LAST CENTURY WORLDWIDE SEISMICITY ANALYSIS: A NEW VIEW OF EARTHQUAKE PREDICTION BASED ON THE BRITTLE-DUCTILE INTERACTION HYPOTHESIS

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ABSTRACT:

World-wide, regional, and local earthquake catalogues are used to analyze seismic time variation at global, regional and local scale. The quality of the catalogues is discussed and the magnitude of completeness is estimated. Taking into account the availability of regional data, their time and magnitude completeness threshold and their rate of seismic activity, three countries/regions are chosen for regional analysis: Spain, Colombia and Taiwan. Finally, a seismic station in Colombia is selected for a detailed local analysis. In fact, the final target of this work is to test the lithosphere brittle-ductile interaction hypothesis as a mid-term predictor. The time evolution of seismic activity represents the brittle zone behavior while the one of the ductile zone is characterized by the time evolution of the coda-Q quality factor. Correlation analysis between seismicity and attenuation would lead to a mid-term prediction. Thus, at local scale, for the selected station, both seismicity and attenuation functions are analyzed. Cross correlation of the time series of the seismic rates with those of the attenuation, is calculated. Significant variations, in both the seismic activity and the Q quality factor, are detected, and seismic patterns, such as cycles are distinguished at all scales. The effects of the complex and deep activity in the Colombian region in the correlation analysis are discussed and compared with results of analogous studies in other dissimilar tectonic areas.

KEYWORDS: Worldwide seismicity, seismicity evolution, coda-Q, seismic attenuation. Brittle-ductile interaction hypothesis.

1. INTRODUCTION

Seismic prediction has been many times considered an unattainable challenge of seismology, a utopia. We can even find authors that defend the unpredictable nature of earthquakes. Nowadays, seismic prediction is considered a social obligation of seismology and this topic has recovered importance as a future challenge (Keilis-Borok & Soloviev, 2003).

However, seismicity analyses are essential to tackle this kind of studies, assuming that future activity won't be very different of that of the past. So, we study the space time distribution of the world seismicity along the whole twentieth century, in order to look for patterns such as, for instance, activity migration and cycles. To reach these targets, high quality data are needed. The election of data sets is made in base of their quality and availability. We evaluate this quality through two parameters, the time completeness threshold and the magnitude completeness threshold. Several methods are described and used for this determination. This completeness study is mandatory in each zone in order to avoid misusing available data.

At local scale, let say for a relatively small region near a single seismic station, the brittle-ductile interaction hypothesis states that seismicity is a good indicator of the brittle behaviour of the lithosphere-asthenosphere system while Q-quality factor is a good monitor of its ductile behaviour. In previous studies in Japan and California, the time series of the attenuation and of the seismicity correlated quite well for calm periods, while a strong un-correlation was found for about one or two years before a large event. Thus, correlation means that brittle and ductile areas are well coupled, un-correlation means uncoupling of the ductile and brittle zones. This uncoupling would lead to a great earthquake. We test for this hypothesis in a seismic station in Colombia. We compare our results with those obtained in previous studies. We also discuss the effects of complex and deep seismic activity.

2. CATALOGUES AND CATALOGUES QUALITY

For the analysis of the seismicity at global scale and for Taiwan area we use the ANSS (*Advanced National Seismic System*) catalogue because of its completeness. For Spain and Colombia we respectively use the catalogues provided by the *Instituto Geogáfico Nacional* (IGN) and by the *Red Sísmica Nacional de Colombia* (RSNC).

2.1 Completeness

The first step to determine the reliability of an earthquake catalogue is to establish a time threshold from which the quality can be considered high enough. Changes in density, geometry and sensitivity of the seismic networks are some of the facts causing time heterogeneities. These heterogeneities can also be induced by changes in the parameterization procedures which can result in serious alterations in the compilations and in significant variations in earthquake magnitudes, leading to under- or over-estimate them in some sites and periods because of the use of different formulations (Perez, 1999). Calculating the so called magnitude of completeness is one of the ways of controlling the quality of earthquake catalogues. This is, the minimum magnitude from which a catalogue includes 100% of the events in the space-time window we are working on (Rydeleck & Sacks, 1989; Wiemer & Wyss, 2000). It is not a strict mathematical definition and most of the times it appears related to the hypothesis of power-law behaviour of the seismic activity (Woessner & Wiemer, 2005).

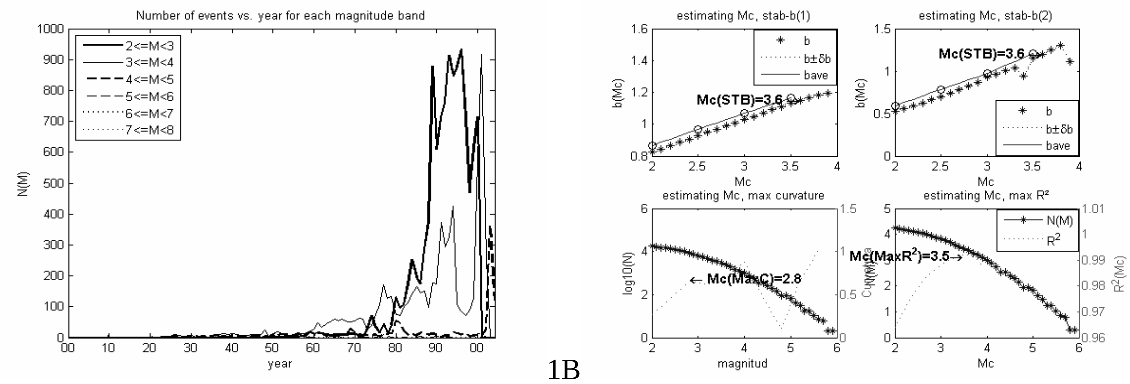
Depending on the kind of study and the characteristics it requires from the data, it will be convenient to increase one of the thresholds in benefit of the other. Whichever the case, a compromise must be achieved when choosing these parameters so that the deficiencies generated by the selection do not affect significantly to the conclusions.

2.2 Estimating M_C

Several methods to estimate the magnitude of completeness are based on the assumption that the frequency-magnitude distribution is well fitted by a simple-power law, what relies in the hypothesis that the earthquake rate is a self-similar, scale-invariant process, satisfying the Gutenberg-Richter equation. Based on these assumptions, Wiemer & Wyss (2000) proposed two different methods to estimate M_C. A quick way to estimate the completeness is calculating the point of maximum curvature of the frequency-magnitude relationship from the maximum of its first derivative. In practice, this point matches with the maximum of the non-cumulative frequency-magnitude distribution. Despite the simplicity and the relative robustness of the approximation, M_C is usually underestimated (Woessner & Wiemer, 2005) because the curvature of the distribution is gradual due to spatial heterogeneities.

Other quick and effective way to obtain M_C is computing the correlation coefficient of the data and the frequency-magnitude distribution considering each minimum magnitude. R^2 is calculated for a confidence level of fit of the 95% and M_C is set as the magnitude for which it is maximum. Cao & Gao (2002) used the b-stability method, based in the assumption that b-value increases with M_{min} when $M_{min} < M_C$, keeps constant when $M_{min} \geq M_C$, and increases again when $M_{min} >> M_C$. M_C is then arbitrarily defined as the point where the change in b value, $\Delta b(M_{mn})$, for consecutive values of M_{min} is lower than 0.03. Woessner & Wiemer (2005) found that this criterion is unstable because the event rate in a magnitude range is highly variable, so to stabilize numerically the method these authors introduced as a criterion the Shi and Bolt's (1982) uncertainty for b value: $\delta b = 2.3b^2\sqrt{\sum_{i=1}^{N}(M_i - \langle M \rangle)/N(N-1)}$. Where $\langle M \rangle$ is the mean magnitude and N the total number of events. M_C is defined as the minimum magnitude for which $\Delta b = \left| b_{average} - b \right| \leq \delta b$, $b_{average}$ is the arithmetic mean of consecutive b-values in successive cut-off magnitudes in half a magnitude range. Large magnitude ranges are preferable (Woessner & Wiemer, 2005) that's why dM is stated in 0.5. But when the size of the space-time window increases, and therefore the number of events grows, the criterion introduced to stabilize the method is of no use. δb will reduce when N grows, what implies a physically meaningless increase of the magnitude of completeness.

The method to estimate the parameters of the frequency-magnitude distribution is other source of controversy. Least-squares regression analysis is a common option, but when regression analysis is applied to cumulative data, independent observations hypothesis is broken. Besides, they are not Gaussian, what is an underlying assumption for the least squares regression. Moreover, the possibility of no observations is ignored, either over a certain magnitude threshold or in a given interval. Mcguire (2004) proposes an alternative to this approximation using the maximum likelihood method. Both approaches have been considered for b estimation in this case study and, subsequently, to obtain M_C. Usually, least squares regression overestimates the magnitude of completeness, not though in the example shown below, where the result is the same for both determinations (Fig 1Ba and 1Bb).



1A) 1B

Figure 1: Example of the completeness thresholds determination for the Iberian Peninsula. 1A) Time evolution of the number of earthquakes for a first preview of thee data set. 1B) Determination of the magnitude of completeness using the different methods detailed before

More than the first half of the century is affected by an important lack of completeness, both for the global study and for regional and local ones. Technology wasn't advanced enough to have seismic networks deployed at the level they are actually, besides the fact that plate tectonics theory was not fully accepted until the 60's. The amount of data starts growing around 1963 and it's in 1973 when data from foreign associations are included, before this date, data are almost exclusively correspond to the United States seismic events. Different pairs (M_C, t_C) are compared for several regions and the most suitable results are shown in Table 2.1.

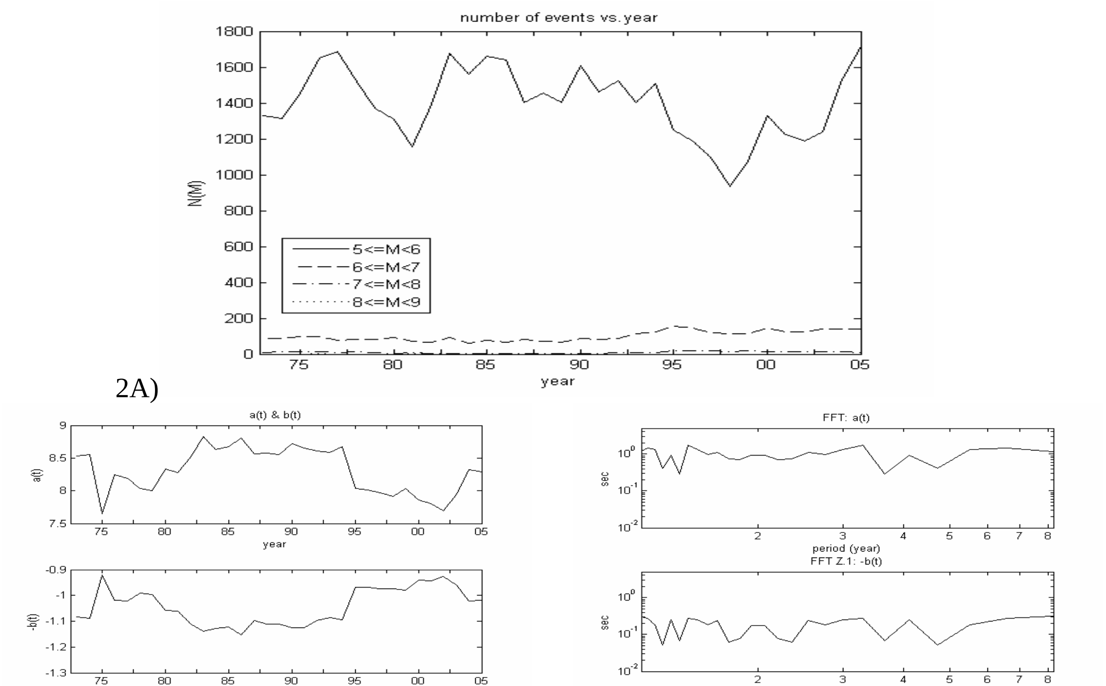
Table 2.1: Time and magnitude completeness thresholds for each region.

Region (CATALOGUE)	t_C	M_C
Whole World (ANSS)	1973	5
North Hemisphere (ANSS)	1973	4.3
South Hemisphere (ANSS)	1973	5
Atlantic Ridge (ANSS)	1973	5
Iberian Peninsula (IGN)	1980	3.5
Colombia (RSNC)	1993	3
Taiwan (ANSS)	1973	4.5

The completeness magnitude for wide areas is, as expected, the same as the one corresponding to the most incomplete sub-area. In the case of Colombia, the time window has been considerably reduced in benefit of the magnitude one. This is because the RSNC starts working in 1993, making the amount of data grow considerably from this time on, and we consider that the reduction of the time window is worth, because a small increase on the time window would increase the completeness magnitude drastically. Moreover, the correlation study that will be carried out later needs a complete seismicity study during the time period considered, this is 1993-2007, for which the wave-forms have been obtained from *Ingeominas*. In the case of Taiwan this growth in the number on data happens too late (1999), and the time window would not be large enough for the seismicity analysis.

3. LAST CENTURY'S WORLDWIDE SEISMICITY ANALYSIS

Once the catalogues quality has been analyzed, the seismicity time evolution is studied. First results are shown in Fig. 2. Evolution of the seismicity is analyzed through the variation of the number of earthquakes and of the parameters of Gutenberg-Richter power law. In all the cases, including large and small regions, is notable the good correlation between *a* and *b*. Furthermore, more or less pronounced maximums can be observed in their Fourier transforms around 3 and 4 years periods, when the time window is long enough, in all cases.



2A)

2B)

2C)

Figure 2: Worldwide seismicity analysis. 2A) Time evolution of the number of earthquakes vs. year for the complete ANSS catalogue. 2B) Evolution of the Gutenberg-Richter parameters a and b. 2C) Corresponding amplitude Fourier spectra.

The values found for the parameters of the Gutenberg-Richter equation are shown in Table 3.1.

Table 3.1: Gutenberg-Richter *a* and *b* parameters at global and regional scales.

Region	**Period**	**Mc**	**a**	**b**	**R**
Whole World	1973-2007	5	10.66 ± 0.36	1.190 ± 0.054	0.9929
Iberian Peninsula	1980-2007	3.5	7.51 ± 0.19	1.140 ± 0.038	0.9965
Colombia	1993-2007	3	7.15 ± 0.15	0.993 ± 0.029	0.9961
Taiwan	1973-2007	4.5	7.51 ± 0.23	0.976 ± 0.038	0.9945

4. CREEP MODEL

In 1979 Chouet observed the existence of a relationship between the attenuation of coda waves and volcanism. He associated an increase of the high frequency energy release to earthquakes with a similar magnitude and location, and a change in the shape of the spectra associated to a decrease in *Qc* values. Later on, Jin & Aki (1989, 1993) analyzed in detail the correlation between the time evolution of Q_C^{-1} and the one of the seismicity, finding a good, positive, simultaneous correlation for certain magnitude bands. They finally proposed that the time variation of the attenuation could be related to creeping fractures in the ductile part of the lithosphere. An increase in the fracture creeping would develop into an increase of the attenuation, promoting the occurrence of earthquakes of a given magnitude, so called characteristic magnitude, M_{ch}, which would correspond to the characteristic size of the fracture in the region. But this just explains the good correlation between the two series, what has no utility as a precursor. The model, reviewed by Aki (2004), says that the period with good correlation between the time series, would correspond to a certain stage of the regional seismic cycle, being positive and simultaneous during the period of normal loading of tectonic stresses, breaking a few years before a big earthquake takes place in the area. When the accumulated stresses in the brittle part reach the breaking point, preparing the zone for a mayor event, a change in the mechanical properties of the whole system is expected. This change in the loading process can break the correlation that Q_C^{-1} and $N(M_{CH})$ presented.

This may not appear for human-made tremors (it can be broken artificially). Induced seismicity can change the loading process perturbing the parameter evolution. Furthermore, there are cases in which the attenuation doesn't show significant changes, like in a poorly developed brittle-ductile region, or in areas, where the coda Q shows no variation at all during the normal stage of the loading process, being a local permanent characteristic, in these cases we will be required to find another indicator of the loading process of the ductile part of the lithosphere. Moreover, in regions with a low level of shallow seismicity, coda Q is determined by using long hypocenter-station paths, thus sampling great volume regions. In these cases the obtained results may not be well represented by our simplified models which assume hipocentral distances minor to 100 km, so, the time evolution and further correlation may be bad determined.

4.2. Region and Data

Colombia exhibits a very complex seismic activity. This country is located in the convergence of four tectonic plates: The North Andes block (part of the South American plate), the Panama block, the Caribbean plate and the Nazca plate (see Figure 3).

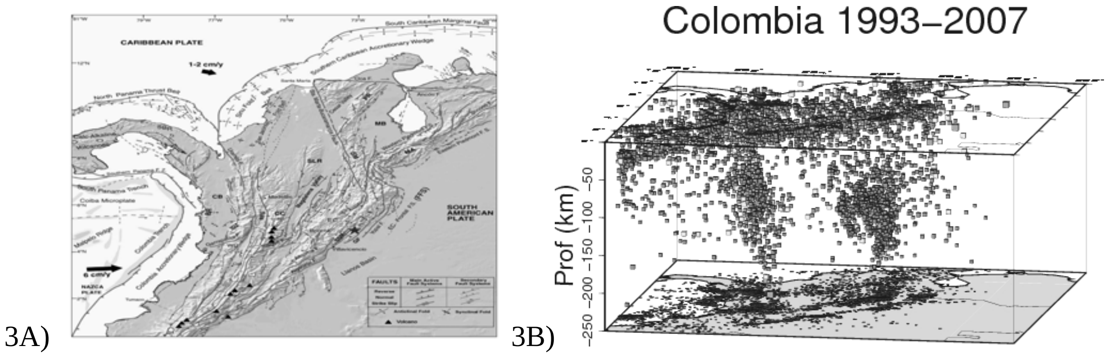


Figure 3. 3A): Neo-tectonic map of Colombia with the main fault systems (Pulido, 2003). CB, Panama-Choco block; WC, Western Cordillera; CC, Central Cordillera; EC, Eastern Cordillera; RFS, Romeral Fault System. Solid arrows indicate plate velocity relative to South-America. 3B) Earthquake distribution ($M_L\geq3$) in the Colombian territory during the period 1993-2007. Code: $3\leq M_L<4.5$ 'smaller dark cubes'; $4.5\leq M_L<6$ 'medium white cubes'; $M_L\geq6$ 'big grey cubes'.

In addition, the Colombian territory includes two important subduction zones and its seismic activity is between the most multifaceted in the world. The Bucaramanga Nest is one of these subduction zones. It has an unusually dense seismic activity at intermediate and large depths. It is located in the north-east of Colombia, centred at 6.8ºN, 73.1ºW and at about 155 km depth. (Zafiri & Havskov, 2003). The case of the Bucaramanga Nest differs from others because of the concentration of a higher rate of activity in a smaller volume in relation with others (Schneider et al., 1987; Zafiri & Havskov, 2003). The nature of this nest is yet unresolved because of the lack of completeness of the data sets and the complexity of the tectonic processes that take place.

4.1. Attenuation Analysis

The seismograms for the attenuation analysis have been obtained from the Colombian National Seismic Network. The period of the study is not as long as we would like, but the Colombian network didn't start working, with enough seismic stations until 1993, when 13 of the current 21 seismic stations where implemented. Barichara is one of these stations (Figure 4). The quality of these data has also been analyzed and the useful wave forms have been carefully selected. Signals can be rejected for different reasons like a high noise level, overlapping of signals, too short signal and others.

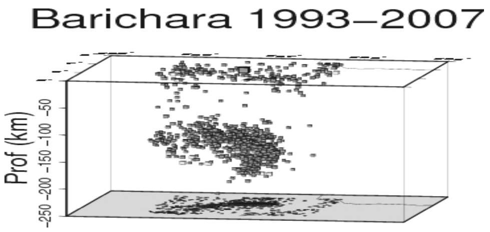


Figure 4: Location of the foci of the waveforms from the RSNC used to analyze the attenuation and its time evolution. Code: 3≤M<4.5 'smaller dark cubes'; 4.5≤M<6 'medium white cubes'; M≥6 'big grey cubes'.

According to the single back-scattering model (Aki & Chouet, 1975), the coda amplitude for a seismogram of a local earthquake in a lapse time t and with a frequency f can be expressed as $A(f,t)=A_0 t^{-\alpha}\exp(-\pi f Q_C^{-1} t)$, where A_0 represents the source term, $t^{-\alpha}$ is the geometrical spreading (for body waves $\alpha=1$). Q_C^{-1} is the inverse of the coda Q and f is the frequency of the seismic waves.

The baseline correction is applied to all the digital seismograms and low frequency noises are eliminated. The Coda amplitudes are the calculated using a 5 seconds sliding time window, with an overlap of 2.5 second from $2t_S$ to 80s or the Signal-to-Noise ratio equals 2, whatever it comes first. Band-pass filters are used to get a signal for each frequency band, for which Q_C^{-1} is calculated. Q_C^{-1} shows a frequency dependence of the form $Q_C^{-1}(f)=Q_0^{-1}\left(f/f_0\right)^{-\eta}$ -The coefficients Q_0^{-1} and η are obtained taking $f_0=1Hz$ as the reference frequency.

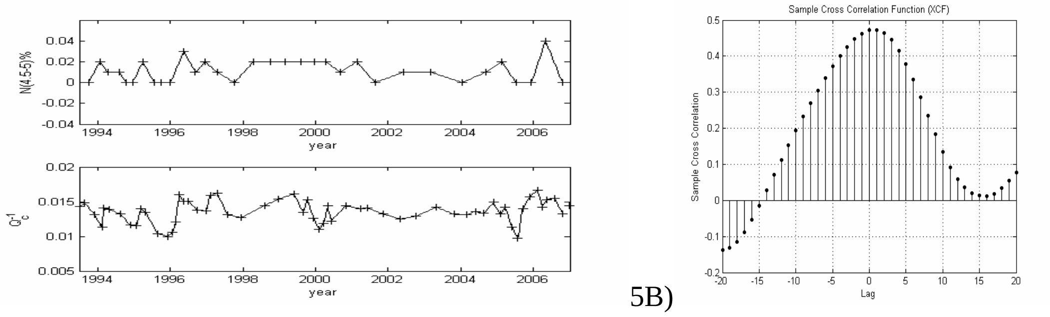
We use wave forms of seismograms corresponding to seismic events within 150 km from the recording site and $2.8\leq M\leq 4$. As it is shown in Figure 3, we are constrained to use such a big region because of its tectonic characteristics. This can affect the results, for instance smoothing the cross correlation functions. The amount of available waveforms is big; we have collected over 17000 short period vertical seismograms. Around 4500 fulfil the magnitude completeness conditions and give coda Q values with correlation coefficients $r^2\geq 0.7$. Over 3600 of these happened at hipocentral distances smaller than 150km. So for the time evolution we average over 50 values of Q_0^{-1} with an overlap of 20, setting the time of each averaged measure to the middle of the origin times of the corresponding 50 events.

4.3. Seismicity Analysis

The data for the seismicity analysis during the period 1993-2007 are obtained from the catalogue available in Ingeominas' web page. As in the seismicity analysis, the quality of the catalogue is first analyzed, because an incomplete data set would lead to misinterpretations and misleading final statements. We find that the completeness magnitude, $M_{Complet}$, for the considered time period is 3. $N(M_{Ch})$ is then calculated as the evolution of the percentage of earthquakes of a half unit magnitude interval, considering events with $M_L \geq 3$.

4.4. Correlation Analysis

The two series have non-coincident data so to evaluate their correlation we have to interpolate them to equally spaced points. We use linear interpolation. The correlation found is reasonably good (see Figure 5) though not as good as the ones founded in previous works (Jin and Aki, 1989, 1993; Aki, 2004; Zaliapin et al., 2005). This disagreement with previous results can be due to several reasons. 1) Our time series are short; no longer than 14 years. 2) Interpolation can affect the time series trends. Probably the multiple trend analysis applied by Zaliapin et al. (2005) would lead to better results. But, in our opinion, the greatest difference is due to the kind of seismic activity we are dealing with. 3) The deepness of the Bucaramanga nest constrains us to work with too large hipocentral distances sampling large and heterogeneous regions. So, both time series may be severely affected, and we really are not analyzing local characteristics and effects but better we are sampling and averaging different brittle-ductile coupling behaviours. These three causes may smooth the correlation function the way it appears. The characteristic magnitude that gives the best results is also slightly different, being half a unit of magnitude bigger than the ones found by others. This magnitude is assumed to be a local characteristic of the area (Aki, 2003), but it also may be affected by the long distance ranges involved in this seismic station.



5A) 5B)

Figure 5. 5A) Time evolution of the seismicity and the attenuation for Barichara between 1993 and 2007. 5B) Cross correlation between the two series.

Any way, despite the complexity of the region, we find a reasonably correlation between seismicity and attenuation supporting the brittle-ductile interaction hypothesis. It is worth noting that no great earthquakes occurred in the region during the time period here analyzed.

5. CONCLUSIONS

Special importance has been given to preliminary analysis on data quality because we are dealing with big and heterogeneous data sets. This data quality estimation is needed for obtaining reliable results and conclusions. Seismicity analysis seems to indicate the existence of time dependence at all scales. A remarkable peak of activity with a period of about 3 years seems to appear. We have also significant indications for space dependence. The lack of complete data sets for wider time windows does not allow us determining longer significant trends leading worldwide seismic activity. But these preliminary results encourage keeping on studying the space-time evolution of the seismicity.

Following Jin & Aki’s (1989, 1993) creep model; we have tested for the hypothesis of the brittle-ductile interaction of the lithosphere in a complex region. Despite the complexity of the site, compared to the ones analyzed by others, make the correlation not so remarkable, it is clear that the relation between the two time series exists. The un-correlation cannot be tested yet in this area because no big earthquake has taken place in the region during the period for which we have data, so its possibilities of use as a precursor for this region, keep yet unsolved. In spite of the limited results of this work, perhaps our more important conclusion is the need of saving and analyzing permanently high quality data. One extra century of more, denser and higher quality data collected around the entire world will help us to go towards the mid-term and, perhaps in many cases, accurate short-term predictions.

5. ACKNOWLEDGEMENTS

This work has been partially sponsored by the Spanish Ministry of Education and Science and with FEDER funds (project: CGL-2005-04541-C03-02/BTE). The first author has a FPI scholarship from the Education, Universities and Investigation Dept. of the Basque Government (Spain).

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