

# Seismic fault zone trapped noise

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**Abstract.** Systematic velocity contrasts across and within fault zones can lead to head and trapped waves that provide direct information on structural units that are important for many aspects of earthquake and fault mechanics. Here we construct trapped waves from the scattered seismic wave field recorded by a fault zone array. The frequency dependent interaction between the ambient wave field and the fault zone environment is studied using properties of the noise correlation field. A critical frequency  $f_c \approx 0.5$  Hz defines a threshold above which the in-fault scattered wave field has increased isotropy and coherency compared to the ambient noise. The increased randomization of in-fault propagation directions produces a wave field that is trapped in a waveguide/cavity-like structure associated with the low velocity damage zone. Dense spatial sampling allows the resolution of a near field focal spot, which emerges from the superposition of a collapsing, time reversed wave front. The shape of the focal spot depends on local medium properties, and a focal spot based fault normal distribution of wave speeds indicates a  $\sim 50\%$  velocity reduction consistent with estimates from a far field travel time inversion. The arrival time pattern of a synthetic correlation field can be tuned to match properties of an observed pattern, providing a noise based imaging tool that can complement analyses of trapped ballistic waves. The results can have wide applicability for investigating the internal properties of fault damage zones, because mechanisms controlling the emergence of trapped noise have less limitations compared to trapped ballistic waves.

## 1. Introduction

The ambient seismic noise field has been used extensively in the last decade to image numerous structures across a wide range of spatial scales covering the crust, lithosphere, upper mantle, and the Earth core [Vandemeulebrouck *et al.*, 2009; Shapiro *et al.*, 2005; Stehly *et al.*, 2009; Verbeke *et al.*, 2012; Boué *et al.*, 2013; Lin *et al.*, 2013]. Noise based imaging requires that the ambient wave field is sufficiently isotropic [Weaver *et al.*, 2009]. In seismology, source averaging replaces the theoretical ensemble average over the disorder, i.e., wave field isotropy is predominantly controlled by the excitation patterns. The applicability of noise based imaging further benefits from randomization of propagation directions through scattering and mode conversions. Seismic heterogeneities control the efficiency of wave diffusion in environments ranging from relatively homogeneous cratonic areas [Poli *et al.*, 2013] to highly scattering volcanic edifices [Wegler, 2003] and fault zone (FZ) regions [Hong and Menke, 2006; Hillers *et al.*, 2013].

The ambient seismic wave field in a FZ environment is characterized by frequency dependent superposition of scattered, guided, bended, and reflected surface and body wave components. Several studies used correlations of ambient seismic noise to image FZ environments [Roux *et al.*, 2005; Roux, 2009; Hillers *et al.*, 2013; Zigone *et al.*, 2014] at wavelengths ( $\lambda$ ) that are large compared to the width of the low-velocity FZ damage zone ( $\lambda_0$ ). Fault zone head and trapped waves propagating along velocity contrast interfaces and the damage zone provide high-resolution information on the internal components of fault structures [Ben-Zion and Aki, 1990; Li

*et al.*, 1990; Lewis and Ben-Zion, 2010]. Here we extract signatures associated with fault zone trapped noise from the ambient seismic field using data recorded across the Calico fault zone in California. The results provide an important new high resolution tool for imaging the internal structure of fault damage zones. Significantly different wave field properties within and outside the FZ reflect the trapped nature of the wave field at frequencies above a critical value for noise-FZ interaction ( $f_c$ ). Properties of noise correlation functions can be understood in the context of time-reversal experiments [Cassereau and Fink, 1992; Derode *et al.*, 2001] and suggest that the low velocity zone (LVZ) acts as a waveguide [Ben-Zion and Aki, 1990; Roux *et al.*, 2008] or a reverberant cavity [Lobkis and Weaver, 2001; Catheline *et al.*, 2008]. The noise-based method developed and applied here can have wider applicability than methods based on ballistic fault zone waves since it does not depend on the limited existence of appropriate ballistic sources [Jahnke *et al.*, 2002; Fohrmann *et al.*, 2004; Lewis and Ben-Zion, 2010].

## 2. Location, Data, and Methods

We analyze frequency dependent noise-FZ interactions by processing data of a dense seismic array installed across the Calico fault [Cochran *et al.*, 2009], one of several  $\sim 35^\circ$  NW oriented, subparallel strike slip faults in the Eastern California shear zone (Fig. 1a). The wide ( $\lambda_0 \approx 1-2$  km) compliant fault damage zone around the mapped surface trace is characterized by a shear modulus reduction of factor two compared to the more competent host rock [Fialko, 2004]. Fault zone trapped waves excited by local earthquakes and shots [Cochran *et al.*, 2009] indicate that the structure of the low velocity waveguide is sufficiently continuous in the along strike direction [Igel *et al.*, 1997] on length scales associated with the hypocenter distances ( $O(10$  km)). The strong velocity contrast across the LVZ boundaries further leads to multiple fault-internal body waves reflections [Yang *et al.*, 2011]. Together, these ballistic phases indicate that the LVZ is characterized by a north dipping  $P$  wave velocity contrast of 40–60% down to 5 km depth. In addition to the analyses

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of these phases, continuous data recorded by the network has been processed to study short period noise excitation along the Pacific coastline [Zhang *et al.*, 2009] and local scale noise propagation properties [Zhang and Gerstoft, 2014].

The data was acquired by a temporary field experiment consisting of a 2-D broadband array and a collocated short period line, which cover the damage zone and an area  $\sim 2$  km SW to the fault (Fig. 1b). The minimum inter-station distance of broadband and short period sensors normal to the fault strike is 50 m and 25 m, respectively. The horizontal components are oriented normal to the fault strike (Fig. 1b), with channel denoted R pointing at  $55^\circ$  (radial), and channel T pointing at  $325^\circ$  (transversal). The letters T' and R' denote these components after application of the Optimal Rotation Algorithm (Section 2.5). The network recorded between Julian days (JD)  $\sim 150$  and  $\sim 330$  in 2006. We retrieve the complete data set from the IRIS facility [Scheingraber *et al.*, 2013], but we focus on  $\sim 90$  d beginning JD 235 when both the complete 2-D array and the line were continuously recording.

We apply multiple processing and analysis techniques to decipher the complex, frequency dependent wave propagation situation in a challenging FZ environment. In the remainder of this section we discuss general and technical aspects associated with estimates of kinetic noise energy ratios, details of the correlation procedure, spectral properties of noise correlations, correlation-based beamforming, and the Optimal Rotation Algorithm (ORA). Readers familiar with these applications can continue to Section 3. Based on the results obtained with the multi-component analysis, we estimate the fault-normal velocity structure in Section 4. Construction of synthetic correlation fields for FZ imaging is detailed in Section 5.

### 2.1. Kinetic Energy Ratio

A stable ratio of shear and longitudinal deformation energy indicates that mode conversion through scattering is balanced [Weaver, 1982; Shapiro *et al.*, 2000; Hennino *et al.*, 2001; Margerin *et al.*, 2009; Sánchez-Sesma *et al.*, 2011], and that energy propagation can be described by a diffusion process. The ratio itself is a consequence of scattering and absorption properties. The kinetic energy ratio  $H^2/V^2$  can be used as an alternative proxy [Hennino *et al.*, 2001; Sánchez-Sesma *et al.*, 2011] and is generally easier to compute than estimates of the deformation energy [Shapiro *et al.*, 2000].  $H^2$  and  $V^2$  denote squared velocity amplitudes recorded on the horizontal components and the vertical component, respectively. To avoid analysis of the entire data set, we estimate  $H^2/V^2$  ratios using continuous short period data from 20 randomly chosen days. At each of these days we randomly choose three hours of bandpass filtered data from which we compute  $H^2 = h_1^2 + h_2^2$  and  $V^2 = Z^2$ , where  $h_{1,2}$  and  $Z$  denote data from the two horizontal channels and the vertical channel. The traces are smoothed with a moving average of length  $\Delta t$  s separated by  $dt$  s, the inverse of the upper limit of the frequency band. Ideally,  $\Delta t$  is of the order of the mean free time [Shapiro *et al.*, 2000; Hennino *et al.*, 2001], which is, however, difficult to estimate [Campillo, 2006]. We test a wide range of constant and frequency dependent  $\Delta t$  values, and compare estimates associated with multiple selections of the randomly drawn time windows. We find insensitivity to choices associated with smoothing and timing parameters. This indicates that the obtained  $H^2/V^2$  statistics are related to local material properties, and are not biased by transient changes of wave field properties.

### 2.2. Noise Correlations

With the exception of the  $H^2/V^2$  ratios our conclusions are based on analysis of noise correlation functions. Correlation move-out patterns contain information on propagation directions and speeds, and particle motions indicate wave polarization and can help to constrain wave field constituents.

Here we compute only intra-array correlations, i.e., we correlate only between the broadband or the short period sensors, but considering potential inter-array applications we first removed the instrument response and homogenized the sampling rate to 50 Hz. Further data processing steps generally target the optimization of the correlation signal-to-noise (SNR) ratio by minimizing bias associated with non-stationary components of the wave field. Our strategy includes spectral whitening and amplitude clipping at three times the standard deviation of the amplitude distribution in a multi-hour yet sub-daily time window, and we remove windows containing suspiciously large amplitudes indicative of earthquakes [Poli *et al.*, 2012b, a; Boué *et al.*, 2013; Hillers *et al.*, 2014]. The application of whitening and amplitude clipping reduces biasing effects of variable noise spectral power and potential band-limited transients. We tested other strategies neglecting spectral normalization but including 1-bit temporal normalization and found that the choices emphasize different constituents of the wave field and can have significant effects on the resulting correlation patterns and responses of the associated correlation-based beamforming (Section 2.4). However, here we are concerned with estimates of the coherency, and thus focus on whitened and clipped seismograms using a clipping threshold of three times the standard deviation in a processing window. We compute daily coherency estimates between two stations A and B,  $C_{AB}(\tau)$ , i.e., the time domain equivalence of

$$\gamma_{AB}(\omega) = \left\langle \frac{u_A(\omega)u_B^*(\omega)}{\{|u_A(\omega)|\}\{|u_B(\omega)|\}} \right\rangle. \quad (1)$$

Here,  $\tau$  denotes lapse time,  $\omega$  angular frequency,  $u_{A,B}$  seismograms at stations A and B, and the asterisk represents complex conjugate. Curly brackets  $\{\cdot\}$  indicate a spectral average, i.e., the cross spectrum is scaled by the total energy of the signals recorded at A and B. The brackets  $\langle \cdot \rangle$  mean either an ensemble average over the disorder, or a time/frequency average of a single realization, or averaging of fields produced by a set of sources [Campillo, 2006]. The latter situation applies in seismology, where source-averaging is realized by temporal averaging. That is, the (unscaled) correlation in the time domain can be expressed as  $C_{AB}(\tau) = \langle u_A(t), u_B(t) \rangle_T$ , where  $\langle \cdot \rangle_T$  denotes correlation over the time interval  $T$ , and  $T \rightarrow \infty$ . All daily correlations are stacked over the  $T = 90$  d observation period.

Preprocessing includes whitening in a wide frequency range (0.05–10 Hz) for the broadband records. Frequency dependent analyses performed on these data (beamforming and ORA) are achieved by applying a bandpass filter to the broadband correlations. Note that beamforming and the ORA are only weakly sensitive to the precise value of the correlation amplitudes. In contrast, the focal width method (Sections 3.3, 4.1) applied to the short period data for local estimates of the wave speed and length requires unbiased estimates of amplitude. To avoid biases associated with the spectral properties of the constructed coherency estimates, short period data are narrow-band whitened prior to correlation.

It should be noted that ZZ and TT correlations both represent motion that is excited and recorded orthogonal to the fault-normal direction. We find that ZZ and TT patterns are often very similar, and that TT correlations are frequently characterized by better SNR compared to the ZZ functions. Moreover, particle motion in the TR-TT plane is often equivalent to trajectories in the more familiar ZR-ZZ plane, which permits the distinction of body and surface waves based on ellipticity [Landès *et al.*, 2010].

### 2.3. Critical Frequency for Interaction

Coherency power spectra indicate the frequency dependent distribution of coherent energy built up by correlation. Generally, peak values correspond to double-frequency microseism excitation around 0.2 Hz, beyond which the spectrum falls off towards higher frequencies. To assess the spectral shape in the Calico FZ environment, we analyze correlations from all broadband station pairs. From systematic differences between spectra associated with station pairs in- and outside the LVZ, a critical frequency for interaction can be estimated above which the wave field is affected by the low velocity structure. The location and extension of the LVZ is estimated from previous analyses [Cochran *et al.*, 2009], which is compatible with our noise-based results discussed below. The results (Fig. 2) show that the wave fields differ significantly across  $\sim 0.5$  Hz, indicating that there is increased coherent energy within the LVZ. Particular wave field properties in the 1–2 Hz range are implied by the peak of the distribution, and the distinctiveness of this frequency band is confirmed by several observations in our analysis. It should be noted that the station density does not bias this conclusion due to potentially increased attenuation associated with larger distances outside the fault or the sampling of the large-amplitude focal spot within the fault. Spectral properties of trapped waves exhibit the same sensitivity to the FZ structure (Fig. S1), which is a strong indicator of a consistent critical frequency for interaction  $f_c \approx 0.5$  Hz that applies to ballistic and scattered wave fields alike. With an appropriate velocity model, the effective width of the velocity reduction of the LVZ can be estimated from  $f_c$ . We consider this threshold in the following frequency dependent analysis.

### 2.4. Beamforming

We apply conventional plane wave beamforming to ZZ correlation functions. Beamforming on seismic noise records usually consists of processing up to several hours long seismograms to accumulate a coherent phase signal in the cross spectral density matrix [Gerstoft and Tanimoto, 2007; Roux, 2009; Hillers *et al.*, 2012]. Accumulation of coherent energy is similarly achieved by the correlation procedure. The correlation-based beamforming performed here constitutes a spectral delay-and-sum approach applied to time series—correlation functions—that are short compared to the original noise seismograms. The method resolves the strongest, i.e., most coherent arrival, in contrast to statistical estimates [Wagner, 1998] that can isolate multiple superimposed components of variable strength and directivity [Vandemeulebrouck *et al.*, 2009]. As demonstrated below, the Calico FZ wave field constitutes such a complex situation. It should therefore be noted that correlation-beamforming in the present context is sensitive to normalization strategies (Section 2.2), and that beams formed from seismograms or correlations can differ because of data processing choices. In standard array beamforming techniques the network center is usually chosen as the reference point. Here we assign the reference station  $S_{\text{ref}}$  (station A in Eq. 1) of each correlation pair as the origin for the phase delay estimate, which emphasizes the assumption of a model plane wave propagating with constant velocity across the network. Considering frequency dependent wave field properties within and outside the FZ, we use frequency dependent sub-arrays consisting of all stations at low frequencies, and in-fault stations for  $f > f_c$  (Fig. S2). To avoid bias associated with the dense spatial sampling of the center line (Fig. 1b) we homogenize the spatial sampling in all directions.

### 2.5. The Optimal Rotation Algorithm

The Optimal Rotation Algorithm [ORA; Roux, 2009] minimizes energy on the transverse components ZT, TZ,

RT, and TR of the correlation tensor by allowing each station to freely re-align in the incident noise direction (Fig. S3). It assumes that Love and Rayleigh waves impinge on a network with the same propagation direction, and the alignment is intended to make the noise-correlation tensor compatible with a surface wave Green’s tensor. The minimization of energy is achieved by virtually rotating the coordinate system at stations A and B around two independent azimuths  $\Psi_A$  and  $\Psi_B$ , and around two corresponding tilt angles. Tensor optimizing tilt angles are usually small and can be neglected, so that  $\Psi$  distributions provide the dominant information about pair dependent surface wave propagation directions. Application of the ORA to the dense broadband station line (16 stations) yields 120  $\Psi_A$ ,  $\Psi_B$ , and residual estimates associated with the 120 possible pairs (Fig. S4). The residuals measure the energy on transversal traces that could not be suppressed by the virtual rotation. From these data we construct average long-range and short-range fault normal profiles (supplementary material) that synthesize the information on horizontal propagation directions.

## 3. Results

### 3.1. Low Frequency Regime: Superposition of Wave Field Constituents

Low-frequency ( $f < f_c$ ) fault-normal ZZ and TT correlation arrival patterns are characterized by a pulse with high apparent velocity,  $v_a \approx 8–10$  km/s (Fig. 3a). When the reference station  $S_{\text{ref}}$  is located within the LVZ, consistent longitudinal polarization in the radial-vertical (ZR-ZZ) plane indicates a  $P$  wave arrival. If  $S_{\text{ref}}$  is located on either side of the LVZ, we observe a gradual change of the longitudinal to an elliptical motion associated with Rayleigh surface wave propagation (Fig. 3d). A similar spatial change of longitudinal motion to progressively more circular particle trajectories is also observed for other component combinations. The distribution of kinetic energy ratios (Fig. 4a) supports the hypothesis that fault-normal wave field variations control the observed complex mixture of body and surface wave components.

Beamforming and application of the ORA can constrain individual modes of the composite wave field. Conventional beamforming assuming a plane wave is, however, challenged by the mixture of multiple propagation modes. The 2-D ZZ correlation field is dominated by surface wave energy propagating SE→NW along the fault strike at  $v_a \approx 1$  km/s (Fig. 5a). In contrast, beamforming on all ZZ correlations from the dense fault-normal line extracts arrivals associated with SW→NE  $P$  propagation with  $v_a \approx 4–5$  km/s. The long-range ORA synthesis (Fig. 4b, blue) also indicates energy arriving from westward azimuths approximately normal to the fault, which is compatible with excitation along the Pacific coastline [Schulte-Pelkum *et al.*, 2004; Stehly *et al.*, 2006; Gerstoft and Tanimoto, 2007; Zhang *et al.*, 2009; Hillers *et al.*, 2013]. The short-range average (Fig. 4c, blue) shows that the incident propagation is relatively insensitive to the LVZ, which is also confirmed by the similarity of motion patterns in the station reference frame and the optimally rotated frame.

Combined, these results imply that the low frequency ambient wave field is characterized by a superposition of body and surface waves, and a mixture of ambient propagation directions associated with oceanic excitation and components that move along the FZ strike. The SE→NW propagation indicates sensitivity to the structure at  $f < f_c$ , i.e., at  $\lambda > \lambda_0$ , which can partially be controlled by regional deformation related anisotropy indicated by subparallel faults SW and NE to the Calico fault (Fig. 1a).

### 3.2. Intermediate Frequency Regime: Noise-FZ Interactions

Wave field complexity persists at  $f > f_c$  (0.5–1 Hz). ZZ correlations associated with receiver stations located within the LVZ (Fig. 3b) are dominated by a longitudinally polarized arrival characterized by high apparent velocity  $v_a \approx 5$  km/s. It implies that far-field  $P$  wave energy [Zhang et al., 2009] is channeled into the FZ [Zhang and Gerstoft, 2014], and coherent secondary arrivals at  $|\tau| \approx 3 - 4$  s are possibly manifestations of associated fault internal body wave reflections. Focusing on correlation fields where  $S_{\text{ref}}$  is located to the SW of the fault, fault-normal ZZ and TT move-out patterns exhibit two arrivals with  $v_a \approx 5$  km/s and  $v_a \approx 2.5$  km/s (Fig. S5b), which propagate approximately perpendicular to the fault in NE directions. Longitudinal and circular particle motions observed in the ZR-ZZ and TR-TT planes indicate that the fast arrival is the previously identified body wave and the slow arrival a surface wave. Thus, coherent body and surface wave propagation is resolved across the velocity gradient if  $S_{\text{ref}}$  is located outside the LVZ, but the surface wave component can not be recovered if  $S_{\text{ref}}$  is within the LVZ. This is a situation where beamforming results are relatively unstable, and where data processing choices (Sections 2.2, 2.4) or sub-array configurations can help resolving the superimposed wave field components.

Considering the  $v_a \approx 2.5$  km/s phase, move-out patterns associated with  $S_{\text{ref}}$  outside the LVZ exhibit time-asymmetry associated with the ambient energy flux (Fig. S5b). In contrast, amplitudes of correlations associated with in-fault  $S_{\text{ref}}$  locations are more symmetric, indicating increased wave field isotropy and thus different FZ noise properties compared to the surrounding field. The increased spectral power for  $f > f_c$  associated with in-fault correlations (Fig. 2) is a manifestation of larger coherency within the LVZ which is ultimately controlled by better randomization of FZ noise propagation directions.

Similar to the  $f < f_c$  regime, ORA rotation angles (Figs. 4b, c) suggest surface wave excitation in SW direction, presumably along the Pacific coast. Evidence for ambient noise-FZ interaction comes from progressive alignment of propagation directions with the fault-normal (Fig. 4b, red), and from short-range variations within the LVZ (Fig. 4c, red). This indicates that ray-bending [Roux, 2009] can potentially bias travel-time inversions in FZ environments at wavelengths comparable to the LVZ width  $\lambda_0$ .

### 3.3. High Frequency Regime: Emergence of the Focal Spot

Surface waves at  $f > 1$  Hz are characterized by wavelengths smaller than  $\lambda_0$ . Compared to the intermediate frequency range, stronger differences in wave field properties within and outside the FZ indicate a transition to a different regime of noise-FZ interaction. For  $S_{\text{ref}}$  located within the LVZ (Fig. 3c), TT and ZZ time-distance patterns are characterized by three features: (1) A large amplitude focal spot that quickly decreases with increasing station offset, (2) an X-shaped move-out pattern with time-symmetric amplitudes within the LVZ, and (3) asymmetric arrival structure outside the LVZ. In addition, coherency across the FZ boundary is reduced compared to stations within the LVZ at similar distances (Figs. S5c, S5d). It should be noted that these characteristics, notably the near-field feature (1), are best seen if amplitudes are scaled by the peak value of the correlation field. Normalizing each trace individually emphasizes the far-field properties of the pattern (Fig. S5d). Similar to the intermediate frequency regime, the fault-normal TT and ZZ far-field X-patterns consist of a  $v_a \approx 0.7$  km/s slow phase exhibiting elliptical motion in the TR-TT and ZR-ZZ planes. The  $P$  wave associated with the longitudinally polarized arrival and  $v_a \approx 5$  km/s persists in

the ZZ correlations, but it is weaker compared to the situation at 0.5–1 Hz.

In-fault 2-D array beamforming at 1–2 Hz returns a speckle pattern (Fig. 5b) which implies a similarly symmetric arrival time structure (feature 2) between stations characterized by bearings that are different from fault normal. It is thus the consequence of a more isotropic distribution of propagation directions within the LVZ. We verified that the pattern is not controlled by aliasing of the array response to a 1.5 Hz plane wave impinging from various directions and with different speeds, and the homogenized inter-station distances (Section 2.4; Fig. S2) guarantee that the focal spot does not influence the response.

Rotation angles indicate larger variability of propagation directions across the LVZ (Figs. 4b, c, black) compared to lower frequencies. These results are associated with larger residuals due to energy on all nine components (Fig. S3b), which implies a mixture of scattered surface and bulk waves. The combined pattern of the near-field focal spot and increased in-fault amplitude symmetry is a manifestation of an isotropic surface wave field that is spatially sampled at sub-wavelength intervals. These wave field properties have long been studied in the context of time-reversal experiments [Fink et al., 1989], where a pulse is emitted into a potentially heterogeneous medium that is enclosed by a virtual surface called the time-reversal mirror. If records of multiple scattered wave motion passing through this surface are time-reversed and sent back into the medium, the resultant field emerging from the surface converges toward the initial source, and the time reversed beam focuses back on the source at the focal spot [Fink, 1997, and references therein]. The spatial focalization obtained by an active time-reversal process can be recovered using cross-correlation [Derode et al., 2003; Benech et al., 2009], i.e., the converging, collapsing, and diverging wave can be reconstructed from the correlation field at different lapse times. In this sense, the time-distance plot (Fig. 3c) represents a snapshot of the converging and diverging wave field. The X-shaped move-out pattern is generated by propagation along the fault normal direction, and the longitudinally polarized focal spot (Fig. 3f) emerges where a time reversed wave collapses at the location of  $S_{\text{ref}}$ . The consistency between ZZ and TT results indicates that the large amplitude feature in the ZZ pattern constitutes a focal spot and is not controlled by a possibly trapped  $P$  wave. A ZZ body wave focal spot can be superimposed on the reconstructed surface wave spot, but the similarity and consistency again suggest that such an interference does not govern the results.

Increased correlation time symmetry within the LVZ implies a significantly more isotropic wave field compared to the more directional energy flux associated with asymmetric amplitudes at stations in the adjacent crust (Fig. S5d). In this context, the velocity gradients bounding the LVZ can be considered as reflectors [e.g., Ben-Zion and Aki, 1990], which should not be confused with virtual time-reversal mirrors. Rather, the reflectors tend to trap energy inside the LVZ, which leads together with internal FZ scattering to time symmetry and improve the time-reversal performance. The resulting wave field is similar to that trapped in a cavity, which in our case with along-strike dimension much larger than fault-normal dimension is also a FZ waveguide.

The shape of the focal spot in the space-time domain is described by the amplitude distribution  $A(r)$  at  $\tau = 0$  (Fig. 6), where  $r$  denotes the distance between  $S_{\text{ref}}$  and receiver stations in both directions. In time-reversal experiments the shape is controlled by the symmetry properties of the wave field, and depends in the elastic case on the excitation direction of the applied force, the associated radiation pattern, and the analyzed component of motion [Catheline et al.,

2008]. The distribution of the time reversed wave energy and the focal spot shape are therefore not radial symmetric. The same principle should hold for focal spots emerging in a correlation field considering different excitation and recording components. This has not been tested experimentally, and radial symmetry cannot be assessed here due to the limited spatial sampling in directions different from fault normal. However, the observed fault normal amplitude symmetry around the location of the virtual source  $S_{\text{ref}}$  (Fig. 6) constitutes a further indicator for a homogeneous intensity distribution along the direction of the linear array. Local propagation properties can be estimated from focal spots, and the smallest dimension of the refocusing spot remains of the order of half a wavelength [Cassereau and Fink, 1992; Catheline et al., 2008; Benech et al., 2009]. The experimental results allow us to estimate the fault-normal velocity structure of the LVZ cavity/waveguide from focal spot properties, and to compare them to results of a travel time inversion based on far-field move out patterns.

## 4. Estimates of Fault Zone Properties

### 4.1. Estimates From the Focal Spot

Energy focusing has been discussed in seismology in the context of amplitude enhancement through backscattering [Larose et al., 2009] and passive Green's function retrieval [Gallot et al., 2011], but focal spot shapes have not been inverted for estimates of medium properties as in elastography or medical imaging [Catheline et al., 2008; Brum et al., 2009; Benech et al., 2009]. In these 3-D applications,  $\lambda/2$  is estimated from the  $-6$ -dB or half width of the spot following the Rayleigh criterion, without further reference to the spot sinc-function shape [Cassereau and Fink, 1992]. Here, we are interested in a general parametrization of the amplitude (coherency) distribution  $A(\tau = 0, r)$  to connect our estimates with a thorough understanding of the focal spot properties. We focus on the 1–2 Hz regime.

Considering the 2-D problem of an equipartitioned surface wave field, the coherency  $\gamma_{AB}(\omega)$  (Eq. 1) is described by a Bessel function of the first kind of order zero,  $J_0(kr)$ , with  $k$  being the wave number  $\omega/c$  [Aki, 1957]. Equipartitioning implies  $\text{Im}[\gamma] = 0$  and hence  $\text{Re}[\gamma] = J_0(kr)$ , and from observing  $J_0(kr) \propto \text{Im}[G_{AB}]$  [Sánchez-Sesma and Campillo, 2006] it follows that the time domain correlation function gives an estimate of the impulse response [Lobkis and Weaver, 2001]. To first order, the estimate of the band-limited inverse Fourier Transform (IFT) of the frequency domain  $\gamma(\omega) = J_0(kr)e^{-\alpha r}$  indicates that the time domain focal spot shape also takes the form of an attenuated Bessel function (supplementary material)

$$A(\tau = 0, r) \approx J_0(kr)e^{-\alpha r}. \quad (2)$$

We find that attenuation has to be considered to obtain reasonable fits to  $A(r)$  observations (Fig. 6) using Equation 2, i.e., the IFT was applied to  $J_0(kr)$  weighted by  $e^{-\alpha r}$ , with  $\alpha$  denoting the attenuation coefficient. This approach [Prieto et al., 2009] extends the original formulation associated with a homogeneous lossless medium [Aki, 1957]. Given the current controversy related to its validity and accuracy for noise based attenuation estimates [e.g., Tsai, 2011; Liu and Ben-Zion, 2013; Weaver, 2013; Lawrence et al., 2013], we focus on wave speed estimates in our discussion.

Since the focal spot is distorted by anisotropic intensity of the converging field, we fit 1–2 Hz correlation amplitudes at distances along the fault  $|x| < 1.5$  km using coherency estimates limited to  $r < 1$  km, which emphasizes the near-field character. The free parameters are  $k$  and  $\alpha$  from which we estimate the phase velocity  $c_{\text{focal}}$  using  $\omega = 2\pi\bar{f}$ , with  $\bar{f}$  the central frequency 1.5 Hz. Estimates of ZZ  $c_{\text{focal}}$  are symmetric around  $x = 0$ , whereas ORA corrected T'T' results

(Section 2) show variations within the LVZ characterized by smaller speeds on the SW side of the fault trace compared to the NE side. For the area  $0 < x < 0.5$  km we find partially distorted focal spots and overall higher residuals (Fig. S6) compared to other locations in the LVZ, which may be attributed to media changes across the fault trace and hence scatterers within the array that distort the spot shape.

In contrast to elastography applications that measure  $\lambda/2$  from the spot half width, we estimate  $3\lambda/8$  from the first zero crossing of the obtained distribution, which makes it insensitive to  $\alpha$ . The factor  $3/8$  is related to the asymptotic approach of the Bessel function to a cosine with a phase shifted argument by  $-\pi/4$  [Eq. 9.2.1 in Abramowitz and Stegun, 1965]. That is, while the zero crossing of  $\cos(kr)$  is at  $\pi/2 \times \lambda/2\pi$ , the phase shifted crossing occurs at  $3\pi/4 \times \lambda/2\pi = 3\lambda/8$ . In the example of Figure 6,  $\lambda \approx 8/3 \times 0.3$  km = 0.8 km agrees well with the  $k$ -based estimate  $\lambda = c/\bar{f} \approx 1.5$  km s/1.5 s = 1 km. This confirms that  $\lambda < \lambda_0$  and supports the interpretation of cavity-like LVZ characteristics. Applying the half-width approach to the attenuation free amplitude at  $J_0(kr) = 1/2$  yields a consistent estimate of  $\lambda \approx 4 \times 0.2 = 0.8$  km.

### 4.2. 1-D Travel Time Inversion

The validity of the focal spot estimates can be assessed by comparison to traditional travel time results [Catheline et al., 2008; Brum et al., 2009; Benech et al., 2009]. We compute phase ( $c$ ) and group ( $U$ ) velocity profiles from the arrivals that constitute the 1–2 Hz X-pattern using data from all inter-station correlation pairs (supplementary material). Similar to the focal spot analysis the inversion is constrained to  $|x| < 1.5$  km due to difficulties in isolating high SNR arrivals across the FZ boundary. Application of the ORA improves the inversion results through arrival time shifts associated with the free re-alignment (ZZ $\rightarrow$ Z'Z', TT $\rightarrow$ T'T') in the incident wave field, e.g., T'T'-based inversions are characterized by smaller residuals compared to TT results (Fig. S7). The improvement is most significant in regions of strong velocity gradients, and demonstrates the mitigation of directional propagation [Roux, 2009]. The results indicate that the Z'Z' and T'T'  $c$  and  $U$  distributions are consistent with the associated  $c_{\text{focal}}$  estimates (Figs. 4d, e). Both methods indicate  $\sim 50\%$  reduced velocities in a 1–2 km wide zone, and also agree on details such as the velocity variation across the fault trace (Fig. 4d). Differences in the absolute values are related to the sensitivity of the inversion to the starting model (1 km/s), which implies an advantage of the focal spot method due to its independence on algorithmic choices. Overall, the compatibility of the two methods supports again their applicability and increases the confidence on the fault-normal LVZ variations resolved independently by the near- and far-field data.

## 5. Synthetics

To confirm further our results, we construct synthetic correlation fields that exhibit characteristic features associated with fault zone trapped noise. (The solution includes an overall velocity contrast across the fault, but this is not used here.) The synthetic calculations are based on the analytical solution of Ben-Zion and Aki [1990] for the scalar wave field in a halfspace with a vertical fault zone layer. The computed seismograms contain the direct wave, and potential head and trapped waves for near-fault stations. The interference patterns controlling the waveform character of the FZ waves depend strongly on the width, velocity, and attenuation of the FZ layer along with propagation distance within the FZ structure [Ben-Zion, 1998]. The sensitivity of ballistic and

scattered wave fields to FZ velocity variations alike (Sec. 2.3) allows the application of synthetic earthquake waveforms to study first order features of noise-FZ interaction. We compute a suite of synthetic seismograms for a model FZ structure with properties corresponding to the Calico fault environment [Cochran *et al.*, 2009], and for a homogeneous half space model. Seismograms associated with a range of sources recorded by each station of the short period station geometry (Fig. 1b) are processed as in an earthquake waveform correlation method [Roux and Ben-Zion, 2013], correlated for each station pair, and source averaged.

The effect of the vertical LVZ layer on arrival time patterns is obvious when compared to synthetics generated with a homogeneous velocity structure (Fig. 7). The in-fault move-out structure resembles the X-pattern observed within the Calico fault (Figs. 3c; S5), and the break in slope across the LVZ boundary is controlled by the imposed velocity contrast. Correlation asymmetry on both sides of the FZ is related to the lack of transparency for waves originating on the respective opposite sides. We use a dozen sources that are homogeneously distributed away from the FZ, i.e., the emerging pattern is governed by the symmetry properties of the direct arrival pattern. In this configuration, no ballistic trapped waves are generated [Ben-Zion, 1998] and correlated. The results highlight that features characterizing correlations of the FZ wave field are a consequence of the symmetry properties of trapped noise propagation directions.

The reproduction of the main features associated with FZ noise suggests that an iterative reduction of correlation travel time misfits by tuning model parameters can yield estimates of FZ properties. Such a noise based FZ imaging tool can complement analyses of trapped or reverberating ballistic waves [Li *et al.*, 1990; Ben-Zion *et al.*, 2003; Cochran *et al.*, 2009; Lewis and Ben-Zion, 2010; Yang *et al.*, 2011] for systematic study of FZ properties in regions of low or no seismicity.

## 6. Discussion and Conclusions

We developed new analysis techniques to extract high resolution information from the ambient seismic wave field around and within fault zone structures, and demonstrated that the results are compatible with observations obtained with traditional methods based on earthquake waveforms. Moreover, certain aspects of the scattered ambient wave field allow conclusions on properties of the low velocity zone that augment previous interpretations based on analysis of ballistic phases.

Fault-normal velocity profiles (Figs. 4d,e) are compatible with models based on trapped waves [Cochran *et al.*, 2009] regarding location and average velocity contrast. We emphasize that the focal spot method facilitates direct local measurements of medium properties that are compatible with traditional inversion methods. The width of the low velocity layer is also consistent with estimates of the damage zone probed with space geodesy [Fialko *et al.*, 2002; Fialko, 2004]. The results provide independent confirmation of a wide compliant zone for the Calico fault with relatively small offset, while demonstrating the utility of noise based measurements in this challenging seismological situation. Constraints on the deeper parts of the fault, i.e., estimates of its dip [Yang *et al.*, 2011], are limited due to the analysis of high-frequency surface waves. The application of double-beamforming techniques offers a potential tool to focus on noise wave field components that are sensitive to properties at deeper parts of the fault [de Cacqueray *et al.*, 2013]. The identification of a critical frequency  $f_c$ , above which the wave field within the FZ has significantly different properties compared to the surrounding region, is also compatible with observations based on ballistic waves. Using  $v \approx 1$  km/s for in-fault propagation speeds (Figs. 4d,

e), the associated wavelength  $\lambda_c = v/f_c$  is about 2 km, and therefore compatible with the estimated width of the LVZ,  $\lambda_c \approx \lambda_0$ .

The derived geometrical and rheological properties of fault damage zones provide high-resolution information on the internal FZ structure [e.g., Ben-Zion and Sammis, 2003, and references therein]. This information is important for deriving accurate earthquake source properties [e.g., Oppenheimer *et al.*, 1988; Kilb and Hardebeck, 2006], understanding the distribution of seismic ground motion near faults [e.g., Spudich and Olsen, 2001; Pischiutta *et al.*, 2012; Kurzon *et al.*, 2014], and assessing likely dynamic regimes of earthquake ruptures [e.g., Ben-Zion and Huang, 2002; Huang and Ampuero, 2011; Huang *et al.*, 2014]. Local estimates of reduced elastic moduli in the FZ also constrain the rotation of background stresses [Faulkner *et al.*, 2006], which affects the mechanics during fault slip, and amplified geodetic fields [Fialko *et al.*, 2002; Fialko, 2004].

Noise based methods extend the toolbox of imaging and analysis techniques targeting the interaction of fault zones and seismic wave fields, as demonstrated with the focal spot method. The Optimal Rotation Algorithm constitutes another method providing observables that can exclusively be inferred from processing of the ambient field. Results include intermediate-frequency ray bending (Fig. 4b) and a significant distortion of high-frequency propagation directions within the fault (Fig. 4c). These findings imply that images of FZ environments constructed from ballistic and scattered wave fields can be biased near the mechanically most interesting LVZ damage zone because of these interactions.

Our analysis techniques and results establish connections between fault zone seismology and other wave physics domains. The increased correlation time-symmetry indicates the high-frequency wave field can be considered trapped within the LVZ. The scattered in-fault wave field is associated with efficient mixing of trapped energy, where reflections at LVZ boundaries and scattering at internal heterogeneities contribute to the randomization of incident propagation directions. This motivates the LVZ analogy with a noise cavity/waveguide for  $f > f_c$ , therefore providing a framework to explain specific characteristics of the wave field. Correlation of reverberations—internal reflections related to the FZ/cavity finiteness—leads to distinct signatures [Roux *et al.*, 2008] that differ from correlations of a scattered coda or noise wave field [Lin *et al.*, 2013; Boué *et al.*, 2013]. The lack of multiple fault-normal reflections indicates that reverberations do not dominate the correlation field, owing to data processing which minimizes the influence of earthquake signals, although the analyzed seismic energy within the LVZ may not be fully diffusive. The emergence of multiple body wave reflections in high-frequency FZ correlations [Zhang and Gerstoft, 2014] can likely be tuned by data windowing and processing choices. The cavity-analogy suggests that separate processing of earthquake waveforms [Roux and Ben-Zion, 2013] or noise data segments [Boué *et al.*, 2014] provides an efficient strategy to image FZ structure with ballistic trapped waves and trapped noise in regions with sufficient background seismicity. Strategies enhancing in-fault reverberations from noise contribute towards monitoring the LVZ material response to perturbations [Johnson *et al.*, 2008].

The application of time-reversal concepts help understanding the emergence of the near-field focal spot, and developing focal spot based wavenumber estimates. The imaging approach can generally be applied in environments exhibiting properties of a cavity, e.g., low velocity zones (this work), buildings [Sneider and Safak, 2006], or soft tissue phantoms [Catheline *et al.*, 2008]. The effect of refocusing also occurs

in open media, e.g., in the situation of a diffuse Rayleigh wave field propagating across the surface. The time-reversal situation associated with the reconstructed correlation field similarly requires radial symmetry of the field intensity for unbiased local measurements based on the focal spot. This constraint is related to the requirement of isotropic source or scatterer distributions for unbiased noise based imaging [Weaver et al., 2009; Froment et al., 2010]. Implications of the SPAC method [Asten, 2006], iterations of the correlation procedure [Stehly et al., 2008], and filtering [Gallot et al., 2011] can be used for bias assessment and mitigation of frequently occurring inhomogeneous intensity distributions, thus facilitating the study of local medium properties from the collapse of a time reversed converging wave field.

We demonstrate that properties of damage FZ layers can be estimated from synthetic correlation arrival times. This can furnish an imaging tool for investigating FZ structure that is complementary to traditional waveform modeling of ballistic FZ waves. Different theoretical solutions [Ben-Zion and Aki, 1990; Ben-Zion, 1998; Li et al., 2007] combined with variable source distributions control the arrival time pattern in synthetic FZ waveforms and in the associated correlation fields that is indicative of the FZ structure. This allows systematic study of the relative contributions of source distribution, multiple reflected phases, and direct and trapped waves.

The emergence of ballistic trapped waves depends on the location and orientation of the source with respect to the trapping structure [Ben-Zion, 1998; Fohrmann et al., 2004; Lewis and Ben-Zion, 2010], and on a sufficiently homogeneous waveguide between source and receiver [Igel et al., 1997; Jahnke et al., 2002]. Mechanisms controlling the emergence of FZ trapped noise depend only on the velocity contrast and the scattering heterogeneity and are thus more general, which provides additional possibilities for imaging internal FZ structures. Trapped noise based tools can thus facilitate the imaging of structural properties along aseismic faults.

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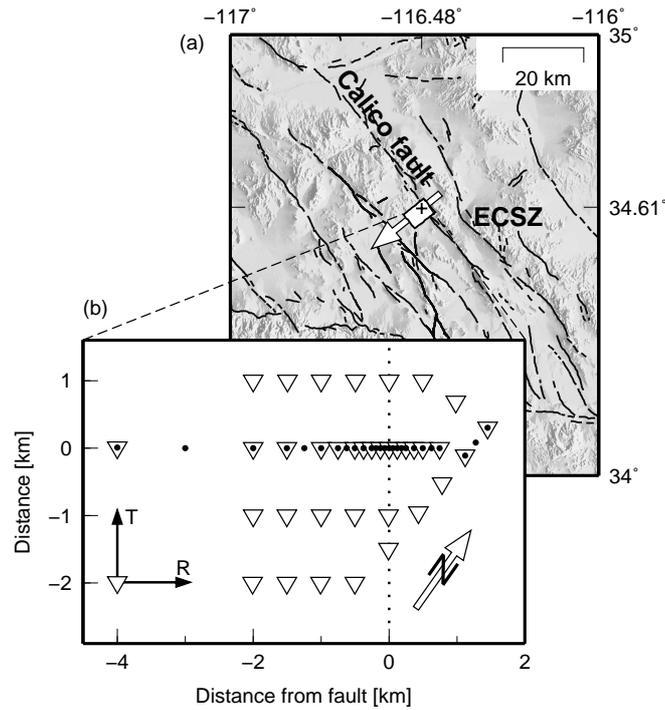
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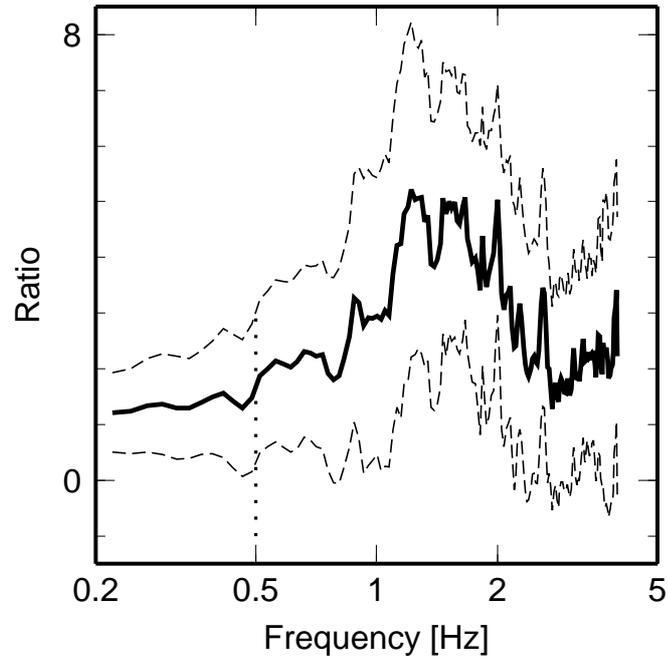
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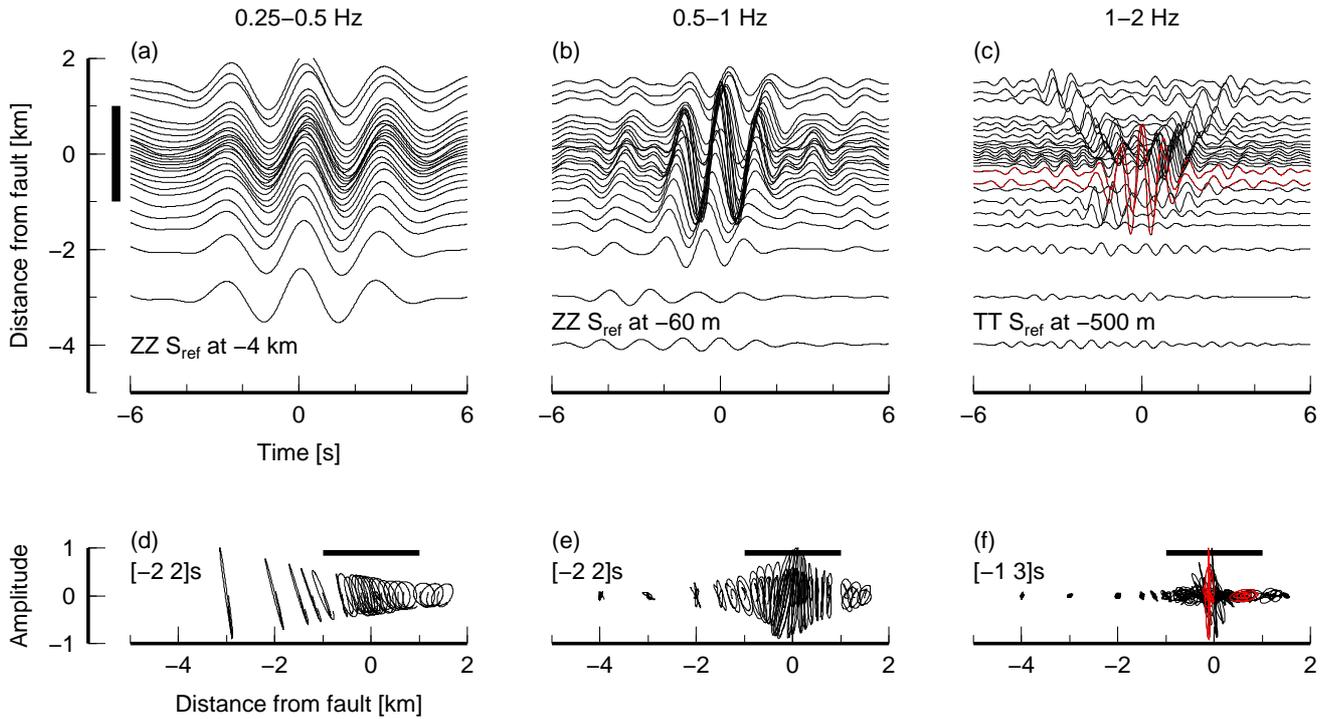
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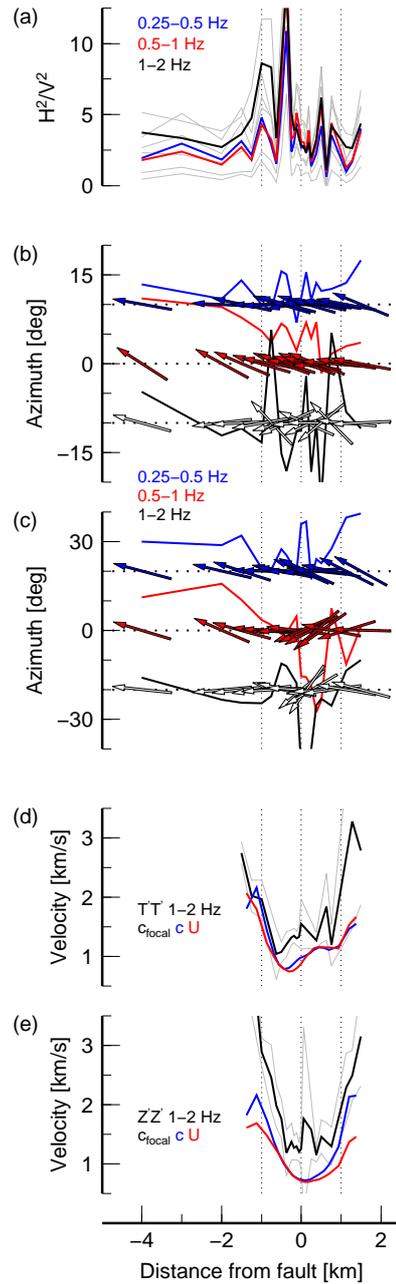
**Figure 1.** (a) Shaded relief map of the Eastern California Shear Zone (ECSZ) surrounding the Calico fault zone array. The arrow is oriented normal to the fault and points towards the Pacific coastline, which is the direction from which noise impinges on the fault. The arrow is aligned with the horizontal dotted lines in Figs. 4b and c. Black lines show geologically mapped faults. (b) Rotated array geometry. The array position is indicated in (a) by the white box, where the ‘+’ sign marks the origin. Triangles and dots denote broadband and short period sensors, respectively. The fault trace (dotted line) is estimated from maximum InSAR strain [Fialko, 2004] and deviates from mapped surface fault strands. R and T indicate fault radial and transverse directions. The variable  $x$  used in Section 4 is associated with the abscissa.



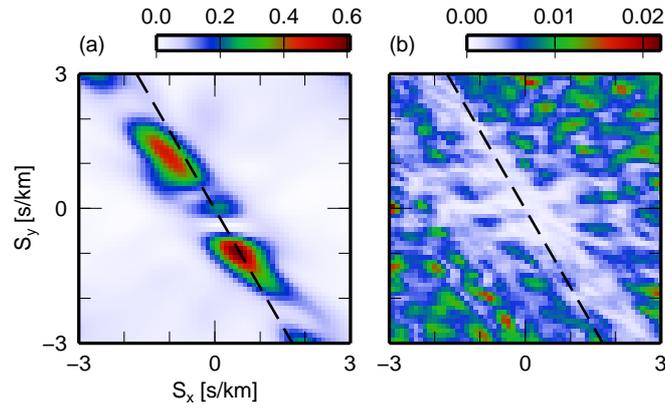
**Figure 2.** Average amplitude spectra of windowed ( $[-20, 20]$  s) in-fault ZZ correlation functions scaled by an average constructed from correlation pairs located outside the fault zone. One standard deviation is indicated by the dashed lines. The distribution indicates a sensitivity of the noise wave field to the structure of the low velocity zone above the critical frequency for interaction,  $f_c \approx 0.5$  Hz. The scale on the abscissa is logarithmic.



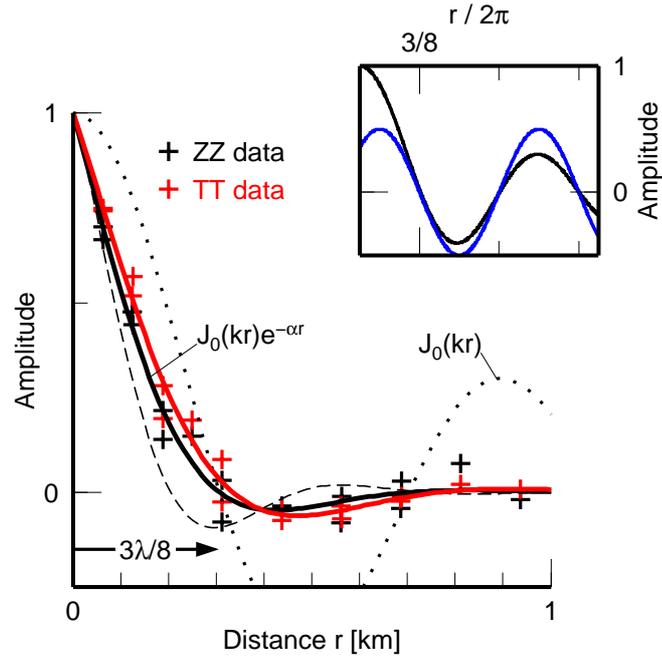
**Figure 3.** Frequency dependent correlation amplitude (a-c) and polarization (d-f) patterns constructed from fault-normal short period data (ordinate corresponds to abscissa in Fig. 1b). Energy at negative (positive) times propagates towards (away from) the correlation reference station  $S_{\text{ref}}$ . Move-out patterns illustrate variable noise-FZ interactions, ranging from a transparent fault at low frequencies (a) to the symmetric in-fault signature of trapped noise (c). Traces are scaled to their maximum (a) or to the pattern maximum (b-c); large amplitudes associated with the focal spot are highlighted in (c). See Figure S5 for complementary patterns. All polarization patterns (d-f) show radial-vertical ZR-ZZ motion in the fault-normal direction (abscissa corresponds to abscissa in Fig. 1b). Values are scaled to the pattern maximum, and radial and vertical amplitude scales are equal. The position of  $S_{\text{ref}}$  and the indicated time windows correspond to the move-out patterns above. In (f) the polarization of the focal spot and the surface wave are highlighted.



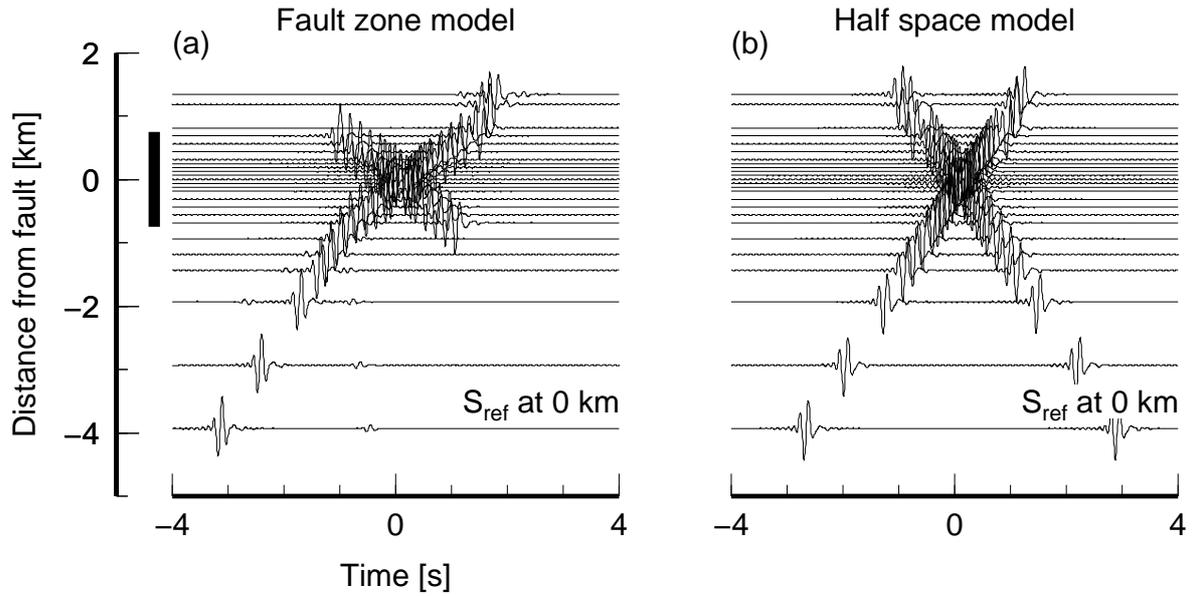
**Figure 4.** Fault-normal distributions of wave field and fault zone properties. The abscissa corresponds to abscissa in Fig. 1b. (a) Variations of spectral ratios  $H^2/V^2$  are strongest in the region of the SW velocity gradient. Long-range (b) and short-range (c) averages of propagation directions based on the Optimal Orientation Algorithm are indicated by graphs and arrows. The ordinate corresponds to the graphs which are offset by (b) [10, 0, -10], (c) [20, 0, -20]; the zero-levels are indicated by the dotted lines, and correspond to the fault-normal direction indicated by the arrow in Fig. 1(a). Zero azimuth indicates propagation perpendicular to the fault. Orientation of arrows is exaggerated by a factor (b) 3 and (c) 1.5 for better visibility of the fault-normal trends. (d) & (e) Phase (c) and group (U) velocity profiles obtained from focal spot properties and an inversion of c and U arrival time estimates as in Fig. 3(c). T'T' and Z'Z' results in (d) and (e) are based on the ORA-rotated correlation field.



**Figure 5.** Horizontal slowness maps obtained with correlation-based beamforming from (a) 0.25–0.5 Hz and (b) 1–2 Hz ZZ correlations. The dashed line denotes the approximate orientation of the Calico fault strike. In (a) energy travels in SE→NW directions. Energy in the opposite NW quadrant is an aliasing artifact (Fig. S2). The pattern in (b) implies that high-frequency energy propagates randomly within the low velocity zone. See Figure S2 for associated synthetics and array configurations.



**Figure 6.** The shape of the 1–2 Hz focal spot emerging at  $x_{\text{ref}} = -50$  m. Crosses denote measured coherency amplitudes along  $\tau = 0$  s, and the solid lines are  $J_0(kr)e^{-\alpha r}$  functions with best-fitting  $k$  and  $\alpha$  values. The dotted line corresponds to the corresponding undamped ZZ function, and the dashed line shows the damped function for a 50% larger  $k$  value. The wavelength can be estimated from the zero crossing of the data and the Bessel function fit.  $3\lambda/8$  indicates the zero crossing of the associated ZZ Bessel function at  $r = 300$  m. The inset illustrates that the Bessel function (black) and the  $-\pi/4$  shifted cosine (blue) have approximately the same zero crossings, the first one at  $3/8$ .



**Figure 7.** Synthetic correlation patterns using the Calico array station geometry. Correlations are scaled by the maximum in each time series. (a) For  $S_{\text{ref}}$  located in a 1.5 km wide low velocity zone characterized by a 50% wave speed reduction, the arrival structure is characterized by high in-fault symmetry and anisotropic properties outside the fault, similar to observations (Figs. 3c, S5d). Inter-station correlations are averaged over sources that are located between [5 7] km and between [-5 -7] km at a depth of 100 m. (b) The correlation field associated with the same source/receiver configuration in a half-space.