths, our Vp model is consistent with the high-resolution refraction model of Hole et al. [2001], which approximately coincides with our Y = −3 km section (Figure 2b). Many details in the Vp structure are also consistent with the MT resistivity models of Unsworth et al. [1997, 2000], which also fall within our model. These include (1) an apparent vertical offset in the basement about 4 km SW of the SAF, (2) a roughly 1-km-wide zone extending to a depth of about 3 km on the SW side of the SAF where a very-low-resistivity zone coincides with a drop in Vp, and (3) a region NE of the SAF extending to as deep as about 8 km near the SAF, and shallowing to the NE.

Figure 1. Map view of the PASO array and permanent network stations (triangles) along the SAF near Parkfield, CA. Fault traces are indicated by the lines, filled circles are our relocated epicenters, and nodes used for the 3D inversion are indicated by crosses.

Figure 2. (a–f). Selected SW-NE cross-sections through the 3D models of Vp (a–c) and Vp/Vs (d–f) structure. The SAF trace is at 0 km, and depths are relative to sea level. Vp values are in km/s, and Vp/Vs values are dimensionless. Earthquakes within 1 km of the section are shown as filled circles. The white dashed line indicates the region considered to be resolved adequately (resolution matrix diagonal element >0.25).
where a low-resistivity zone coincides with a low Vp zone. We suggest that the zone of reduced seismic velocities just SW of the seismic activity (2 above) marks a damage zone in the granites adjacent to the fault. We note that most of the earthquakes lie very close to the surface trace of the SAF, consistent with the findings of Eberhart-Phillips and Michael [1993]. The one notable exception is a deeper zone of seismicity in the southeastern part that is offset to the SW from the fault trace (Figure 2c), consistent with the results of Michelini and McEvilly [1991].

[8] Variations in Vp/Vs are substantial both across and along strike (Figures 2d–2f). Perhaps the most salient feature is a high Vp/Vs zone adjacent to the SAF. We associate this zone with the low-resistivity fault zone in the MT model of Unsworth et al. [1997, 2000], interpreted to be fluid-rich [Eberhart-Phillips et al., 1995]. Toward the NW, a shallow high Vp/Vs zone is present on both sides of the fault, whereas to the SE, in the vicinity of the 1966 Parkfield hypocenter, this zone lies along SW of the fault and penetrates to substantial depth (about 9 km); however, resolution in this part of the model is relatively low. A zone of high Vp/Vs near the Parkfield hypocenter was previously reported by Michelini and McEvilly [1991]. High Vp/Vs values are also present at about 2 to 6 km depth towards the NE in some sections (X = 2 to 4 km, Figures 2d and 2e), consistent with the presence of fluids and low resistivities at the base of the Parkfield syncline [Jongmans and Malin, 1995; Unsworth et al., 1997, 2000]. On the SW side of the fault, Vp/Vs values typical of granites (<1.7) are present where the model is well resolved, consistent with the presence of Salinian basement [Page, 1981].

[9] In March 2001, our array recorded a magnitude ~2 earthquake that is a potential target repeating event for the final stage of SAFOD drilling (W. Ellsworth, personal communication). Our location for the event (2001-03-17, 03 h 30 m 24.38 s, 35°59.18′N, 120°32.46′W, 2.45 km deep) indicates that it is about 100 m SW of the SAF surface trace and 3.1 km below the surface. The calculated location uncertainties are 64 m in epicenter and 86 m in depth (2σ), but in an absolute sense the uncertainties are larger. This is mainly due to inadequate constraints on the very near surface velocity structure (mainly the top 500 m), a situation that will be improved by planned active-source experiments and borehole seismic observations [Zoback, 2001].

[10] We carried out two non-linear analyses to investigate further the issue of relative and absolute location uncertainty for this target event. Using a grid search location algorithm with the 3D model and a 200 m grid, we calculated probability density functions (PDFs) [e.g., Tarantola and Vallette, 1982; Rittger et al., 2001] for the hypocenter of the target event using the estimated arrival time uncertainties and adding an additional 2% uncertainty to allow for unmodeled wave speed error. The PDF contours are relatively symmetric about a vertical axis. The PDF was integrated over the coordinate normal to the SAF to produce a marginal PDF (MPDF), which was integrated again to show the confidence regions at various levels (Figure 3), indicating a 95% confidence region (the outermost contour) of 300 m horizontally and 700 m vertically. This provides a fully non-linear estimate of relative location uncertainty. We also carried out a suite of full simultaneous inversions for location and 3D structure with the same dataset but treating this target event as a “blast” - an event of known (fixed) location but unknown origin time. The fixed location was varied systematically from the above “free” solution to determine an estimate of the 95% confidence region for the absolute location. Figure 4 shows contours of the solution variance for the target event as a function of offset from the
free solution in depth and longitude (again, the contours are relatively symmetric about a vertical axis). The 95% confidence region extends about 200 m horizontally and about +200 m/−550 m vertically.

4. Discussion and Conclusions

[11] The inversion of arrival-time data from local earthquakes along the Parkfield, CA, section of the SAF recorded by a dense temporary seismic array, augmented by permanent network data, provides the most detailed view yet of the 3D structure of the SAF at seismogenic depths. The primary features of the models for Vp and Vp/Vs structure are generally consistent with the results from previous work. There is a very strong and relatively sharp velocity contrast across the SAF, on the order of 20–25%, with the SW side fast, consistent with previous studies. The bulk of the seismic activity is concentrated approximately beneath the fault trace. Regions of high Vp/Vs are found at shallow depths near the fault trace and in the vicinity of the 1966 Parkfield main shock hypocenter (the latter consistent with Michelini and McEvilly [1991], although not well resolved in our model), strongly suggestive of the presence of fluids in the fault zone. We note, however, that these high-Vp/Vs regions are virtually aseismic, indicating that fault slip in these zones occurs either as creep or via dynamic rupture in larger earthquakes such as the 1966 event. A detailed analysis of relative and absolute location uncertainty for a potential target event for drilling, estimated to be 100 m SW of the SAF trace and 3.1 km below the surface, indicates horizontal and vertical uncertainties on the order of 200–300 m and 500–700 m, respectively.

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References


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