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Felix Waldhauser
U.S. Geological Survey

William L. Ellsworth
U.S. Geological Survey

Alex Cole
U.S. Geological Survey

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Felix Waldhauser, William L. Ellsworth, and Alex Cole

U.S. Geological Survey, Menlo Park, California

Abstract. A high-resolution relative earthquake location procedure is used to image the fine-scale seismicity structure of the northern Hayward fault, California. The seismicity defines a narrow, near-vertical fault zone containing horizontal alignments of hypocenters extending along the fault zone. The lineations persist over the 15-year observation interval, implying the localization of conditions on the fault where brittle failure conditions are met. The horizontal orientation of the lineations parallels the slip direction of the fault, suggesting that they are the result of the smearing of frictionally weak material along the fault plane over thousands of years.

Introduction

Ideas about the nature of earthquakes, and in particular their spatial and temporal distribution range from purely stochastic models [*Kagan*, 1982] to those in which earthquakes are organized in both space and time [*Oppenheimer et al.*, 1988; *Vidale et al.*, 1994; *Nadeau et al.*, 1995]. A major impediment to a better understanding of the processes that control earthquake occurrence and interaction is the poor spatial resolution of earthquake locations routinely determined by seismic networks. This is particularly problematic for the imaging of structures within the core of active faults, because the errors in network location (several hundred meters, with depth more poorly constraint than the epicenter) are typically many times larger than the spatial dimensions of the earthquakes themselves (10 m to 200 m for M1-2 earthquakes).

Here we present high precision, relative event locations that resolve the fine scale structure of seismicity along the northern Hayward fault, California (Figure 1). We use the U.S. Geological Survey's Northern California Seismic Network (NCSN) catalog travel-time data together with waveform analysis methods and a joint relative hypocenter determination algorithm to locate the earthquakes. We find a characteristic pattern of horizontal alignments of hypocenters within the fault zone.

Earthquake Relocation Method

The accuracy of hypocenter locations is controlled by several factors, including the network geometry, available phases, arrival time reading accuracy, and knowledge of the crustal structure [*Pavlis*, 1986; *Gomberg et al.*, 1990]. The effects of errors in structure can be minimized by using relative location methods [*Got et al.*, 1994; *Shearer* 1997]. We can further improve the locations by improving the accuracy of the arrival time readings. Given a high degree of signal similarity, the differential P- and S-wave travel times between two earthquakes at a specific station can be determined with sub-sample accuracy by cross- spectral analysis [*Poupinet et al.*, 1984] (Figure 2). Two waveforms recorded at a specific station are considered similar when half of the coherency values exceed 0.9 in the frequency range 2-10 Hz of a tapered 2.56 s (256 samples) window containing the P-wave or S-wave train. The travel-time difference, *dt*, between two windowed signals is proportional to the slope of the phase of the cross spectrum. Cross correlation measurements are particularly important for S- waves, for which the first arrival time cannot be picked to even 200 msec, whereas the differential travel time can be measured to 1-2 msec from data digitized at 10 ms intervals.

To maximize the value of the cross-correlation measurements, we use a double difference relocation method that directly uses differential travel times. The name "double-difference" comes from the use of the residual between the observed (dt^{obs}) and calculated (dt^{cal}) travel-time difference for a pair of events as the data. Ordinary joint-hypocenter-determination methods require absolute travel times that sacrifice the accuracy of cross-correlation data. We combine P- and S-wave differential travel times derived from waveform cross correlation and P-wave catalog travel-time differences into a system of linear equations with each event pair (*k*,*l*) at each station (*i*) forming the equation

$$\begin{bmatrix} \frac{\delta t_{ik}}{\delta \mathbf{n}} & -\frac{\delta t_{il}}{\delta \mathbf{n}} \end{bmatrix} \begin{bmatrix} \mathbf{r}_k \\ \mathbf{r}_l \end{bmatrix} = dt_{ikl}^{obs} - dt_{ikl}^{cal}, \qquad (1)$$

where $\mathbf{r}$ is the relocation vector and $\mathbf{n}$ is the 4-vector of cartesian coordinates and origin time. A layered 1D velocity model for the area of investigation is used to compute the partial derivatives and dt^{cal} in equation (1). The system of linear equations is solved by means of weighted least-squares with weights according to the a priori data uncertainty and misfit during iteration. Catalog data are typically down-weighted by a factor of 1000. Initial hypocenter locations are obtained from the catalog, and the inversion process is then iterated with the hypocenters, slowness vectors and weights updated at each step. The mean location of all earthquakes does not move during relocation.

By combining the cross-correlation travel times with first motion travel times we are able to determine inter-event distances between correlated events that form a single multiplet to the accuracy of the cross-correlation data while simultaneously determining the relative locations of other multiplets and uncorrelated events to the accuracy of the absolute travel-time data. It should be noted that because waveform cross correlation measures the whole earthquake radiation process, the earthquake locations based on these measure-

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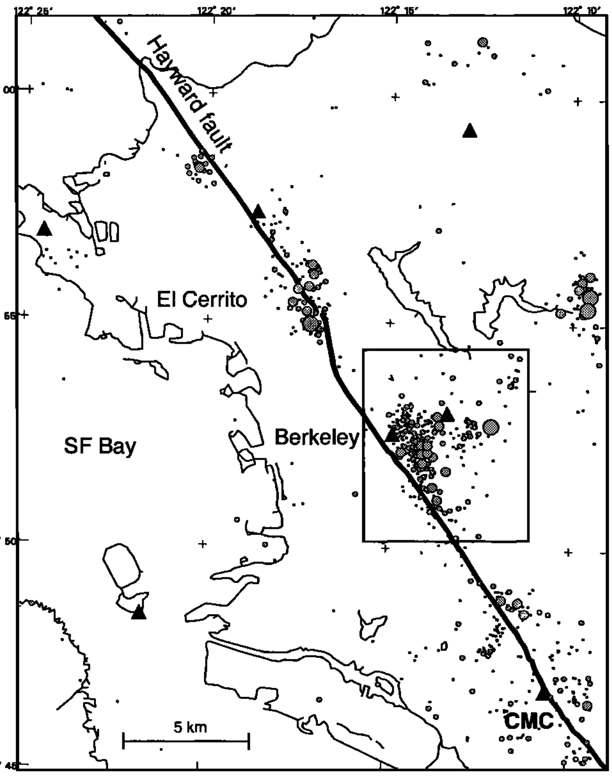

Figure 1. Hayward fault seismicity 1984 - 1998 as located by the Northern California Seismic Network (NCSN). Circles represent epicenters with size proportional to magnitude in the range from M0 to M4. Black triangles represent seismometer locations. Solid line maps surface trace of the Hayward fault. Box indicates area shown in Figure 2A,C.

ments are the positions of the centers of moment release or hypocentroids. In contrast, the first motion travel-time data measure the initiation points of ruptures, or hypocenters.

Relocation Results

We applied the double-difference relocation method to two earthquake clusters of about 300 earthquakes on the northern Hayward fault (Figure 1) near Berkeley and El Cerrito, respectively. The earthquakes were recorded by the NCSN between 1984 and 1998 and have magnitudes from M1.0 to M4.1. We measure about 19,000 differential times by cross correlation (37 % of which are S-waves), in addition to about 570,000 P-wave travel-time differences that we obtain from the catalog. Figure 3A,B shows the NCSN catalog locations of earthquakes in the Berkeley cluster. The seismicity forms a northwest-striking zone associated with the Hayward fault (inside box, Figure 3A), and a diffuse zone of earthquakes about 2 km northeast of the fault zone (outside box, Figure 3A). In cross section, the catalog locations of earthquakes along the fault zone are scattered, but tend to concentrate at depths around 10 km (Figure 3B). After relocation (Figure 3C,D) a sharp picture of seismicity is obtained with average horizontal and vertical 2σ relative location errors of 15 m and 34 m, respectively.

In map view, the on-fault seismicity collapses to a thin line (Figure 3C), with hypocenters located at depths between 3 and 13 km (Figure 3D). The relocations define a nearly planar, vertical fault zone striking in direction of the surface trace of the Hayward fault [*Oppenheimer et al.*, 1993]. The events on the planar fault are preferentially arranged in linear, horizontal arrays of hypocenters (Figure 3D) similar to results recently reported for the San Andreas fault [*Rubin et al.*, 1998]. Such lineations, although not as pronounced, are contained in the cluster of earthquakes to the NE of the fault near Berkeley (Figure 3C) and in the cluster near El Cerrito (see Figure 1 for location). The lineations in the El Cerrito cluster occur a 5 km and 9 km depth. We performed several tests to rule out the possibility that the lineations and/or their relative position to each other are an artifact of the relocation procedure. Relocation of some multiplets using P-wave and S-wave data independently results in nearly identical structures. These structures are also robust against changes in the velocity model used to determine the partial derivatives as well as against variations in the initial hypocenter locations.

We focus on the two longest lineations in the Berkeley cluster at about 10 km depth (Figure 3D) and in the El Cerrito cluster at about 5 km depth, respectively. To obtain a more accurate picture of the highly correlated events in these lineations, we separately relocate the correlated events in the Berkeley and the El Cerrito multiplet using only the cross-correlation P- and S- wave travel times (Figure 4). As we are using only cross-correlation differential travel times, the resulting locations are strictly hypocentroid locations. For each multiplet, we obtain location uncertainties in the range of a few meters to a few tens of meters and *rms* travel-time residuals that are similar to the error with which cross-correlation travel-time differentials are measured (1-2 msec).

Discussion and Conclusion

A constant stress-drop, circular earthquake rupture model [*Brune*, 1970] is used to explore the spatial characteristics of the two multiplets. In Figure 4 the earthquakes are represented by their rupture area computed with an assumed stress drop of 3 MPa. Note that the assumption of an average stress-drop of 3 MPa is not critical because rupture dimension scales as the cube-root of the stress drop for a given magnitude. The hypocentroids are projected onto the fault plane over perpendicular distances smaller than 60 m.

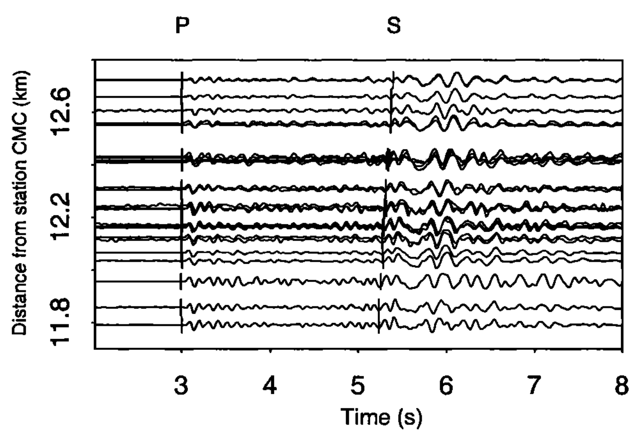

Figure 2. Seismograms (bandpass filtered between 0.1 and 8 Hz) of events located in the Berkeley cluster and recorded at station CMC (see Figure 1). Seismograms are aligned on the P-arrival. Relative position of P- and S-wave picks derived by waveform cross correlation are indicated. The move-out of the S arrivals for events at greater distance from the station is clearly visible.

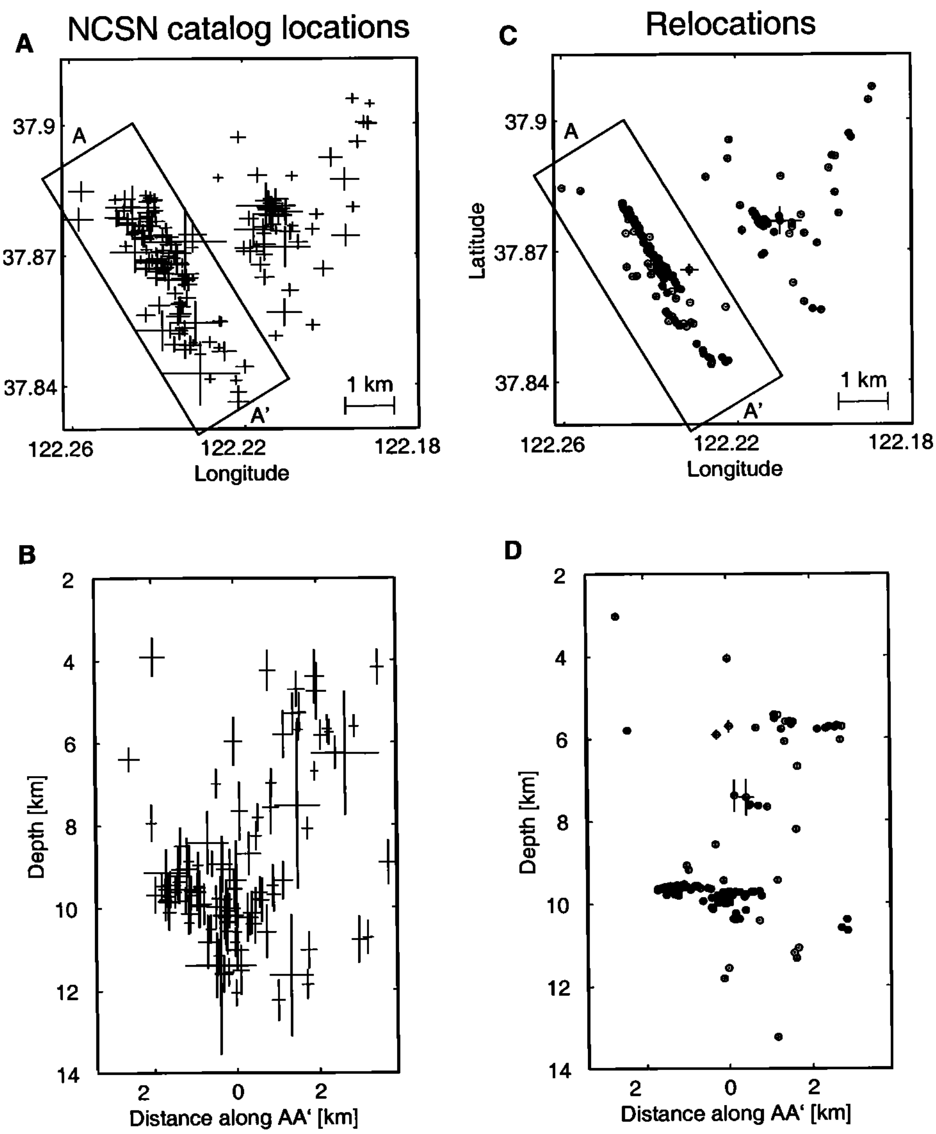

Figure 3. Seismicity near Berkeley before and after relocation. Map view (A) and longitudinal cross section (B) of routinely-determined hypocenters (NCSN catalog locations). Hypocenters are represented by crosses that indicate the 1σ confidence interval (A,B). Map view (C) and longitudinal cross section (D) of hypocenters after relocation. Relocated events are marked by a solid circle if they correlate and by an open circle if they do not correlate. Relative location uncertainties (2σ) are shown and average about 50 m. The box in the upper panels outline the area that includes the seismicity shown in the lower panels.

Strong overlapping of source areas at some locations in both clusters suggests that subsequent events re-rupture the same fault area, since their hypocentroids are nearly identical. In contrast to creeping portions of the San Andreas fault and Calaveras fault [*Vidale et al.*, 1994; *Nadeau et al.*, 1995] where repeating earthquakes are the norm, the two Hayward fault clusters less frequently exhibit repeating behavior. Most events occupy distinct areas on the fault plane that are in close proximity to one another. The few events with identical sources repeat no more than three times within the 15 year observation interval, whereas repeats on the creeping part of the San Andreas fault have been found to occur about five times more often [*Nadeau et al.*, 1995]. The slow repeat rate is suggestive of a high frictional resistance on the fault patch. This is consistent with findings from repeated geodetic surveys across the Hayward fault indicating that the fault is frictionally locked between about 3 and 13 km depth [*Savage and Lisowski*, 1993].

The horizontal, linear alignment of the hypocenters on the fault plane is unlikely to be the result of a purely stochastic process, and argues for an underlying structural or mechanical control. One possibility is that these lineations mark stress concentrations on the fault, such as at the edge of a rising screw dislocation. The alignments on the Hayward fault, however, are stationary and contain some repeating earthquake sources, making this explanation somewhat unlikely. Fluid pressure models (for a review see *Hickman et al.*, [1995]) may explain elongated seismicity concentration through periodic rupturing of a low-permeability seal that acts as a barrier against upwelling fluids within the fault zone. However, we observe lineations at depths that are too shallow for the process of chemical sealing, and also lack evidence for vertical growth of the lineations over the 15-year observation period. The lineations could mark the intersection of different rock strata with the fault plane. In this case, however, it is unlikely that only horizontal in-

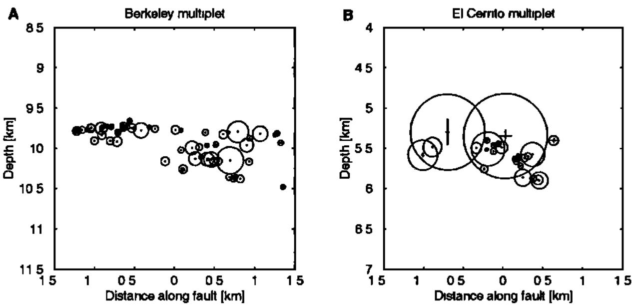

Figure 4. Relative locations of correlated earthquakes from prominent lineations in the Berkeley cluster (A) and the El Cerrito cluster (B). The Berkeley multiplet contains 72 events (50% of the local seismicity), the El Cerrito multiplet contains 27 events (30% of the local seismicity). Earthquakes are represented by circular fault areas for a 3 MPa constant stress drop source model. The hypocentroid of each rupture is marked by 2σ location error. Average horizontal and vertical errors are 7 m and 15 m, respectively. Figure 2 shows the seismograms of events located in the left half of the Berkeley multiplet.

tersections would occur. Similar horizontal alignments of hypocenters have been found in the rift zones of Kilauea volcano, Hawaii, where it has been interpreted a being associated to the brittle-ductile transition [*Gillard et al.*, 1996]. The brittle- ductile transition might play a role in the location of the deepest lineations, but cannot explain their presence at multiple depth levels.

The pronounced linearity of the multiplets, particularly for events within the Berkeley cluster, suggests a mechanical origin because the alignment is co- linear with the horizontal slip direction of the Hayward fault. Such a horizontal alignment could arise through a wear process in which the host rock in contact with the fault zone core [*Chester et al.*, 1993] is smeared out along the slip direction as a consequence of cumulative fault displacement. Lineations of one to several km length would take about 100,000-300,000 years to form at a slip rate of 9 mm/year [*Savage and Lisowski*, 1993]. Thus, these earthquakes may define very long-lived seismic structures that persist through many earthquake cycles. Spatially stable patterns of microearthquakes have been noted to persist through one to a few cycles of adjacent M4-M6 earthquakes elsewhere within the San Andreas fault system [*Ellsworth*, 1975; *Oppenheimer et al.*, 1988; *Vidale et al.*, 1994].

As the static strength of brittle materials varies from one rock type to another [*Byerlee*, 1978], these lineations may outline the weakest material on the fault plane, where failure will initiate at the lowest stress level. We can not resolve whether the earthquakes occur within streaks of weak but brittle material, or whether stress is concentrated around weak ductile material.

The double difference earthquake location procedure introduced here successfully resolves fine scale structural details within the core of the Hayward fault. It reveals characteristic horizontal alignments of hypocenters that extend along the fault zone, indicating that the spatial distribution of earthquakes is organized rather than random. This method provides a powerful new tool for the study of other seismicity structures, such as segment boundaries and fault bends that are believed to play important roles in the initiation and arrest of rupture.

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F. Waldhauser, W.L. Ellsworth, and A. Cole, U.S. Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025. (e-mail: felix@andreas.wr.usgs.gov)

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