A STUDY OF THE SPECTRAL CHARACTERISTICS OF ACCELEROGRAMS FROM RECENT EARTHQUAKES OF ITALY AND NEARBY REGIONS

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SUMMARY

We consider a set of accelerograms recorded on rock during recent earthquakes of Italy and Yugoslavia. While the Fourier spectra of the $5.0 \leqslant M_L \leqslant 6.0$ events are typical of band-limited white noise, those of the $M_L \cong 6.5$ events exhibit an ω^{-1} decay for frequencies $\gtrsim 1-2$ Hz. These features are modeled by a stochastic approach with two source correlation parameters, or corner frequencies. Appropriate model expressions are fitted to the autocorrelations computed from the records' S-wave windows, to estimate the source parameters. One corner frequency appears to be nearly independent of source size and, hence, possibly governed only by the size of significant subevents, whereas the other depends on seismic moment and controls the significant bandwidth.

INTRODUCTION

Prominent among recent developments in strong-motion studies is the use of source models of varying complexity for estimating high frequency ground motion parameters. For instance, the Brune source model, associated with a constant stress-drop of 100 bar, predicts well several characteristics of California accelerograms (Ref. 1). Its acceleration spectrum is flat between the corner frequency f_o, which depends on the fault length, and an assumed upper frequency $f_{max} = 10 - 15$ Hz for earthquakes of engineering interest. However, a large number of California records are on deep alluvium, such as in the Los Angeles area or the Imperial Valley. Multiple wave scatterings occurring in deep sediments may change the spectral shape with respect to rock sites, and make it flatter in the frequency band of interest. This is illustrated in Fig. 1 between about 0.5 and 3 Hz; the spectra shown are calculated by regressions (Ref. 2) based on a data set which includes virtually all the records from the larger California earthquakes up to 1977. If, in addition, we consider that the seismotectonic environment of California differs from those of other regions where important strong-motion data are now becoming available (such as Italy), it may be unwarranted to conclude

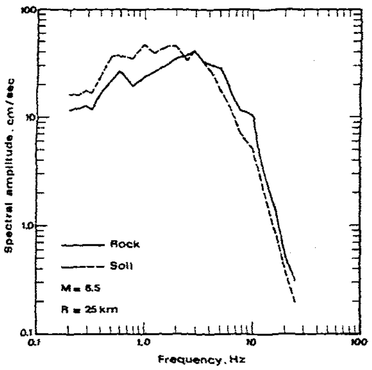

FIG. 1

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that band-limited white noise (BLWN) is a model of general validity for describing high frequency strong ground motions, as we shall presently see.

More flexible models (Refs.3, 4) contain BLWN as a particular case, and provide a better physical link between the characteristics of high frequency radiation and the inhomogeneities of the source process, such as jumps in rupture velocity, local stress drop, or length and duration of coherent rupture episodes. The usefulness of the latter approach is illustrated in the following through a set of records on rock sites from destructive events of Italy and Yugoslavia during the period 1976-1980. We shall show that their spectral and autocorrelation features agree with a formulation recently developed by the senior writer (Ref. 4) on the basis of the Haskell stochastic source spectrum (Ref. 5). One asset of this formulation is that it yields simple analytical expressions for engineering parameters such as the Arias intensity, the r.m.s. acceleration, and others, which make possible a direct estimation of the source parameters from the data. In the present version, the full capability of the model with two independent source parameters is explored, thus extending the work of Ref. 4 where only one independent parameter was used. The general usefulness of a stochastic approach in the context of engineering applications, as opposed to deterministic descriptions of the source process which often pose great difficulties in estimating the large number of parameters needed, has been stressed in other studies discussed in Ref.4.

STRONG-MOTION DATA SET

The earthquake source parameters are listed in Table 1. The events belong to two bordering tectonic regions; one including Friuli and Montenegro (Eastern and Dinaric Alps), with predominant thrust faulting, and another including the Apennines where normal faulting is instead prevalent. Events 6, 7 and 9 were the strongest earthquakes occurring in Italy and Yugoslavia during the last few decades. In Table 1, M_o and M_L denote seismic moment and Richter magnitude, respectively. The M_o - values of events 4, 7, 8, 9 are from body waves, and are less than the surface wave values; the choice is believed to be more consistent with our approach, which considers only S waves. In addition to Ref. 4, M_o - values for the Friuli sequence are discussed in Ref. 6, while the parameters of event 8 are given in Ref. 7. Rupture durations shown in parentheses in Table 1 are estimated via an empirical correlation with M_o (Ref.4), while the other values are from seismological studies. Hypocentral depths are typically less than 10 km, but increase to 15-20 km for events 7 and 9.

Several characteristics of the strong-motion accelerograms are listed in Table 2. Here, R denotes the source - to - site distance (in most cases hypocentral distance, see Ref.4), I_a the Arias intensity, $\bar{a}_h$ and a_{ph} the r.m.s. and peak horizontal acceleration, respectively. The values of I_a, $\bar{a}_h$ and a_{ph} are calculated from the horizontal plane acceleration history, defined as the square root of the sum of the squares of the two orthogonal components of horizontal ground acceleration. The r.m.s. value is computed over an interval equal to the rupture duration of Table 1 and beginning with the S-wave arrival. The individual horizontal components of the last column of Table 2 are those used for the spectral and autocorrelation analyses discussed below.

All of the accelerograph stations are on sedimentary rock except for Calitri which is on stiff soil, and are either free-field or housed in small structures; we are thus concentrating on data as free as possible from local soil and soil-structure interaction effects. Given the restricted range of distances considered, the homogeneity of site conditions and the fairly wide range of seismic moment values, we believe that the data set is suited for stu

Table 1 - Earthquake Source Parameters

No.	Event (day/mo./gr.)	M_o (dyn.cm)	M_L	Type of faulting	Angle of rupture propagation	Rupture duration (s)
1	Friuli,16/9/77 (2348)[a]	4.8×10^{23}	5.2	DS[b]	-	(2.2)
2	Friuli,11/9/76 (1631)	5.0×10^{23}	5.3[c]	-	-	(2.3)
3	Friuli,11/9/76 (1635)	2.5×10^{24}	5.7[c]	DS	-	(3.4)
4	Friuli,15/9/76 (0315)	3.6×10^{24}[d]	6.0	DS	-	3.3
5	Friuli,15/9/76 (0921)	8.0×10^{24}	5.9	DS	-	3.5
6	Friuli, 6/5/76 (2000)	3.0×10^{25}	6.3	DS	N 94° W	4.5
7	Montenegro, 15/4/79	1.0×10^{26}	6.7	DS	N 45° W	10.0
8	Valnerina, 19/9/79	5.0×10^{24}	5.6	N	-	(3.5)
9	Irpinia, 23/11/80	6.0×10^{25}	6.5	N	N 42° W	6.0

(a) GMT origin time in parentheses after the date, when required for proper event identification; (b) DS = dip-slip, N = normal;
(c) Average of TRI and RMP; (d) Value from short period body waves.

Table 2 - Strong-motion Data

Event No. of Table 1	Accelerograph station	R (km)	θ[a] (degrees)	I_a (s)	$\bar{a}_h$ (cm/s^2)	a_{ph} (cm/s^2)	Component analyzed
1	Somplago E	10	-	10.7	53	192	EW
2	Somplago D	10	-	2.2	34	87	NS, EW
3	S. Rocco	21	-	7.6	37	100	NS
	Somplago D	17	-	4.8	42	119	EW
	Kobarid	21	-	12.6	43	103	EW
4	S. Rocco	19	-	11.8	44	124	NS
5	Tarcento	14	-	30.9	58	133	NS, EW
	Robic	25	-	7.2	26	87	EW
6	Tolmezzo	22	25	192.6	158	461	NS, EW
7	Ulcinj-2	15	110	301.4	85	232	NS, EW
	Herceg Novi	80	15	117.6	78	285	NS, EW
8	Cascia	15	-	42.7	86	212	NS, EW
9	Bagnoli I.	22	318	72.5	70	177	NS, EW
	Calitri	25	98	139.	74	155	NS, EW

(a) Azimuth from the direction of rupture propagation, measured clockwise

dying the influence of the seismic source on high frequency ground motions in the study region. Complete information on the digitized data sources and the adopted correction procedures can be found in Ref. 4. Additional processing carried out for this study includes the acceleration Fourier amplitude spectra (FAS) and the autocorrelation functions (AF). Both were computed over a window beginning with the direct S-wave arrival and lasting not less than the rupture duration of Table 1. Among the accelerograms originally available from rock sites, we discarded a few recordings in which resonances attributable to the local geologic structure appear to significantly influence the spectral shape and AF. However, we retained the important Tolmezzo recording of the Friuli main event of May 6, 1976, even if it is not entirely free from local effects.

Shown in Fig. 2 are four representative acceleration histories and their respective FAS, computed via an FFT algorithm; the selected time windows correspond to the segments over the accelerograms. The signals in Fig. 2a and 2b are typical of the smallest events considered, and are compatible with a BLWN representation, with significant spectral bandwidth between 1-2 Hz and 10 Hz. The correlation time of these signals is of the order 0.03 seconds, as illustrated by the autocorrelation coefficient of Fig. 3a (corresponding to the signal of Fig. 2b).

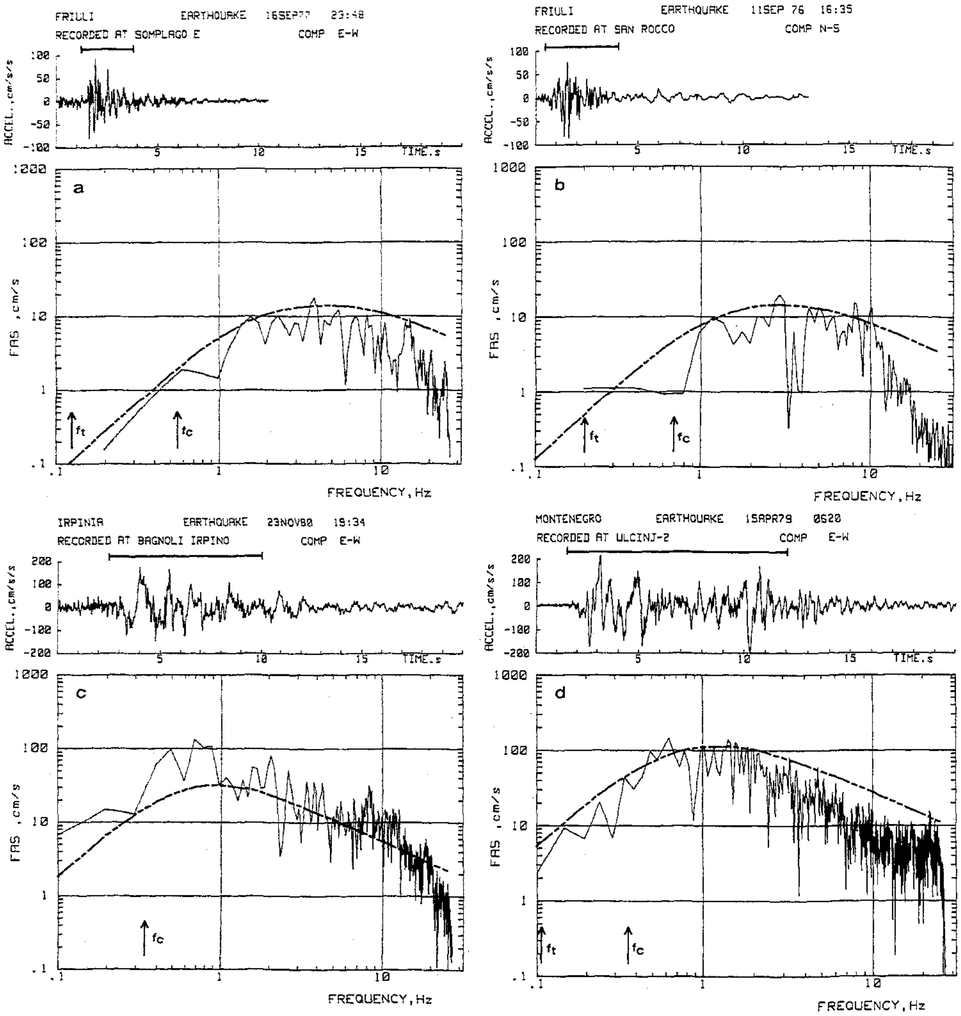

FIG. 2

On the other hand, the signals of Fig. 2c and d are typical of the largest events, with relatively low-frequency outbursts of energy probably due to separate and dominant episodes of coherent rupture of comparable size. As a result, the FAS of these signals is no longer consistent with BLWN and tends to have a peaked shape, decaying as ω^{-1} beyond about 2 Hz. This change is also evident in the AF, as shown in Fig.3b, computed from the signal of Fig. 2c; the significant correlation time is now of the order of 0.15 seconds and random fluctuations appear greatly reduced. Towards the long-period end, the four spectra of Fig.2 exhibit a corner frequency between about 0.5 and 1.5 Hz, which is higher than both the termination (f_t) and cut-off frequencies (f_c) of the Ormsby filter employed for accelerogram correction, also shown in the figure. This relatively constant value of the lowest corner frequency recoverable from the acceleration signals is found also in the other spectra of the sample and will be discussed later.

DESCRIPTION OF THE MODEL

We express the S-wave, far-field FAS of acceleration, $|A(\omega)|$, as the product of a constant C times a propagation factor times the source spectrum. For the source we take the statistically inhomogeneous model proposed by Haskell (Ref. 5), where the fault slip acceleration is regarded as a stationary random process in space and time, characterized by an AF which ensures that most of the radiated energy is associated with small spatial and temporal lags. Fault rupture, although highly irregular in detail, is assumed to occur unilaterally at constant mean speed v_R, and to be governed by two independent correlation parameters, namely the rupture correlation length (or coherent length) k_L^{-1}, and the correlation time k_T^{-1}. The parameter k_L^{-1} is considered to be a fraction of total fault length and, likewise, k_T^{-1} as a fraction of total rupture duration. This model, discussed in Ref.4, leads to simple analytical expressions for integral measures of ground motion. Specifically, we have:

$$|\text{source spectrum}| = \frac{M_o}{\rho}\,\omega^2 \left[1 + \left(\frac{\omega}{\omega_1}\right)^2\right]^{-1/2} \left[1 + \left(\frac{\omega}{\omega_2}\right)^2\right]^{-1} \qquad \ldots (1)$$

where ω is the circular frequency, ρ the density of the medium, and ω_1, ω_2 the spectral corner frequencies given by

$$\omega_1 = v_R/\left[(1-m\cos\theta)\;k_L^{-1}\right] \qquad \omega_2 = k_T \qquad \ldots (2)$$

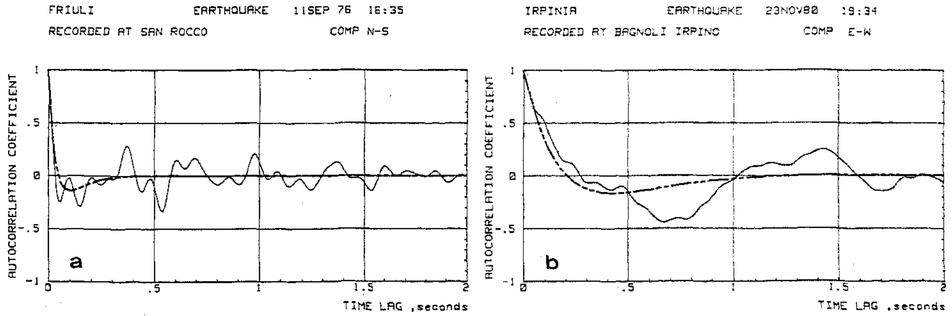

FIG. 3

In (2) $m = v_R/\beta$, with β=S-wave velocity, and θ = angle between the direction of rupture propagation and the radius vector from hypocenter to receiver. After introducing the directivity term $\lambda = 1 - m \cos\theta$ and the ratio $\xi = \omega_2/\omega_1 = \lambda\ (k_L^{-1}/v_R\ k_T^{-1})$, we can rewrite (1) as

$$|\text{source spectrum}| = \frac{M_o}{\rho}\,\omega^2 \left[1 + \left(\frac{\xi\omega}{\omega_2}\right)^2\right]^{-1/2} \left[1 + \left(\frac{\omega}{\omega_2}\right)^2\right]^{-1} \qquad \ldots (3)$$

For a partially uncorrelated rupture process with $k_L^{-1} \to 0$, i.e. $\xi \to 0$, expression (3) reduces to the well known BLWN spectrum with the single corner frequency ω_2.

In addition to the R^{-1} term for geometric attenuation of body waves, we introduce inelastic attenuation through the usual term $\exp(-\omega R/2Q\beta)$, with R=distance. Upon taking the quality factor Q linearly dependent on frequency, i.e. $Q = Q_o f$, the attenuation term can then expressed as $\exp(-qR)/R$, with $q = \pi/(Q_o\beta)$. The previous assumption on Q is well supported by the spectral properties of the records analyzed here, as shown in more detail elsewhere (Ref.4). The values of Q_o determined for the Friuli, Irpinia and Montenegro events range between 40 and 80. This implies that, within distances of 100 - 150 km, the average shape of the FAS for a given earthquake depends only on the source, since the propagation term $\exp(-qR)/R$ is just a scaling factor.

Finally, the constant C consists of the product of three terms, namely a free-surface correction factor FS=2, a vectorial partition factor $VP=1/\sqrt{2}$ (as we are looking at single horizontal components of motion), and the average value of the shear wave radiation pattern $\overline{R}_{\theta\phi}=0.63$. The complete expression of the FAS of ground acceleration is therefore:

$$|A(\omega)| = 0.89\,\frac{M_o}{4\pi\rho\beta^3}\,\frac{\exp(-qR)}{R} \left[1 + \left(\frac{\xi\omega}{k_T}\right)^2\right]^{-1/2} \left[1 + \left(\frac{\omega}{k_T}\right)^2\right]^{-1} \qquad \ldots (4)$$

The AF corresponding to (4), after normalization by its value for zero time lag, has the form:

$$\begin{aligned} r_a\ (\tau;\ k_T,\ \xi) &= R_a\ (\tau;\ k_T,\ \xi)/R_a\ (0;\ k_T,\ \xi) \\ &= \{\exp\ (-k_T|\tau|\ /\ \left[(1-\xi)^2\ (2+\xi)\right]\}\ \{2\exp\left[k_T(1-\xi^{-1})|\tau|\right] \\ &\quad + \xi\ (\xi^2-3) + (1-\xi^2)\ k_T|\tau|\} \end{aligned} \qquad \ldots (5)$$

Likewise, the expression for the ground velocity AF is:

$$\begin{aligned} r_v\ (\tau;\ k_T,\ \xi) &= \exp\ (-k_T|\tau|\ \{(1+\xi^2)\ /\ (1-\xi)^2 \\ &\quad - \left[2\xi/(1-\xi)^2\right]\ \exp\left[k_T(1-\xi^{-1})|\tau|\right] - k_T\,|\tau|\,(1+\xi)/(1-\xi)\} \end{aligned} \qquad \ldots (6)$$

It follows from (6) that:

$$\lim_{\xi \to 0}\ r_v\ (\tau;\ k_T,\ \xi) = \exp\ (-k_T|\tau|)(1 - k_T|\tau|) \qquad \ldots (7)$$

Since the Haskell source model is primarily an autocorrelation model (Ref.5), we chose to estimate the source parameters k_T^{-1} and k_L^{-1} (or, equivalently, k_T and ξ) by fitting the AF computed from the selected time windows of the records with

(5) and (6), after integration of the acceleration histories. The fitting was achieved by a multivariable, multi-function optimization procedure (Ref. 8). In most cases k_T and ξ were estimated by the simultaneous use of (5) and (6), but giving the autocorrelation data of acceleration a weight five to ten times larger than to those of velocity, consistently with our emphasis on the characterization of high frequency radiation. When no information on the direction of rupture propagation was available (see Table 1), the directivity term $\lambda=1-m\cos\theta$ of (2) was set equal to one.

For records with correlation times of the order of 0.03 sec (i.e. approaching BLWN, as in Fig.3a) we took $k_T^{-1}=\tau_{ov}$, where τ_{ov} is the zero crossing time of the velocity AF, see Eq.(7). In such cases, ξ was subsequently estimated using the analytical expression of the ratio between the second and zeroth moment of the velocity's power spectral density, not given here. The resulting ξ values are typically less than 0.3, thus confirming that the signals in question are close to BLWN. The largest time lag used in the data fitting ranges from about 0.3 sec, for windows of the order of 3 sec and small correlation times, to about 1.5 sec for windows of 7-10 sec and large correlation times. Tests with larger lags did not result in significant changes of the estimates. The time lag interval was in all cases taken equal to the interval of 0.01 sec of the corrected acceleration data. The dotted curves in Fig. 2 and 3 are examples of the fit obtained for the FAS and AF, based on the average estimates of k_T and ξ for a given event, the data of Tables 1 and 2, and the values $\beta=3.2$ km/s (Friuli) and 3.5 km/s (Montenegro, Irpinia), $m=0.72$, $\rho=2.6$ gr/cm^3.

DISCUSSION OF THE RESULTS

The average estimates of $f_2=k_T/2\pi$ for each event are illustrated in Fig.4 as a function of M_o. The c.o.v. of the average values for the largest events, where four different horizontal components were fitted, is of the order of 30%. Except for the Irpinia event, all f_2 values fall between 1.5 and 1.0 Hz, with a slightly decreasing trend as M_o increases. Also shown for each value of f_2 is the mean value of the long period filter frequencies $(f_t+f_c)/2$. This is typically 1/3 to 1/4 of f_2, so that we believe our estimates of f_2 to be physically meaningful. This circumstance suggests that in the source process there is a characteristic rupture time almost independent of source size (for $10^{23} \lesssim M_o \lesssim 10^{26}$ erg), apparently typical of shallow earthquakes in the study region. The lower f_2 value for the Irpinia event, which had a focal depth of 18 km, might be and indication that the characteristic time in question varies with depth. The low-frequency, high-amplitude waves of the accelerograms of Figs. 2c and d point to the occurrence of subevents, or patches of coherent rupture, having comparable dimension. The latter could be controlled by rupture propagation in the direction either of the length or of the width of the fault. We may remind the remarks by Aki (Ref. 9) to the effect that "there is accumulating evidence supporting the existence of certain unique scale lengths governing earthquake pheno-

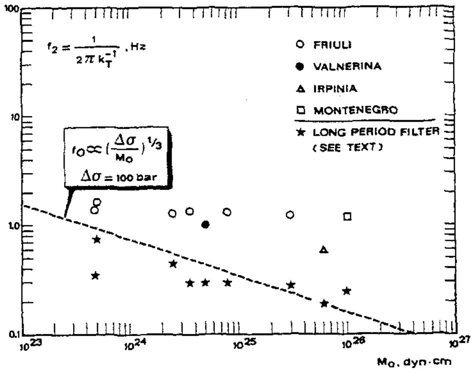

FIG. 4

mena if we restrict our attention to earthquakes of a certain range of magnitude occurring in a specific area", and that this "suggests a significant departure from the idea that there is no unique physical length governing earthquake phenomena".

Finally, we note that the corner frequency of the Brune model, computed as $f_o = 4.9 \times 10^6 \beta (\Delta\sigma / M_o)^{1/3}$ with a constant stress drop $\Delta\sigma = 100$ bar (Ref.1), is substantially smaller than f_2 and falls very close to the mean filter frequency $0.5\ (f_t + f_c)$, so that it can hardly be identified in the S-wave spectra.

The estimated values of ξ, the parameter which measures the significant bandwidth of the source spectrum, are more uncertain than those of k_T^{-1}, since the functions (5), (6) are not very sensitive to the value of ξ; in particular, for ξ small, the alternative procedure mentioned in the previous section was adopted. Thus, we found $0.1 \lesssim \xi \lesssim 0.3$ for the events with $M_o \lesssim 10^{25}$ dyne cm; this corresponds to well separated values of ω_1 and ω_2 (with $\omega_1 > \omega_2$) and to flat spectra such as these of Fig. 2a and b. We can therefore speak of a "BLWN domain" of ξ values in this case; virtually all of the Friuli earthquakes and the Valnerina earthquake fall in this category. For the Irpinia and Montenegro events we obtain (after correcting for directivity) $\xi = 1.54 \pm 0.9$ and $\xi = 2.8 \pm 1.8$. Despite the large standard deviations, the latter estimates show that ξ is an increasing function of M_o for $M_o \gtrsim 10^{25}$ dyn cm. The increase of ξ corresponds to the change of shape of the FAS from the cases of Fig. 2a, b to those of Fig. 2 c, d. The question of whether ξ reflects a true source property is partly related with the issue of the nature of "f_{max}", i.e. the high-frequency spectral limit seen at 10 - 15 Hz in the FAS of Fig. 2 a, b, but not in those of Fig. 2 c, d. If f_{max} exists and is a site property, then ξ is probably also site-dependent. Otherwise, the physical meaning of ξ and its behavior as a function of the seismic moment should be more closely investigated by simulation with stochastic models of source rupture. Assuming k_T^{-1} to be mainly controlled by the fault width, i.e. a quantity with modest variations within our set of events, it is conceivable for k_L^{-1} to be independently controlled by rupture propagation in the direction of the fault length and to depend on total source dimensions, at least in some tectonic environments. The study of these aspects is currently under way.

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