Slip-Parallel Seismic Lineations on the Northern Hayward Fault, California

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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 fractionally 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 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 differences 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

\[
\frac{\delta t_{ik}}{\delta n} - \frac{\delta t_{il}}{\delta n} \begin{bmatrix} r_k \\ r_l \end{bmatrix} = dt_{ik}^{obs} - dt_{ik}^{cal},
\]

where \(r\) is the relocation vector and \(n\) 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-
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 cat-
alog 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 be-
tween 3 and 13 km (Figure 3D). The relocations define a
nearly planar, surface 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 ar-
 ranged 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 possi-
bility that the lineations and/or their relative position to
each other are an artifact of the relocation procedure. Re-
location 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 rep-
resented by their rupture area computed with an assumed
stress drop of 3 MPa. Note that the assumption of an av-
erage stress-drop of 3 MPa is not critical because rupture
dimension scales as the square-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 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-
method provides a powerful new tool for the study of other bends that are believed to play important roles in the initiation structures, such as segment boundaries and fault.

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References


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