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Temporal Variation of Body Wave Attenuation as Related to Two Earthquake Doublets in W. Greece

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Abstract—In this research four earthquakes, which are considered to compose two earthquake doublets, recorded prior to and after a magnitude $M_s = 5.0$ and a magnitude $M_s = 4.8$ event in W. Greece are used to derive temporal variations of P-wave attenuation in the region.

Spectral ratios at four stations are computed and the results indicated a variation (increase) of Q of the order of 15–20%. To confirm that this variation is not an artifact due to changes of the source parameters, a smaller event which occurred at the same hypocentre was used as a Green function and the deconvolution proved that the earthquakes of one of the doublet possessed the same source parameters.

The outcome of this research verifies the possible role of the migration of fluids in the crust in the focal region and their effect on the attenuation of seismic waves.

Key words: Doublets, attenuation, Greece.

1. Introduction

The possibility that earthquakes can be forecast directly from the measurement of variations in seismic wave attenuation and stress drop of smaller events stimulated our interest in investigating the above parameters in the seismically active region of W. Greece. In this region, the seismological laboratory of Patras University recently established a microearthquake network and in addition to the seismic activity it also monitors continuously a range of physical parameters, well-known as earthquake precursors (TSELENTIS and BELTAS, 1992), such as the earth's electric field, electromagnetic anomalies, groundwater chemistry, acoustic emission, etc. This research attempts to derive temporal variations of P body wave attenuation and stress drop in the epicentral region of two medium size earthquakes ($M_s = 5$ and $M_s = 4.8$) which occurred in the region.

There have been numerous studies which have revealed changes in the attenuation of body waves (FREMONT and POUPINET, 1987; CRAMPIN *et al.*, 1985;

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SUEHIRO, 1968; ISHIDA and KANAMORI, 1980; JIN and AKI, 1986; GUSEV and LEMZIKOV, 1985) or in static stress drop (XIE *et al.*, 1991; BOORE and ATKINSON, 1989; MORI and FRANKEL, 1990), associated with an impending earthquake.

FREMONT and POUPINET (1987) have pointed out that earthquake doublets, i.e., pairs of earthquakes with very similar waveforms originating from the same location and expressing stress release on the same part of the faults (GELLER and MUELLER, 1980), are a precise tool to search for possible variations of crustal attenuation. However, there is always the problem of separating the source characteristics from the path and site effects, especially when the earthquake corner frequency is near or higher than the dominant frequencies generated by the propagation and site responses (FRANKEL and WENNERBERG, 1989; MORI and FRANKEL, 1990).

One method for removing the path and site effects in order to derive source parameters more sufficiently is to choose a smaller event such as an empirical Green function and deconvolve its seismogram from the seismogram of the original event (HARTZEL, 1978; MUELLER, 1985; FRANKEL *et al.*, 1986). We have used this deconvolution method to assess source parameters for one "preshock" ($M_s = 3.9$) and one aftershock ($M_s = 3.9$) of a moderate W. Greece event which can be considered to form an earthquake doublet. For the first doublet, the source parameters of the two larger events were evaluated by using a smaller ($M_s = 1.6$) event originating from the same hypocenter as a Green function. We think that the obtained results are reliable enough to confirm a temporal variation in the attenuation of body seismic waves in the crust of the region.

2. Data

Data used in this study were recorded by Patras University short-period digital seismic network (Figure 1). The inner part of the network consists of six stations, all of them with vertical component (1 Hz) seismometers operating at 90 dB dynamic range and in a low noise environment. The signals are radio-telemetered via FM subcarriers to the central recording site at Patras seismological centre in real time. There, each channel signal is filtered for aliasing with a 30 Hz Butterworth low-pass filter, sampled at 100 sps and converted to digital form with a resolution of 16 bits.

During late May to early June 1992, an earthquake activity commenced close to the city of Patras along a well-known active fault with the mainshock measuring $M_s = 5.0R$ (Figure 1). More than 80 events have been recorded by the network and after an extensive investigation into the centre's data base we found two events which can be considered as an earthquake doublet. To investigate such a doublet, an algorithm was developed which scans all the existing data to reveal events with

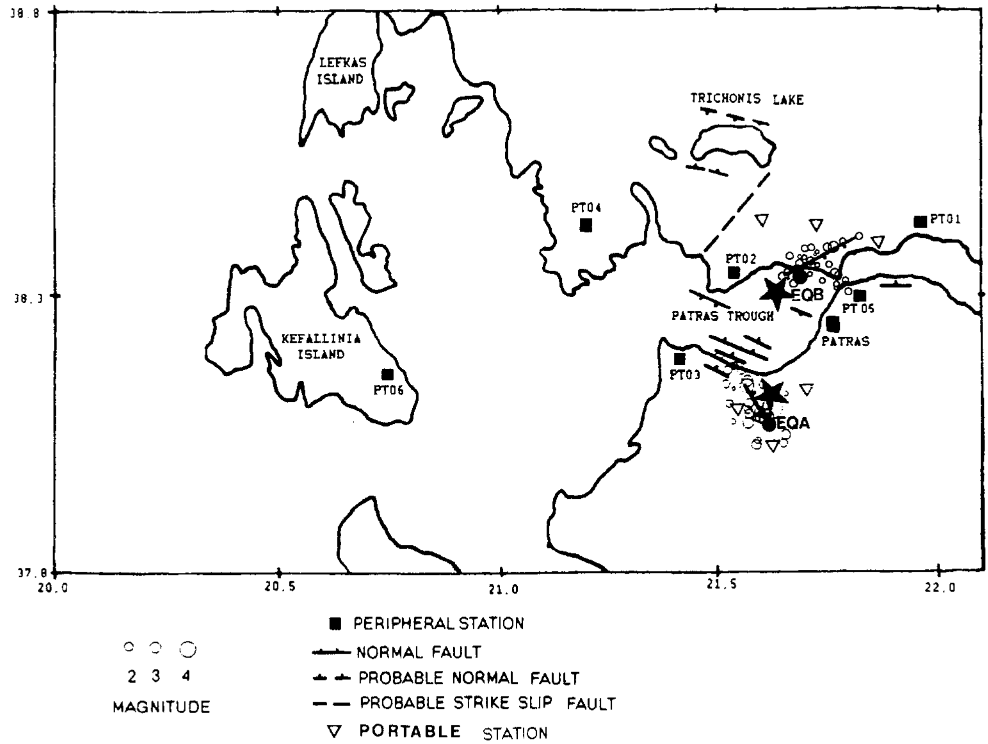

Figure 1
Seismographic stations of Patras Seismological Network used in this study. The star indicates the main shocks. The open circles indicate the aftershock activity. The filled circle indicates the location of the doublet.

strong similarities in their waveforms. The common hypocenter of the events is near the southern tip of the aftershock zone at a depth of 8.7 km. Specifically on 23-12-1991 an event (EQA1), measuring $M = 3.9$ was retrieved from the data base and on 30-5-1992 (five days after the main shock) an earthquake (EQA2) of magnitude $M = 3.9$ occurred at the same location, followed by a smaller event (EQA3) on 7-6-1992 of magnitude 1.6. The similarity of the wave forms (Figure 2) of the above events and their same epicentres indicate that EQA1 and EQA2 can be considered as an earthquake doublet.

The second doublet comprised two earthquakes of magnitude $M_s = 2.7$. The first occurred on 17-6-1992 and the second on 28-11-1992, 17 days after the main event of magnitude $M_s = 4.8$ on 11-11-1992. The common hypocenter of these events is located on a well-known fault towards the NE coast of the Gulf of Patras (Figure 1), at a depth of 7.3 km.

Figure 3 depicts the corresponding wave forms obtained at four stations and their similarity is obvious.

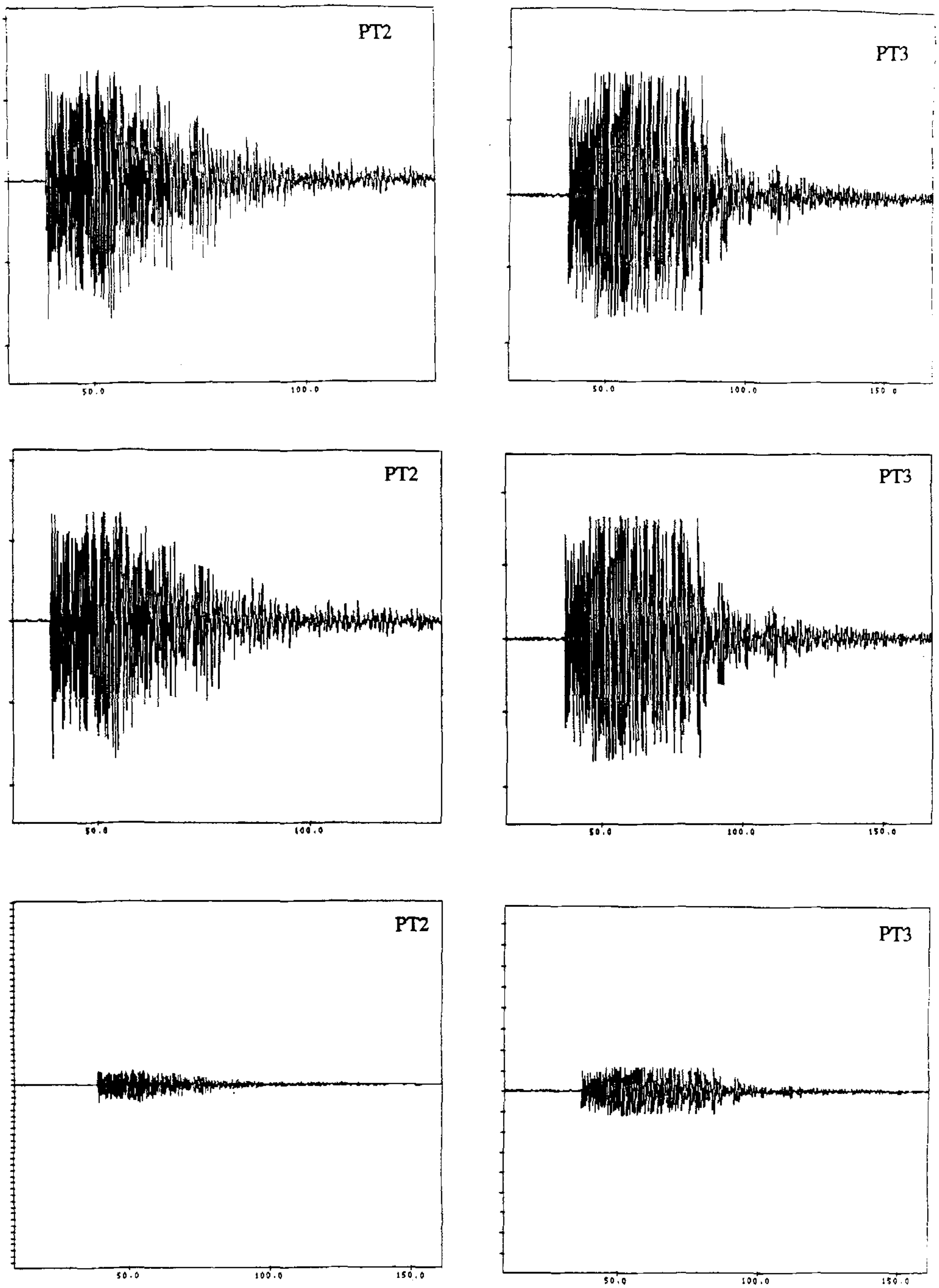

Figure 2(a)

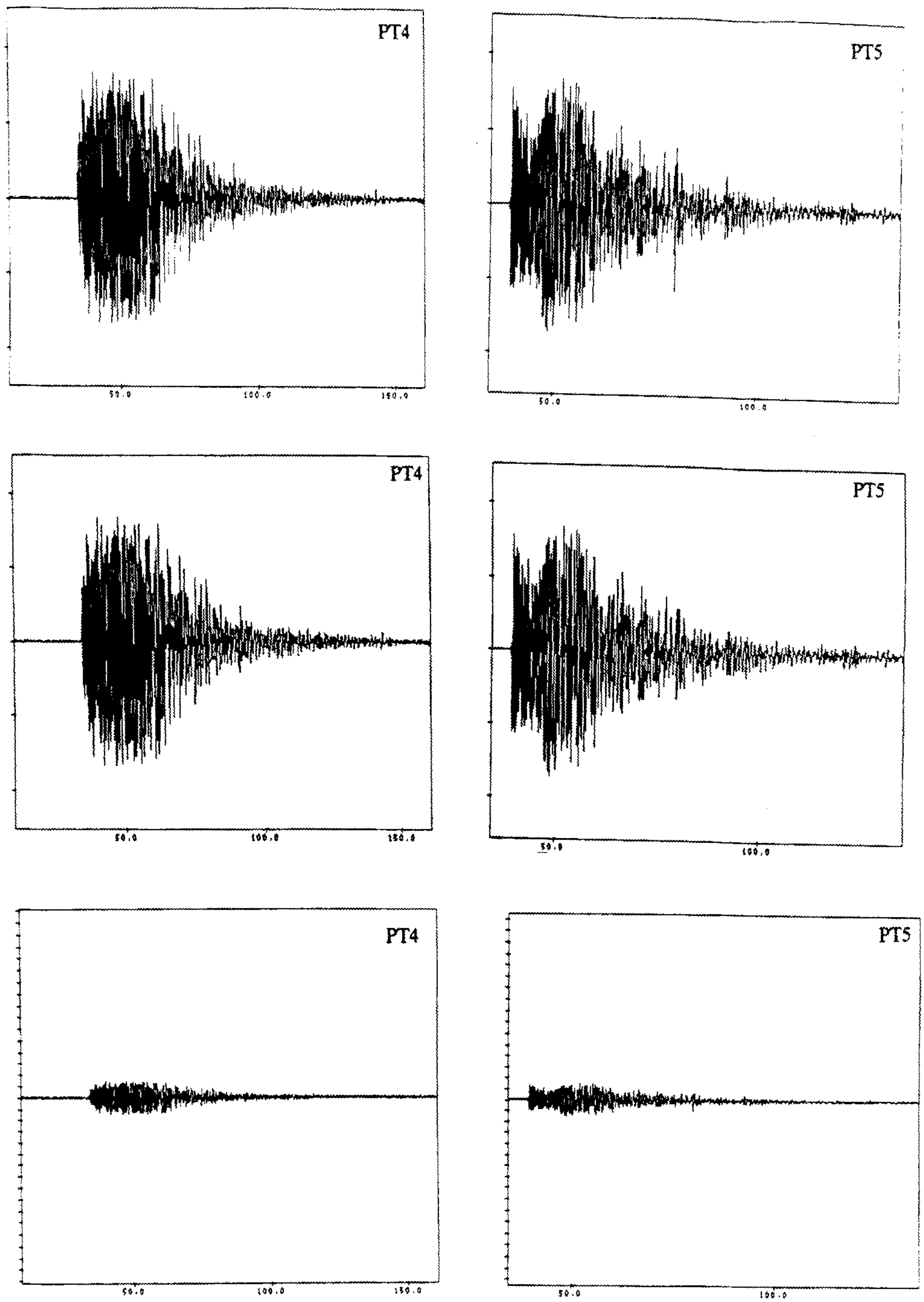

Figure 2(b)

Figure 2
Seismograms of the first doublet and the smaller event used as a Green function at the four stations PT2, PT3, PT4, PT5 (arrival times are not absolute).

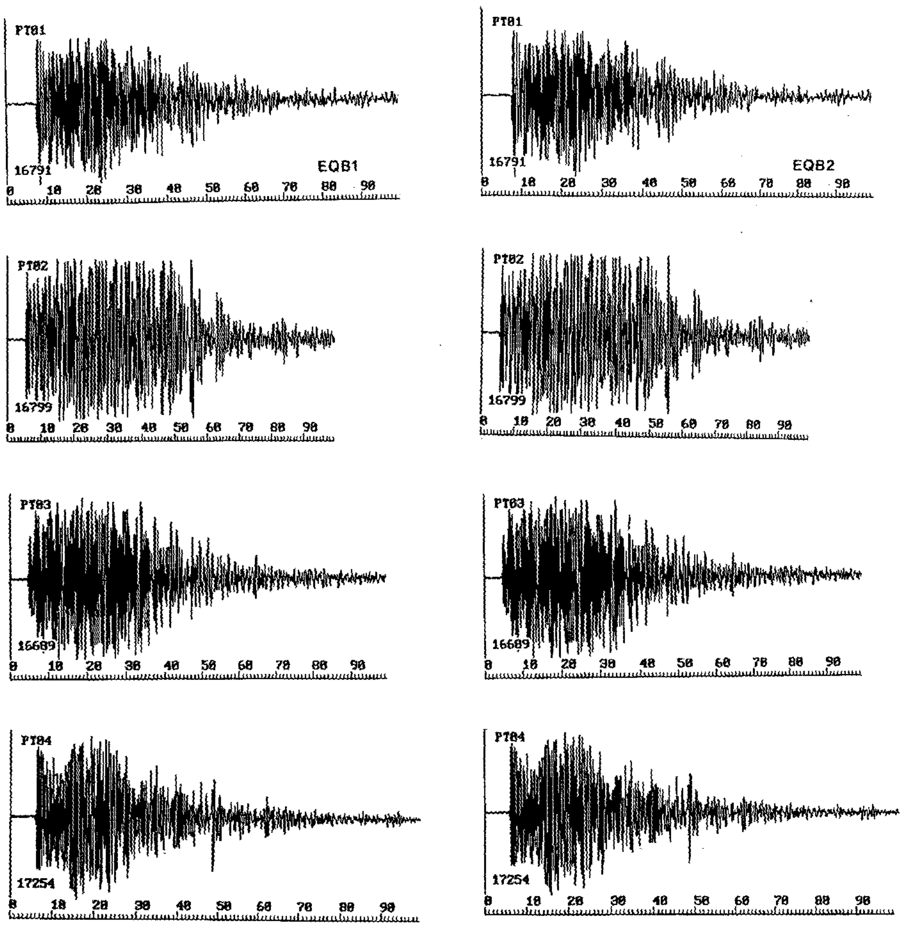

Figure 3
Seismograms of the second doublet at the four stations PT2, PT3, PT4, PT5.

3. *Temporal Variation of Attenuation*

In order to derive the temporal variation of seismic attenuation in the epicentral region and reveal any variation in Q prior and after the main shock, we follow the method proposed by FREMONT and POUPINET (1987), by computing the ratio of the amplitude spectra of the two earthquake doublets EQA1, EQA2 and EQB1, EQB2 recorded at the same station. Usually this procedure eliminates the instrumental response and the geometrical spreading correction. The decimal logarithm of the amplitude ratio between the two events at a specific station is given by

$$\log \frac{A_1(f_1, \theta_1, \phi_1)}{A_2(f_2, \theta_2, \phi_2)} = \log \frac{S_1(f_1, \theta_x, \phi_1)}{S_2(f_2, \theta_2, \phi_2)} - \frac{\pi f}{\ln 10}\left(\frac{t_1}{Q_1} - \frac{t_2}{Q_2}\right) \tag{1}$$

where $A(f, \theta, \phi)$ is the recorded spectrum, $S(f, \theta, \phi)$ is the source spectrum, f is the frequency, θ is the azimuth, ϕ is the take-off angle, t is the propogation time and Q is the average quality factor of the medium between source and receiver considered as independent of frequency. In the case of a frequency-dependent Q model, the amplitudes of the computed Q variations may be modified.

The earthquake doublets EQA1, EQA1 and EQB1, EQB2 were relocated following the method proposed by POUPINET *et al.* (1982), according to which the differences (δ) in P-arrival times were measured using cross-spectral analysis by fitting a line starting at the origin to the phase (φ), expressed in radians, of the cross spectrum described by the relation where f is the frequency

$$\varphi(f) = 2\pi\delta f. \tag{2}$$

This method permits timing precision better than the digitization rate and location accuracy of a few meters and confirmed that the two earthquakes originated from the same fault patch.

Assuming $t_2 = t_1 + \Delta t_1, Q_2 = Q_1 + \Delta Q_1$ where $\Delta t, \Delta Q$ represent variations in propagation times and attenuation during the considered time interval between the two earthquakes in each doublet, equation (1) becomes

$$\log \frac{A_1(f_1, \theta_1, \phi_1)}{A_2(f_2, \theta_2, \phi_2)} = \log \frac{S_1(f_1, \theta_1, \phi_1)}{S_2(f_2, \theta_2, \phi_2)} - \frac{\pi f}{\ln 10}\left(\frac{t_1\,\Delta Q_1 - \Delta t_1 Q_1}{Q_1(Q_1 + \Delta Q_1)}\right). \tag{3}$$

The first term on the right-hand side of equation (3) is related to the source functions while the second term describes the propagation path effects.

If the two events EQA1, EQA2 and EQB1, EQB2 in each doublet can be considered identical then logarithms of source spectral ratios should be constant at all frequencies and equal to 0. Assuming identical events eq. (3) can be written

$$\log \frac{A_1}{A_2} = -\frac{\pi f}{\ln 10}\left(\frac{t_1\,\Delta Q_1 - \Delta t_1 Q_1}{Q_1(Q_1 + \Delta Q_1)}\right) = -\frac{\pi f}{\ln 10}\frac{t_1\,\Delta Q_1}{Q_1^2}. \tag{4}$$

For all recording stations (PT2, PT3, PT4, PT5) amplitude spectra are computed from short windows of signal (1.28 s for P waves). The P window starts 0.4 s before the P arrival.

Examples of (smoothed) spectra ratios for P waves for the two doublets are presented in Figures 4a,b respectively for all the recording stations. Judging from this figure we can see that there is a slope versus frequency in all the stations.

Since the corner frequencies estimated from the amplitude displacement spectra are between 15–20 Hz we fit the spectra ratios to this frequency with a minimum and a maximum slope and values of $t_1\,\Delta Q_1/Q_1^2$ are determined. Then, the quantities $\Delta Q_1/Q_1^2$ are evaluated by dividing by the propagation times t_1 known from the location of the doublet, and the results are presented in Table 1.

It is evident that all four stations depict a clear variation (decrease) of attenuation for the two doublets with a clear trend for an increase of the P-wave quality factor. In order to evaluate relative variations of the quality factor, the estimation of Q values is necessary. The choice of the exact Q value is not crucial but helps to quantify variations in terms of percentage. Recent studies in the region (TSELENTIS, 1992) lead to a value of Q of the order of 100. Considering this value we derive that the attenuation of P waves has decreased by about 20% (average of 4 stations) associated with event A and by about 15% for event B in the vicinity of the two faults. Naturally, the stress release that took place during the main shock should induce an increase in attenuation (decrease in the quality factor) around the focal region. Nevertheless, we observe a clear decrease of about 20% in P-wave attenuation which if it is related to the closing of cracks is not consistent with a stress release.

The observed decrease in P-wave attenuation before and after the main shock may be related to changes in the state of saturation of rocks in the epicentral region. Laboratory results (NUR and SIMMONS, 1969; JOHNSTON and TÖKSÖZ, 1980; WINLER and NUR, 1981), show that total saturation rapidly decreases

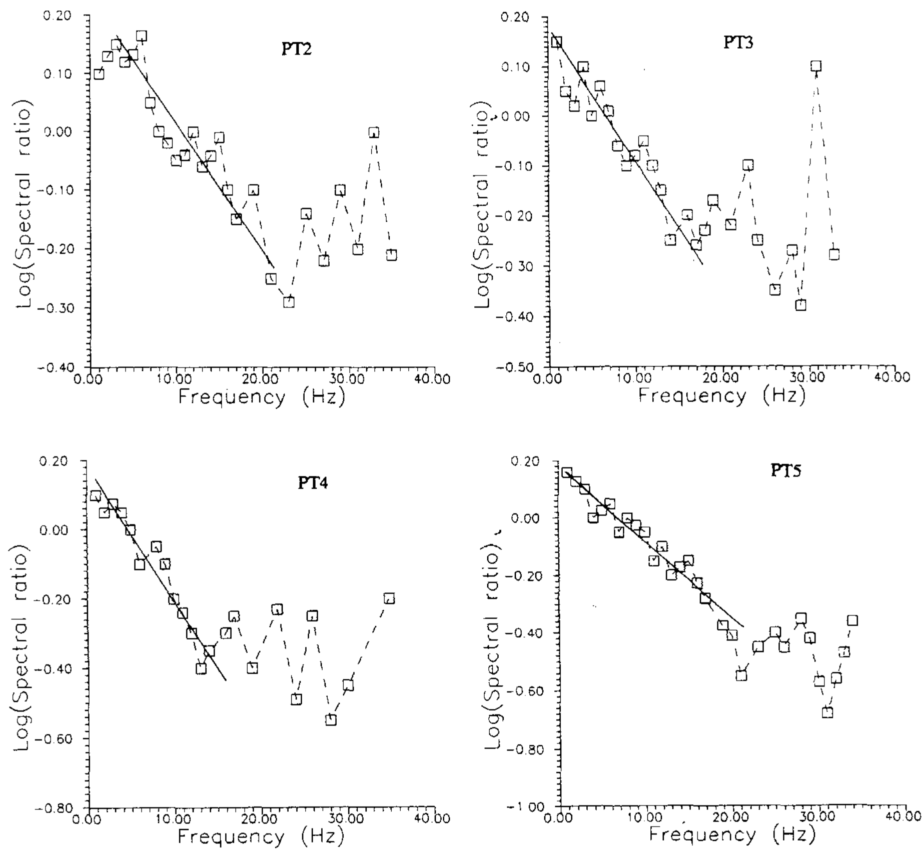

Figure 4(a)

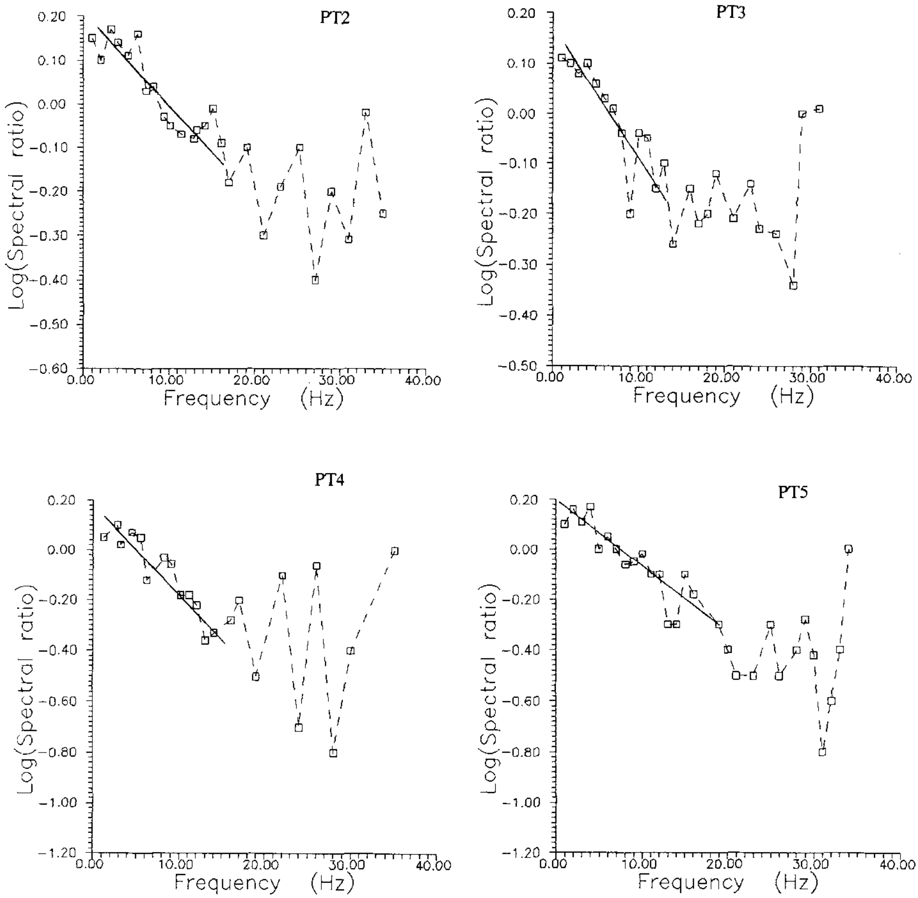

Figure 4(b)

Figure 4

Spectral ratios versus frequency for the events of (a) the first doublet, (b) the second doublet. We evaluated the spectral ratio of EQA1 event over EQA2 event. The line represents the least squares linear fit.

Table 1

Values of $\Delta Q/Q^2$ for the four stations

Station	$\Delta Q/Q^2 \times 10^{-3}$ EQA	EQB
PT2	3.9	1.63
PT3	1.8	1.58
PT4	1.95	1.52
PT5	1.58	1.41

attenuation. As rocks in the upper crust are partially or totally saturated, phenomena related to fluids are important to attenuation.

It is also interesting to note that these changes in the saturation of rocks may be reflected in the recorded bay-like long-period variation of the earth's electric field which was continuously monitored by a pair of dipoles close to the focal region of the earthquake (TSELENTIS and IFANTIS, 1992).

4. Static Stress Drops

As explained previously, the observed slopes of spectral ratios could also correspond to a variation in the source parameters. To investigate this possibility and reveal any changes in the static stress drop in the epicentral region prior and after the main shock we used EQ3 as a δ-like impulse (empirical Green function). Denoting the far-field displacement from the larger events by $u_n G(x, t)$ we can write (XIE *et al.*, 1991)

$$u_n(x, t) = \frac{\mu}{M_0^G} u_n^G(x, t) * s(t) \tag{5}$$

where μ is the shear modulus on the fault, M_0^G is the seismic moment of the Green function event and $s(t)$ is the source pulse given by

$$s(t) = \int\int D\left(x', t + t_0 + \frac{\Delta x' \gamma}{c}\right) d\Sigma(x') \tag{6}$$

where $\Delta x = x' - x_0$.

In the above formulae x, x' are vectors specifying the location of the observation point and the source point respectively, x_0' is a reference point on the fault plane $\Sigma(x')$, γ is the unit vector pointing in the direction of $(x - x_0')$, c is the wave velocity and t_0 is the origin time of the small event.

The source pulses $s(t)$ of events EQA1, EQA2 were deconvolved by taking a Fourier transform of 2.0 s of the P wave for each event and dividing the transform of the larger event by the transform of the smaller event. Any instabilities during the deconvolution process caused by "spectral holes" of the smaller event were eliminated by a "water level" correction (e.g., MORI and FRANKEL, 1990) according to which the "holes" were filled up to a value of 0.5% of the maximum value.

This process reduced the high-frequency limit to about 15 Hz. The low-frequency level of the smaller event was normalized to unity, so that the moment of the larger event remained unchanged after the deconvolution. Transforming back to the time domain we obtained the deconvolved pulses presented in Figure 5. These simple unipolar pulses are interpreted as far-field source-time functions of displacements which have been corrected for path, site and instrument response effects.

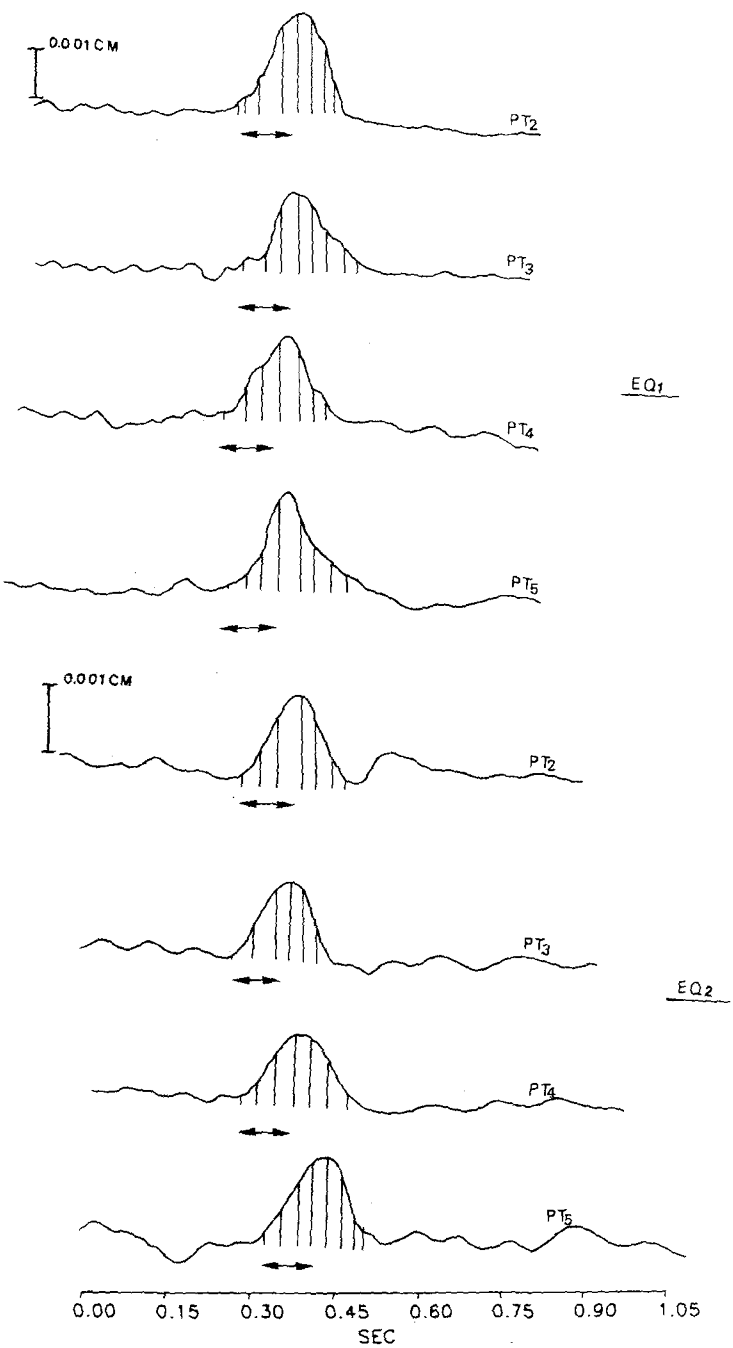

Figure 5
Deconvolved displacement wave forms for EQ1 and EQ2 of the first doublet, at stations PT2, PT3, PT4 and PT5. Shaded region shows the area used for the estimation of the moment. Rise times are indicated by the bars.

Table 2

Source parameters of the events of the doublet

Event	M_0 10^{21} dyne-cm	$\Delta\sigma$ bars	r km
EQ1	4.73	16.2	0.5
EQ2	4.71	16.0	0.5

The moment (M_0) for each earthquake was calculated following the expression from BOATWRIGHT (1980)

$$M_0 = 4\pi[\rho(x_0)\rho(x)c(x)]^{1/2}c(x_0)^{5/2}Ru/F \tag{7}$$

where u indicates the shaded area in the wave forms of Figure 4, $\rho(x_0) = 2.80$ and $\rho(x) = 2.30$ g/cm^3 are the densities at the source and receiver, respectively, $c(x_0) = 6.5$ and $c(x) = 3.40$ km/s are the corresponding velocities, R is the epicentral distance, F is the radiation pattern, including a free surface correction at the receiveer.

Next, the rise times ($T_{1/2}$) of the pulse (depicted by the horizontal bars under the wave forms) were used to calculate fault radius (assuming a circular fault) following the relationship of BOATWRIGHT (1980)

$$r = \frac{\tau_{1/2} V_r}{1 - (V_r \sin\theta/c)} \tag{8}$$

and the static stress drop from the formula of BRUNE (1970)

$$\Delta\sigma = 7M_0/(16r^3) \tag{9}$$

where in the above equations, V_r is the rupture velocity (assumed 90% of the local shear wave velocity), and θ is the take-off angle (assumed on average 45°).

Using the above values as well as equations (7), (8) and (9) and assuming that the source pulse of event EQA3 is δ-like we calculated M_0, r and $\Delta\sigma$ for events EQA1, EQA2. The results are summarized in Table 2 and indicate no considerable change in the source parameters between the two events which could be related with the obtained frequency dependence of the amplitude spectra ratios prior and after the main event.

Conclusions

Spectral ratios of the earthquakes of the doublets at 4 stations indicated a temporal variation (decrease) of P-wave attenuation in the focal region of the order of 15–20%. To verify that this is not an artifact due to different source parameters a smaller event with the same hypocenter as that of the first doublet was used as a Green function to separate source time functions from the propagation effects. The obtained source parameters indicated that the sources can be considered identical for the two events. The outcome of this research verifies the possible role of the migration of fluids in the crust in the focal region and supports AKI's (1985) case about the importance of attenuation measurements in earthquake prediction.

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