Horizontal polarization of ground motion in the Hayward fault zone at Fremont, California: dominant fault-high-angle polarization and fault-induced cracks

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SUMMARY
We investigate shear wave polarization in the Hayward fault zone near Niles Canyon, Fremont, CA. Waveforms of 12 earthquakes recorded by a seven-accelerometer seismic array around the fault are analysed to clarify directional site effects in the fault damage zone. The analysis is performed in the frequency domain through H/V spectral ratios with horizontal components rotated from 0° to 180°, and in the time domain using the eigenvectors and eigenvalues of the covariance matrix method employing three component records. The near-fault ground motion tends to be polarized in the horizontal plane. At two on-fault stations where the local strike is N160°, ground motion polarization is oriented N88° ± 19° and N83° ± 32°, respectively. At a third on-fault station, the motion is more complex with horizontal polarization varying in different frequency bands. However, a polarization of N86° ± 7°, similar to the results at the other two on-fault stations, is found in the frequency band 6–8 Hz. The predominantly high-angle polarization from the fault strike at the Hayward Fault is consistent with similar results at the Parkfield section of the San Andreas Fault and the Val d’Agri area (a Quaternary extensional basin) in Italy. In all these cases, comparisons of the observed polarization directions with models of fracture orientation based on the fault movement indicate that the dominant horizontal polarization is near-orthogonal to the orientation of the expected predominant cracking direction. The results help to develop improved connections between fault mechanics and near-fault ground motion.

Key words: Earthquake ground motions; Interface waves; Site effects; Wave propagation.

1 INTRODUCTION
Large fault zones contain belts of damaged rocks with high crack density and granular materials that extend over widths ranging from tens to hundreds of metres (Ben-Zion & Sammis 2003, and references therein). These damage zones have reduced elastic moduli that lead to amplification of seismic motion. Spudich & Olsen (2001) found a large amplification for 0.6–1.0 Hz waves within ~1–2 km wide low-velocity zone around the rupture of the 1984 Morgan Hill earthquake. Seebert et al. (2000) and Peng & Ben-Zion (2006) documented a factor 5 amplification of acceleration in a station located in the rupture zone of the 1999 Izmit earthquake on the Karadere branch of the North Anatolian Fault with respect to nearby off-fault station. Calderoni et al. (2010) observed a large difference in amplification between earthquakes occurring inside and outside the Pagancìa–San Demetrio Fault during the 2009 April L’Aquila earthquake sequences, central Italy.

Low-velocity fault zone layers having sufficiently coherent geometrical and material properties over length scales of several kilometres or more produce trapped waves that result from constructive interference of critically reflected phases (Ben-Zion & Aki 1990; Li & Leary 1990; Li et al. 1997). Trapped waves with considerable motion amplification have been observed along many active faults (e.g. Li et al. 1990; Ben Zion et al. 2003; Peng et al. 2003; Mizuno & Nishigami 2004; Lewis et al. 2005) as well as near a dormant fault (Rovelli et al. 2002; Culfira et al. 2003). The basic form of trapped waves is Love-type with particle motion parallel to the fault zone layer (i.e. fault-parallel and vertical). However, small changes in the fault zone geometry can produce converted SV and P phases with particle motion normal to the fault. Examinations of large seismic data sets recorded by numerous fault zone stations indicate that while signatures of rock damage are abundant along faults, clear trapped waves are observed only in spatially limited fault sections (e.g. Mamada et al. 2004; Pitarka et al. 2006; Lewis & Ben-Zion 2010).
In several recent studies, polarization of shear waves near faults was found to have a high angle to the fault strike. In four faults of Mt Etna (the Tremestieri, Pernicana, Moscarello and Acicatena faults), Rigano et al. (2008) observed that seismic signals are strongly polarized and their orientation is not fault-parallel as would be expected for trapped waves. Using both volcanic tremor and local earthquakes, Falsaperla et al. (2010) found a strong polarization at seismological stations in the crater area of Mt Etna, with polarization directions varying by site but everywhere transversal to the orientation of the predominant local fracture field. Similarly, Di Giulio et al. (2009) found very stable polarization angles on Mt Etna, in the NE rift segment and in the Pernicana Fault at Piano Pernicana, with horizontal polarization that again was not parallel to the fault strike. They used the expression ‘directional resonances’ introduced by Bonamassa & Vidale (1991) who observed site effects characterized by narrow-band horizontal amplification with varying amplitudes along site-dependent azimuths during aftershocks of the Loma Prieta earthquake.

Di Giulio et al. (2009) ascribed the effect to local fault properties hypothesizing stress-induced anisotropy and microfracture orientation in the near-surface lavas.

Numerous studies documented seismic anisotropy effects close to large fault zones. Boness & Zoback (2006), Liu et al. (2008) and others documented anisotropy of shear wave velocity near the Parkfield section of the San Andreas Fault with approximately fault-parallel fast polarization direction. Savage et al. (1990) found fast polarization direction of shear waves that is approximately parallel to the strike of nearby faults and the mean direction of P axes of earthquake focal mechanism in the Long Valley caldera region of California. Peng & Ben-Zion (2004) demonstrated shear wave splitting with a predominance of fault-parallel fast polarization near the Karadere–Duzce branches of the North Anatolian Fault. Fletcher et al. (1990) and Liu et al. (2005) documented anisotropy of shear wave velocity as well as anisotropy of seismic attenuation near the San Jacinto Fault zone in California and the rupture zone of the 1999 Chi-Chi earthquake in Taiwan.

The existence of cracks in fault zone environments with nearly fault-parallel direction implies anisotropic stiffness with more compliant response at high angle to the fault strike. This, in turn, should lead to motion amplification in the approximate fault-normal direction. In this paper, we investigate polarization of amplified ground motion across the Hayward Fault near Niles Canyon, Fremont, California and additional locations. Using seismic records of seven accelerometer stations installed by the US Geological Survey (USGS) in the Hayward Fault area since January 2008, we observe a tendency of on-fault stations to be polarized in the horizontal plane. This polarization in the region surrounding the fault shows a high angle from the fault strike. Numerical models of the fracture distribution in the fault damage zone indicate that the polarization direction is orthogonal to the expected fracture cleavage developed by the fault activity. The same orthogonal relation characterizes also other faults where ground motion polarization was investigated. The occurrence of a strong horizontal polarization may reflect reduced elastic stiffness in the direction orthogonal to the main fracture field.

2 GEOLOGICAL SETTING

The Hayward Fault belongs to the San Andreas system that separates the Pacific Plate and the Sierra Nevada microplate, accommodating 75–80 per cent (38–40 mm yr⁻¹) of the present relative motion between the Pacific and North American plates (e.g. Argus & Gordon 2001; Wakabayashi et al. 2004), with a total dextral displacement of around 600 km. The San Andreas system is composed of a set of major dextral strike-slip faults, whose activity and distribution has irregularly shifted during the transform fault system history (Wakabayashi 1999). Most faults show pull-apart basins and local transpressional structures related to step-overs and bends.

The Hayward Fault exhibits a quite complex structure with a general strike of N340°. It is predominantly a strike-slip right-lateral fault with about 100 km of offset during the past 12 Ma and at least a few hundred metres of east-up displacement over the past 2 Ma (Kelson & Simpson 1995; Graymer et al. 2002). The active surface trace of the Hayward Fault is well documented from both geomorphic evidence and offsets of man-made structures (Lienkaemper et al. 1991), revealing that it is undergoing a significant creep (Lienkaemper 1992; Savage & Lisowski 1993) with some aseismic patches accommodating 50 per cent or more of the long-term fault displacement. In spite of this, the fault has also experienced moderate to large earthquakes as the ~6.8 magnitude earthquake that occurred in 1868, whose surface rupture was >30 km long (Lawson 1908; Lienkaemper et al. 1991; Yu & Segall 1996; Bakun 1999). A palaeoseismological study in a trench on the Southern Hayward Fault (Fremont) by Williams (1992) concluded that at least six ruptures on the Hayward Fault occurred during the past 2100 yr.

The study area of this work (Fig. 1) is located in the southern sector of the fault in the Fremont district. Here, the Hayward Fault is largely aseismic and exhibits the highest surface creep rate (5 mm yr⁻¹) that is observed along the fault (Lienkaemper et al. 1991). A seismic reflection profile across the creeping trace of the fault indicates that the fault dip is about 70° to the east in the 100–650 m depth range (Williams et al. 2005). The area

![Figure 1](image-url). Location of the accelerometric array area (red square). Cyan lines are the projection of the faults belonging to the San Andreas fault system. Blue circles are the epicentres of the selected earthquakes with event number in Table 1, event date and estimated magnitude. The inset shows stations deployment near the Hayward fault trace at the surface as digitized by Lienkaemper et al. 2001 (red line).
surrounding the fault shows no significant topographic variation, a factor that could have a competing role in causing locally polarized motions (Pischiutta et al. 2011). The persistence of directional local effects in such a flat area confirms that factors other than topography control the polarization of ground motions.

3 DATA
To study ground motion polarization across the Hayward Fault, we used data recorded by an array installed by researchers of the US Geological Survey across the fault near Niles Canyon, Fremont. The array was composed of seven stations equipped with K2 Kinematics digitizer. Each accelerograph has a three-component set of accelerometers digitized at 200 sps. No instrumental correction was applied, as just one type of instrument was used and no data at periods longer than the eigenperiod of the sensor were interpreted. The stations were deployed in the backyards of family homes and are shown in the inset of Fig. 1 (coloured labels) together with the surface creep at the fault (red line) traced by Lienkaemper et al. (1991). The accelerographs were anchored to concrete and synchronized through a GPS receiver.

The array recorded earthquakes since 2008 July, including about 30 events between 2008 July and 2009 March with hypocentres available at the Northern California Earthquake Data Center (http://quake.geo.berkeley.edu/). The corresponding epicentres were located along the San Andreas fault system and have source depths in the range 5–16 km. From the seismic events recorded by the accelerograph array, we selected 12 events with high signal-to-noise ratios and with different focal mechanisms and source backazimuths ranging between N40W and N157E. The epicentres of these events are shown in Fig. 1 with the projections of faults surrounding the fault shows no significant topographic variation, a factor that could have a competing role in causing locally polarized motions (Pischiutta et al. 2011). The persistence of directional local effects in such a flat area confirms that factors other than topography control the polarization of ground motions.

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4 ANALYSIS AND RESULTS
The polarization analysis on the recorded seismic data was performed both in the time and frequency domains. The analysis in the frequency domain involved computing the horizontal-to-vertical spectral ratios (HVSRS), as functions of frequency and direction of motion, to investigate possible directional resonances and detect the frequency band where ground motion is mostly horizontal. The use of spectral ratios after rotation of the horizontal components was first introduced by Spudich et al. (1996), and subsequently exploited by Rigano et al. (2008) and Di Giulio et al. (2009) to detect horizontal polarization of ground motion in fault zones.

The HVSRS values are calculated at each station separately for each event. The employed time windows start from the P waves and include the S and early coda waves. The actual length varies from 10 to 20 s (depending on events magnitude) to include the significant portions of the recordings. A Hanning taper is then applied to the data. The spectra of horizontal motions were computed after rotating the NS and EW components by steps of 10°, from 0° to 180°. Amplitude spectra of the vertical and horizontal components were also smoothed with a running mean filter with a width of 0.5 Hz.

The mean HVSRS averaged over the 12 selected events are shown in Fig. 2. The stations are divided to ‘on-fault’ if they are within tens of metres from the surface trace of the fault trace and ‘off-fault’ if they are more than 100 m from the surface trace. In the upper panels, the 18 spectral ratios for different rotation angles (from 0° to 180°) are shown for each station, whereas the lower panels represent contour plots versus frequency and direction of motion. The on- and off-fault stations do not differ significantly in the HVSR amplitude levels. For all stations, horizontal motions tend to exceed the vertical ones in the approximate frequency band 1–7 Hz, with peak values of spectral ratios ranging from 3 to 4. Examining the top panels for on-faults stations (right column) suggests that the spectral ratio amplitudes at peaked frequencies show a distinct variation as a function of the rotation angle. However, a similar feature is also evident at ND4 station which is about 400 m from the fault trace. In a quantitative comparison between on- and off-fault stations it is difficult to infer a difference between their polarization tendency using the spectral ratios of Fig. 2.

To better quantify the horizontal polarization of stations, the covariance matrix method (Kanasewich 1981) was applied in the time domain. In this approach, a direct estimate of the polarization angle is achieved by computing the polarization ellipsoid through the eigenvalues and eigenvectors of the covariance matrix using the three-component data (Jurkevics 1988). The polarization ellipsoid is estimated over the employed time windows (with data including the P, S and coda waves) using a running window with 0.5 s width and a 20 per cent overlap. Records are bandpass filtered between 1 and 7 Hz according to their spectral content (Fig. 2).

The covariance matrix is calculated separately in each window with the basic assumption that each window shows only one dominant (or null) polarization. This assumes motions that are purely polarized over the window duration. The eigenvalues and eigenvectors are found by solving the algebraic eigenproblem: they are real and positive, since the covariance matrix is positive and semi-definite, and they, respectively, correspond to the axis length and to the axis orientation of the polarization ellipsoid that describe the particle motion in the data window. The polarization azimuth is estimated as the angle between the geographic north and the projection of the largest eigenvector on the horizontal plane (see Appendix A).

Compared to the previous applications of Rigano et al. (2008), Di Giulio et al. (2009) and Falsaperla et al. (2010), we use a hierarchical criterion to give a larger weight to time windows associated with polarization ellipsoids with a large horizontal component (i.e. high values of parameter L) and with a marked elongation (i.e. high values of parameter R). The parameters L and R are defined in Appendix A, where the details of the procedure are described. The results obtained from the analysis of the 12 earthquakes are combined, merging all the instantaneous polarization angles. The obtained trends of horizontal polarization are illustrated in Fig. 3. For each station, the distribution of polarization angles of all the events are plotted in the left-hand panels as rose diagrams. In the right-hand panels, the same values are stacked and plotted versus time with zero time being the P-wave arrival. The dots are shown with different colours depending on the hierarchical class (WH) associated to each polarization value (see Appendix A). The smallest values (yellow) appear in the first part of signals: this indicates that in the P-wave window vertical motions predominate and horizontal polarizations are randomly distributed. The highest values of WH (purple to black) persist during the S and coda waves. As shown in Figs 4a and b, the difference between the P waves and later arrivals is even more evident in the analysis of individual events.

In the rose diagrams of off-fault stations, the polarization angles are scattered with no clear prevailing direction (Fig. 3). This is mostly evident at stations ND1, ND4 and ND5. In contrast, the three on-fault stations ND3, ND6 and ND7 (right-hand panel) show a better defined polarization direction in the horizontal plane.
Figure 2. Average horizontal-to-vertical spectral ratios of each station. The geometric mean is computed over the ensemble of the 12 events selected. In the upper panels, average spectral ratios are drawn separately for rotation angle from 0° to 180°; in the bottom panels, the same spectral ratios are shown in a colour contour representation.

Stations ND6 and ND7 depict a polarization oriented in N83 ± 32° and N88 ± 19° directions, respectively. These are very stable and persistent features especially at ND7. The polarization at ND3 is oriented N146 ± 14°. However, Figs 4c and 5 indicate that the polarization at this station varies as a function of frequency, and this feature is clearer when observing the events separately.

A detailed illustration of polarization results associated with one representative event (8 in Table 1) is presented in Figs 4a and...
b. In panel (A) the array geometry and the epicentre location are shown. Stations are grouped as on-fault (in Fig. 4a) and off-fault (in Fig. 4b). For each station, velocity waveforms are depicted at the top. No evident amplitude variations and differences between on- and off-fault stations are found in the time-series. The HVSRs calculated for each station are shown in Fig. 4c. The covariance matrix analysis was performed for each station using bandpass filtered signals in the frequency band indicated by red dotted squares in Fig. 4c. For on-fault stations, the spectral peak occurs at rotation angles corresponding to the E–W-oriented polarization azimuth identified on the averaged results of Fig. 3. The pattern of ND3 is more complex and will be discussed later on.

The resulting polarization azimuths are plotted versus time and through a rose diagram in the middle panels of Figs 4a and b. At on-fault stations, the polarization directions (Fig. 4a) are close to the ones obtained as average of the whole data set in Fig. 3. In contrast, off-fault stations show polarization directions and amplified frequency bands that vary between stations (Fig. 4b). On off-fault stations, a different pattern of polarization is observed on each analysed seismic event, leading to an isotropic distribution of azimuths when averaging the whole data set (see Fig. 3).

To verify whether polarized motion could be ascribed to a source effect, source polarization at stations was modelled for direct $P$ and $S$ waves using the software ISOSYN (Spudich & Xu 2003). The source-expected polarization was calculated as a function of focal mechanism (given by the Northern California Earthquake Data Center, http://quake.geo.berkeley.edu), station distance and source backazimuth. This computation was made for five earthquakes (#1, 4, 8, 10, 12 in Table 1). As an example, the source polarization modelled for $P$ and $S$ waves for event #8 is shown in Figs 4a and b above the plots of polarization azimuth versus time. Because the distances between stations are smaller by more than a factor of 10 than the distance between the array and the seismic source, the source-expected directions are the same for all the stations. We find that the modelled source polarizations do not agree with the direct body wave polarizations, so the polarized motions at on-fault stations are not controlled by source properties.

A more complex behaviour is observed for the HVSRs of station ND3 that highlights two different amplified frequency bands. In Fig. 5, the HVSRs of ND3 are depicted for event #8, which is the one used in Fig. 4c. The polarization distribution is bimodal corresponding to a first peak with amplitude of 6 in the frequency

**Figure 3.** Horizontal polarization angles computed through the covariance matrix analysis. For each accelerometric station, the polarization angles are represented through rose diagrams on left-hand side (percentage at the bottom indicates the amount of time windows satisfying the hierarchical criterion). On the right-hand side, the polarization angles are also plotted versus time, dot colours varying for different ranges of the weight $WH$. The x-axis starts from the $P$-wave arrival for each of the stacked earthquakes.
Figure 4. (a) Polarization analysis results for one representative event (#8 in Table 1). The array location and the epicentre location are shown in panel (A). Horizontal polarization results of the on-fault station ND6 are depicted in panel (B), whereas results of the two other on-fault stations (ND3 and ND7) are shown in panel (C). For each station EW, NS and Z-components are drawn from the top to the bottom. Units are counts. Below time-series, the covariance matrix analysis results are illustrated. The covariance matrix analysis was performed in the frequency band where HVSRs of each station are amplified. Polarization values are plotted both versus time and as rose diagrams, with the same modality of Fig. 3. On these plots the source expected polarization for direct P and S waves is drawn using a green dotted line for the P waves and a purple one for the S waves. It was modelled using the software ISOSYN (Spudich & Xu 2003) as a function of focal mechanism, station distance and source backazimuth. (b) Polarization analysis results for one representative event (#8 in Table 1) at off-fault stations ND1, ND2, ND4 and ND5. (c) HVSRs of on- and off-fault stations calculated for event #8. Dotted squares represent the frequency band where the covariance matrix analysis was performed (results are shown in Figs 4a and b).
band 1–3 Hz, and a second peak with amplitude of 12 in the frequency band 6–8 Hz. To separate the two directional effects, the covariance matrix analysis was performed in these two frequency bands (middle panels). For each band, the polarization angles versus time are plotted together with the bandpass filtered signals (EW, NS and Z-components from top to bottom). The polarization angles are also plotted as rose diagrams by applying the hierarchical criterion described in the Appendix A. The percentage of time windows exceeding the hierarchical selection is indicated as well.

Similar analyses of events #4, 5, 9, 10 at station ND3 confirm polarization directions that vary in the two frequency bands in agreement with Fig. 5. The combined results of the polarization analysis performed in the frequency band 6–8 Hz on all events (including #8) are depicted in the bottom panel of Fig. 5 as two rose diagrams:
the cyan diagram represents all time windows whereas the blue one is obtained by applying the hierarchical criterion.

**Figure 4. (Continued).**

5 DISCUSSION

Quantifying and understanding the factors controlling horizontal ground motion amplification and dominant polarization in damaged fault zone materials is important for topics ranging from wave propagation in complex media to engineering seismology. As noted in the introduction, classical trapped waves have motion polarities that are predominantly in the fault-parallel and vertical directions (e.g. Ben-Zion 1998). However, natural fault zone structures are generally sufficiently complex to produce mode conversions and/or replace the trapped waves with diffuse amplified wavefield. Indeed, numerous observations indicate that large motions near faults have a high angle from the fault strike (e.g. Rigano et al. 2008; Di Giulio et al. 2009; Pischittta et al. 2010) and tend to be transversal to the local fracture trend (Falsaperla et al. 2010).

In this work, we performed detailed analyses of dominant polarization angles of amplified seismic motion generated by local earthquakes and recorded at a small array of accelerometers near the Hayward Fault (Fig. 1). Similarly to previous seismological studies, the analysis demonstrates a predominant polarization direction of amplified shear waves near the fault zone that is not parallel to the fault strike direction. As discussed in the previous section, the observations cannot be ascribed to the seismic source. Since the possible influence of the seismic path was removed by averaging results of selected earthquakes coming from different azimuths, the dominant directions are likely to have a near-station origin.

At off-fault stations deployed outside the fault damage zone, a somewhat scattered distribution of polarizations is observed. In
Figure 5. Polarization analysis results at station ND3 for one representative event (#8 of Table 1). Top panel: Horizontal-to-vertical spectral ratios of station ND3. Similarly to Fig. 2, contour plot of amplitudes with rotation angle versus frequencies is shown at the bottom, whereas at the top the amplitude spectra of rotated components are plotted. Middle panel: Covariance matrix analysis results in the frequency bands 1–3 Hz (top) and 6–8 Hz (bottom) are depicted with the same modality of Fig. 4. Bottom panel: Covariance matrix analysis cumulated results in the frequency band 6–8 Hz of events #4, 5, 9, 10 at station ND3: the cyan diagram represents all time windows whereas the blue one is obtained by applying the hierarchical criterion (percentage of time windows exceeding the fixed thresholds is written at the bottom). The inset shows the epicentral location of the selected events.
contrast, near-fault stations installed close to the fault trace show a common predominant polarization effect oriented in an average E–W direction, independently of earthquake backazimuth and distance. For station ND3, which is located relatively close to the fault, a variation is found between two frequency bands: in the range 1–3 Hz the predominant polarization is N146 ± 14°, whereas in the range 6–8 Hz the predominant polarization is N86 ± 7° in agreement with the results of other on-fault stations (ND6 and ND7). Therefore, the mean polarization at stations associated with the fault damage zone forms an angle of about 70° with the fault strike direction. The observation of an effect strictly localized in the damage fault zone lead us to hypothesize a role of fracture systems (i.e. cracks). To check this hypothesis, we combine below modelling and additional observational results from different study areas where polarized motions were found.

The damage zone associated with the development of a fault is assumed to be characterized by brittle deformation on both sides of the fault, with lateral extent that could range up to 200 m (Caine et al. 1996). We note that large faults may include intense damage that is strongly asymmetric and may reflect preferred propagation direction of recent earthquake ruptures (e.g. Ben-Zion & Shi 2005; Dor et al. 2006, 2008). However, in the following, we focus on roughly symmetric damage products that reflect the early development stages of faults. Such damage zones are characterized by the presence of cracks (i.e. fracture systems referred also as fracture cleavages or Riedel fracture systems) with a systematic orientation. They are produced by the interaction of the tectonic stress and the near-fault local stress field associated with friction and fractures during the fault activity (Riedel 1929; Harding 1974; Hobbs et al. 1976). As a result, consistent and often very intense closely spaced fracture sets are generated. Individual fractures can reach up to several metres with spacing down to one tenth of their dimension.

5.1 Searching for a relation with fracture fields

Depending on the local stress tensor and the brittle rheology of the hosting rock (Mandl 2000), four types of fractures can develop: i) extensional fracture; ii) synthetic faulting or cleavage (i.e. with movement consistent with the main fault kinematics); iii) antithetic faulting or cleavage (i.e. with movement sense opposite to that of the main fault and iv) pressure solution surfaces. Their orientation depends on the direction of the resulting stress localized around the fault. The stress component due to the fault motion (the so-called kinematic stress component) often exerts the major influence on the final fracture orientation. In such cases, the maximum and minimum principal stress axes form angles of ~45° with the fault plane consistent with the fault motion, and the intermediate stress lies on the fault plane normal to the fault slip vector. As a result, the fracturing (cleavage) developed along a fault creates a damage zone that is characterized by well-oriented fracture systems.

Extensional fractures will develop normal to the minimum compressional axis, forming an angle of ~45° from the fault plane. Synthetic cleavage (i.e. Riedel R planes) will form an angle of ~15° from the fault plane as measured in the sense of the fault motion. Antithetic cleavage (i.e. Riedel P planes) will form an angle of ~65° as measured in the same way. Pressure solution surfaces (i.e. Riedel P planes) will develop at ~45° normal to the maximum principal stress axis (Riedel 1929; Harding 1974). Depending on the stress and kinematic conditions, one (or more) of these fracture types will develop, because the development of one set inhibits the growth of the others in their vicinity, reducing the capability to accommodate the elastic stress field. Typically, in kinematic conditions (as in the San Andreas system accommodating the relative motion between adjacent blocks), the main fracture set that is expected to develop is the synthetic cleavage.

To interpret the observed dominant polarization directions, we computed the direction of the synthetic cleavages expected for the Hayward Fault, using the package FRAP (Salvini et al. 1999). The basic aspects of the package are described in Appendix B. In agreement with Williams et al. (2005), the fault segment was modelled as a 20 × 8 km2 representative surface, with an average strike of N20°W, reaching 11.5 km depth and dipping 70° to the east. No minor irregularities were added on the fault surface since the fault movement occurred over a long timescale. Although Graymer et al. (2005) showed that the Hayward Fault separates very heterogeneous regions with different lithotypes, in this model the rock rheological parameters were chosen to be the same on the two sides of the fault. The rheological parameters were fixed as: density 2400 kg m⁻³, cohesion 5MPa, Poisson ratio of 0.25, friction angle of 30°, stress drop coefficient 50 per cent and shale content 10 per cent. The movement of the Hayward Fault was set to be right-lateral strike-slip with a total displacement of 100 km.

We note that the performed analysis on fracture orientation is independent of the amount of displacement. The used displacement corresponds to the expected maximum displacement for a fault segment of the chosen size and its amount influence only the fracture intensity. According to several works performed in the area to define the orientation of the principal tectonic stress (e.g. Provost &
the axis of maximum compression $\sigma_1$ was set to be oriented N5$^\circ$ and the axis of minimum compression $\sigma_3$ was set to be at N95$^\circ$. Both $\sigma_1$ and $\sigma_3$ were assumed to lie on the horizontal plane and the intermediate axis $\sigma_2$ was set vertical. As previously explained, for the Hayward Fault the applied stress conditions were chosen to enhance the kinematic component caused by the fault movement, reducing the influence of the regional stress field.

Panel (a) in Fig. 6 shows a sketch of a map view with the regional stress field (red arrows), the right-lateral fault movement in N160$^\circ$ direction (black arrows) and the kinematic components of the local stress field ($K_1$ and $K_3$). The expected fracture systems (cleavages and extensional fractures) are also illustrated. The orientation of synthetic cleavage as a projection on the horizontal plane is represented in panel (b) as a rose diagram. To help developing a correlation with measured polarization, the combined results from the analysis of seismic data at stations ND6 and ND7 are also plotted as a rose diagram in panel (c). Although station ND3 lies in the fault zone, it is not considered here because it shows two polarization angles in two frequency bands. Both circular histograms were fitted through a Gaussian curve, obtaining a mean direction of N91 $\pm$ 38$^\circ$ for polarization angle and a mean direction of N1 $\pm$ 4$^\circ$ for synthetic cleavages. A difference in angle of 89$^\circ$ between the mean polarization and expected synthetic cleavages is found, suggesting an orthogonal relation between horizontal polarization and orientation of the most probable fracture system. A consistent perpendicular relation between fractures strikes and polarization has been also found for two other fault zones, the Parkfield section of the San Andreas Fault (Pisciotta et al. 2010), and the Eastern Agri fault system (Pisciotta 2010), where abundant polarization data are available. Detailed results from these studies will be published in a separate paper. Here we only show and discuss, for comparison with the results for the Hayward Fault, the obtained mean horizontal polarization obtained in those two study cases in the middle and bottom panels of Fig. 6.

Data of HRSN network operated by the Berkeley Seismological Laboratory in Parkfield area were analysed to study the occurrence of polarization and its spatial distribution across the San Andreas Fault. Fig. 6 displays (panel f) the mean polarization of ~2000 earthquakes recorded in 2004 at the borehole station MMNB installed in the fault damage zone. We find a predominant polarization in N 88 $\pm$ 40$^\circ$. In the investigated sector, the San Andreas is oriented in N140$^\circ$ direction (sketch in panel d of Fig. 6), with an oblique right-lateral kinematics having a compressive component as revealed by the presence of positive flower structures. The associated most probable modelled fracture fields are synthetic cleavages expected in the N171 $\pm$ 4$^\circ$ direction, as depicted in panel (e) of Fig. 6. According to our results, the dominant polarization in the Parkfield section of the San Andreas Fault is oriented at 83$^\circ$ to the mean direction of the most probable fracture system, thus well approximating perpendicularity.

The Val d’Agri Basin is the other case study where near-perpendicular relation between polarization and fractures was found. This area is characterized by many fault systems, being also well known for oil exploration (Menardi Noguera & Rea 2000; Maschio et al. 2005; Improm & Bruno 2007; Pastori et al. 2009). Fig. 6 shows the results (panel i) for one station located near the Eastern Agri normal fault system (Cello et al. 2000, 2003; Barchi et al. 2007). The polarization analysis was performed on 52 earthquakes and resulted in a mean polarization direction of N54 $\pm$ 12$^\circ$. Similarly to the two previous case studies, in panel (g) the sketch representing the fault and its brittle deformation pattern is drawn, using in this case a vertical section. The fault strike (not shown) is along the NW–SE direction. The representation in a vertical section is required because, in a normal fault, all the expected fracture systems (cleavages, extensional fractures and pressure solution) have the same strike, only differing by the dip angle. To show their variations in dip they are plotted as a Schmidt lower hemisphere projection in the inset of panel (g). The modelling for this case indicates (panel h) that the most probable fracture systems is synthetic cleavage with a mean expected orientation of N139 $\pm$ 4$^\circ$. Thus, also for this fault zone a transversal relation between the horizontal polarization and fracture field strike is found.

The near-perpendicular relation between the dominant orientation of cracks and wave polarization can be explained by considering the effective rock stiffness in different directions. In intensely fractured rocks, possibly mixed with granular materials, the resistance to loadings is strongly anisotropic. The effective Young modulus normal to a highly damaged material is expected to be considerably lower than the moduli in the other directions. This is intuitive and consistent with numerous seismic anisotropy studies indicating the predominance of cracking near large fault zones with orientation close to the fault-parallel direction (e.g. Peng & Ben-Zion 2004; Boness & Zoback 2006), along with additional recent theoretical and observational results.

Griffith et al. (2009) numerically simulated uniaxial compression tests of models of fractured rock with assumed crack distribution taken from mapped fault zone rocks. The results indicated strong anisotropic reduction of the effective fault-normal Young modulus, or increasing compliance with increasing angle between the load and the main fractures direction. Burjanek et al. (2010) observed strong polarization effects on weak seismic events and ambient vibration recorded on the unstable rock slope above the village of Randa (Swiss Alps). They hypothesized a relation with parallel dipping faults associated to the slope instability. According to their model, the rock stiffness is anisotropically reduced by the presence of fractures and horizontal vibrations are more pronounced in the direction of deformation that is also perpendicular to fractures. The results from these and the seismic anisotropy studies are consistent with our inference that the dominant direction of cracks in the fault damage zone may control the frequently observed dominant polarization direction at high angle to the fault strike.

6 CONCLUSIONS

We observed horizontally polarized motions around the Hayward Fault within a limited area corresponding to the fault damage zone. The results are consistent with observations at other fault zones, both in strike-slip and extensional tectonic environments (Parkfield section of the San Andreas Fault and Val d’Agri extensional basin, southern Italy, respectively). Similar polarization effects are also documented near fault zones of Mt Etna volcano in Italy. Modelling of the fracture fields induced by the tectonic motion and fault friction indicates an orthogonal relation between the wave polarization azimuth and the predicted strike of the synthetic fracture cleavage in the fault damage zone.

For the Hayward Fault with N160$^\circ$ strike and right-lateral movement, the observed mean polarization is oriented N91$^\circ$ and the synthetic cleavage is N175$^\circ$, confirming a substantially perpendicular relation. For the Parkfield section of the San Andreas Fault, where the kinematics is right-lateral with a compressive component, the mean polarization observed at station MMNB is also near perpendicular to the expected synthetic cleavage.
Figure 6. TOP: Horizontal polarization across the Hayward Fault. A sketch in a map view is illustrated in panel (a) with the regional stress field (red arrows), the right-lateral fault movement in N160° direction (black arrows) and the kinematic components of the local stress field (K1 and K3). The expected fracture systems, as cleavages (black), extensional fractures (blue) and pressure solution (green) are also illustrated. The orientation of the most probable fracture field as a projection on the horizontal plane (synthetic cleavage) and modelled using the package FRAP 3 is represented in panel (b) as a rose diagram. To correlate theoretical trends with observed polarizations, results of stations ND6 and ND7 are cumulated and plotted as a rose diagram in panel (c). MIDDLE: Polarization across the San Andreas Fault in Parkfield sector where the fault strike is N140°. The fault sketch in panel (d) is drawn with the same structure of panel (a). Similarly to the Hayward Fault, the most probable fracture fields are synthetic cleavages, depicted in panel (e) through a rose diagram. The mean polarization of ~2000 earthquakes recorded in 2004 at the borehole station MMNB installed in the fault damage zone is displayed in panel (f). BOTTOM: Polarization in the Val d’Agri extensional basin. A station close to one of the border dip-slip faults is selected. Similarly to the previous case studies, in panel (g) the sketch representing the fault and its brittle deformation pattern is drawn, in this case as a vertical section. The fault strike (not shown) is along the NW–SE direction. As expected for a normal fault, all the theoretical fracture systems (cleavages, extensional fractures and pressure solution) have the same strike and only differ by the dip angle. To show their variations in dip, they are plotted as a Schmidt lower hemisphere projection in the inset of panel (g). The synthetic cleavage orientation modelled using the package FRAP 3 (Salvini et al. 1999) is depicted in panel (h) as a rose diagram. Results of the polarization analysis performed on several earthquakes are shown in panel (i).
Similarly, in the Val d’Agri Basin characterized by extensional tectonics, the observed polarization is essentially perpendicular to the likely fracture systems produced in the damage zone by the normal fault movement. The comparison between fault fracture modeling and polarization direction reveals that fault-induced crack systems play a major role in controlling the stiffness anisotropy in the fault damage zone, which in turn is responsible for the observed polarization.

The near-normal relationship between polarization and crack orientation is consistent with results of seismic anisotropy studies in the Val d’Agri Basin and Parkfield area that show fast polarization direction approximately parallel to the main fracture fields (e.g. Boness & Zoback 2006; Liu et al. 2008; Pischiuotta et al. 2010). The presence of cracks is therefore responsible for stiffness anisotropy in fault damage zones, leading to the polarized amplified motion investigated in this work, along with shear wave splitting (e.g. Savage et al. 1990; Peng & Ben-Zion 2004) and attenuation anisotropy (e.g. Fletcher et al. 1990; Liu et al. 2005). The discussed results and techniques demonstrate the utility of using seismic signals to explore the distribution of fracture systems in fault zone environments.

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REFERENCES


APPENDIX A: ESTIMATE OF POLARIZATION ANGLE THROUGH COVARIANCE MATRIX DIAGONALIZATION

Spectral ratios using the rotated horizontal components are a powerful tool to recognize directional site effects (see Spudich et al. 1996; Cultrera et al. 2003). However, the spectral ratio may be biased by anomalies in the denominator spectrum. According to Jurkevics (1988), a direct estimate of the ground motion polarization can also be inferred using the covariance matrix.

In our implementation of this method, signals are detrended and the mean is removed, then they are bandpass filtered to restrict the analysis to the frequency band where HVSRs have previously revealed a significant (>2 at least) amplification. To diagonalize the covariance matrix, the code POLARSAC (La Rocca et al. 2004) is applied to the three components of motion in the time domain, using a partially overlapping moving window whose length is tailored depending on the predominant signal frequencies. After the matrix diagonalization, the eigenvalues $\lambda_1 > \lambda_2 > \lambda_3$ and eigenvectors $\hat{u}_i$ (i varying from 1 to 3) yield the axis length and orientation of the polarization ellipsoid in each time window.

The polarization vector is obtained from the vectorial sum

$$PV = \sum_{i=1}^{3} \lambda_i \hat{u}_i.$$  \hspace{1cm} (A1)

It is defined through four parameters that characterize the polarization ellipsoid: $AZ, I, R$ and $P$. These parameters, inferred from the eigenvectors of each time window, are defined as follows.

$AZ$ is the polarization azimuth measured as the angle between the geographic north and the projection of the main eigenvector on the horizontal plane

$$AZ = \arctg \left[ \frac{u_{21} (\text{sign} u_{11})}{u_{31} (\text{sign} u_{11})} \right].$$  \hspace{1cm} (A2)

where $u_{ij}$ ($j = 1, \ldots, 3$) are the three direction cosines of eigenvector $\hat{u}_i$. The sign function has been introduced to take positive vertical component of $\hat{u}_i$ resolving the 180$^\circ$ ambiguity (Jurkevics 1988).

$I$ is the apparent incidence angle, i.e. the angle between the eigenvector associated to the highest eigenvalue $\hat{u}_i$ and z-axis and is given by

$$I = \arccos(u_{11}).$$  \hspace{1cm} (A3)

![Figure A1.](image)
$R$ is rectilinearity, it ranges between 0 (spherical motion) and 1 (rectilinear motion) and indicates to what extent the three axes differ.

$$R = 1 - \frac{\lambda_2 + \lambda_3}{2\lambda_1}. \quad (A4)$$

$P$ is planarity, it ranges between 0 and 1, indicating to what extent the motion is confined to a plane.

$$P = 1 - \frac{2\lambda_3}{\lambda_1 + \lambda_2}. \quad (A5)$$

Among these parameters, $AZ$ is the one used to represent horizontal polarization in this study. It is plotted through a circular histogram (rose diagram) computed from $0^\circ$ to $360^\circ$ at bins of $10^\circ$. Bins that differ by $180^\circ$ are cumulated together as having the same polarization direction, their separation having no physical meaning. To increase the weight of $AZ$ values of time windows with higher degree of rectilinearity and more horizontal motion, a hierarchical criterion is applied in the azimuth statistics.

The hierarchical criterion we establish excludes from the statistics values of $AZ$ associated to $R < 0.5$ and $I < 45^\circ$, semi-spherical or near-vertical polarization solutions being not relevant to our study. The other $R$ and $I$ values in the intervals $0.5 < R < 1$ and $45^\circ < I < 90^\circ$ are normalized linearly between 0 and 1. A weight factor $WH$ is obtained from the product $WH = R \times I$, where $0 < WH < 1$. The value of $WH$ is used as a weight for the horizontal $AZ$ values contributing to the rose diagrams of horizontal polarization.

To visually illustrate the highly restrictive selectivity of our hierarchical criterion, two time windows are shown in Fig. A1 where the corresponding results of $I$, $R$ and $AZ$ are visualized through the polarization ellipsoid. The weight factors calculated for the two time windows are shown as well.

The first time window (identified by an orange square) is characterized by a moderately high weight ($WH = 0.71$) that is controlled by a high incidence ($87^\circ$) and highly rectilinear ellipsoid ($R = 0.88$). The second time window (identified by a blue square) is relative to a very small weight ($WH = 0.06$), lower by more than one order of magnitude than the previous one. In this second case, the ellipsoid still has a moderately high value of incidence ($60^\circ$) and it is still quite rectilinear ($R = 0.59$). Nevertheless the polarization azimuth of the first ellipsoid will give a much higher contribution to the construction of the final polarization histogram.

This hierarchical criterion is intentionally very restrictive, selecting only time windows with a high horizontal polarization degree, rejecting the others even though the polarization ellipsoid still is not so vertical and is elongated in a preferential direction.

To ensure that the statistics are representative of the whole time windows analysed along the signals and that the hierarchical criterion did not lead to exclude too many samples, the percentage of rejected time windows is calculated and plotted near each rose diagram. Moreover, the values of $AZ$ are plotted versus time and along signals to detect any changes with the different seismic phases. The associated weights are represented through a colour scale, as shown in Fig. 3.

**APPENDIX B: THE FRAP PACKAGE**

The presence of faults results in the development of zones of local intense brittle deformations. Typically, fault zones include an internal fault core, characterized by the presence of crushed and grinded material in complex pattern (Caine et al. 1996). Its dimension and amount of evolution of the grinding process are related to the stress conditions and the fault displacement. The fault core is surrounded by the fault damage zone, characterized by the presence of an organized set of brittle deformations and dilations. Again, its width and intensity of deformation are functions of the stress conditions, fault plane geometry and displacement occurring in the fault zone during fault activity.

The Frap Package is a tool that predicts the stress and brittle deformations in fault core and in the fault damage zones. It uses a combination of numeric and analytic approaches.

The fault is discretized into a grid of quadrangular cells, with each being characterized by an attitude and a position in a reference frame. For each cell, the various components of the stresses that acted though time are computed (Fig. B1).

The model considers four stress components. The first one is the regional stress tensor, often responsible of the fault development, evolution and movement. This component can be introduced as a fixed value (as in this study) or may be derived from a spatial distribution function.

The second tensor component is the overburden, that is, the load of the material (e.g. rock, water) above the given cell. The vertical component is the $\sigma_{1ov}$ and can be computed as

$$\sigma_{1ov} = \int_{z_0}^{z_s} (\rho (z) \cdot g) \, dz; \quad (B1)$$

where $z$ is depth, $\rho$ is the density and $g$ is the gravity acceleration.

The overburden stress conditions are assumed to be uniaxial, that is, the two main horizontal components assume the same value as a function of the rock rheology at the cell.

$$\sigma_{2ov} = \sigma_{3ov} = \frac{\nu}{1-\nu} \cdot \sigma_{1ov}, \quad (B2)$$

where $\nu$ is Poisson’s ratio.

The third component is the fluid isotropic pressure within the rock pores that obviously induces a decrease in the brittle strength of the rocks. It is computed from the height of the fluid column $Hcol$ and the fluid density $\rho_f$.

$$P = Hcol \cdot \rho_f \cdot g. \quad (B3)$$

The stress variation due to the pore elasticity component is considered negligible.

The fourth component is referred in the package as the ‘kinematic stress’ and is often the largest one in the fault zone. It is the component resulting from the brittle strain accumulation due to frictional resistance and failures associated to the fault.

This component can be described as a tensor oriented as the main component $\sigma_{2k}$. It lies on the cell surface normal to the movement vector, whereas the $\sigma_{1k}$ main component forms an angle of $45^\circ$ from the surface compatibly with the movement (see Fig. B2, panel a). The $\sigma_{1k}$ module is equal to the strength of the fault surface to fail, computed according to the Coulomb–Navier Criterion (see below). The $\sigma_{2k}$ represents the null axis and has a 0 value.

$$\sigma_{1k} = \Sigma, \quad \sigma_{2k} = 0, \quad \sigma_{3k} = -\Sigma. \quad (B4)$$

In this way, the resulting stress tensor on a cell will be the sum of all these components. The attitude of the kinematic stress tensor
Figure B1. Example of FRAP output showing the grid structure representing the fault zone. For each cell, the stress/deformation components are analytically computed. The enlarged circle illustrates how to numerically compute the cumulative DF. The DF values of the cells falling on the displacement path of the cell are accumulated proportionally to the length of the path.

Figure B2. Panel (a) Fault surface (violet) and orientation of the kinematic stress components (blue arrows) related to the fault movement (red arrows) for a pure strike slip fault (i.e. without transtension or transpression component). Panel (b) Strike and dip values of the fault plane in the $\sigma_1$, $\sigma_2$, $\sigma_3$ reference system.

is a function of the cell surface attitude and the fault movement vector on the cell. Depending on the tectonic scenario, the kinematic component may be negligible, as in the case of no-fault movement. In most cases, as in the fracture produced by the studied fault, it represents the most important stress component.

The resulting stress is then compared to the strength in the cell zone as predicted by available failure criteria. In this study, we choose the Coulomb–Navier Failure Criterion

$$\Sigma = c + \tan \varphi (\sigma_N - P_w),$$

where $\sigma_N$ is the stress component normal to the cell surface and is computed according to Jaeger et al. (2007) as follows:

$$\sigma_N = (\sigma_1 \cos^2 \lambda + \sigma_2 \sin^2 \lambda) \cdot \sin^2 \theta + \sigma_1 \cos^2 \theta,$$

where $\lambda$ and $\theta$ being, respectively, the azimuth and the dip of the fault surface with respect to the fault surface (see Fig. B2, panel b).

The capability to produce fracture at each cell at a given time interval is represented by the Deformation Function $D_f$ that represents the difference between the strength $\Sigma$ and the maximum shear $\tau^*$ acting on the cell surface (Storti et al. 1997), as shown in panel...
(b) of Fig. B2.

\[ D_f = \tau^* - \Sigma, \]

where, according to Jaeger et al. (2007), \( \tau^* \) is given by

\[ \tau_s = -0.5 \cdot (\sigma_3 - \sigma_2) \cdot \sin \theta \sin 2\theta, \]
\[ \tau_d = 0.5 \cdot (\sigma_3 \cos^2 \lambda + \sigma_2 \sin^2 \lambda - \sigma_1) \cdot \sin 2\theta, \]
\[ \tau^* = (\tau_d + \tau_s)^{\frac{1}{2}}. \]

Here, \( \tau_d \) and \( \tau_s \) represent the two components of \( \tau^* \) along the fault dip and the fault strike, respectively.

Thus from the resulting stress tensor at each cell is possible to compute the attitude of the different type of expected fracture sets (Riedel Fractures) as well as their probability to be produced from the statistic interpretation of the \( D_f \). The various types of brittle deformations (e.g. see Mandl 2000) include: the synthetic cleavage (\( R \) Riedel Planes), the antithetic cleavage (\( R' \) Riedel Planes), the extensional fractures (\( T \) Riedel Planes) and the pressure solution surfaces (\( P \) Riedel Planes). The term cleavage is used to describe a fracture set characterized by a spacing significantly shorter than the fracture dimensions.

The package then can compute the total brittle deformation for each cell through time along the trajectory that each cell follows along the fault during displacement (Fig. B1).

In this application, the use of the package was limited to compute the attitude of the main fractures that develop at each cell of the fault surface (i.e. synthetic fractures, \( R \) Riedel).

Finally the resulting fracture field, that is the output of the software, is analysed as structural elements by producing the rose diagrams shown in the article by the Daisy Package (Salvini et al. 1999), freely downloadable at http://host.uniroma3.it/progetti/fralab/.