Scaling in spectral behavior of regional to single-fault seismicity

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Abstract – Power spectral density was applied to analyse the time dynamics of seismicity in Taiwan. Scaling with exponent $\alpha \sim 0.52$ was found, revealing an identical power law behavior from a local fault plane up to a large region and from large earthquakes down to micro-earthquakes.

Statistical approaches to the analysis of earthquake sequences have revealed universal scale-invariant behaviors for the main physical observables [1,2]. For instance, the seismic moment distribution of earthquakes $P(s)$ scales with the seismic moment size s, $P(s) \sim s^{-\gamma}$, where the exponent $\gamma \in [1.6, 1.7]$ in different seismotectonic areas [3]. Furthermore, earthquakes tend to occur in temporal clusters just after the occurrence of a large event; the Omori law, indeed, states that the number of aftershocks at time t, $N_A(t)$, is featured by a power law decay $N_A(t) \sim t^{-p}$ where $p \approx 1$ [4]. The distribution of the seismic interevent times, $P(\tau)$, is non-trivially characterized by a function that does not depend on the geographical region or the magnitude range considered, thus leading to a unique universal distribution if τ is rescaled with the rate of seismic occurrence. And this holds from global to local scales, for quite different tectonic settings and for all the magnitude ranges considered [5]. The power law behavior revealed in these statistics could be considered as the end-product of a self-organized critical state of the Earth's crust, analogous to the state of a sandpile which evolves naturally to a critical repose angle in response to the slowly steady supply of new grains at the summit [6].

Second-order power law statistics are generally performed to investigate the temporal properties of earthquakes, in order to identify their correlation structures [7]. Several techniques could be used, but all are related with the power spectrum [8,9]. In particular scaling behavior is revealed by a spectrum that decays as a power law function of the frequency f, *i.e.* $S(f) \sim f^{-\alpha}$ [10]. The scaling exponent α identifies and quantifies the type and strength of the temporal fluctuations [11]. For purely

random processes, like the Poissonian one, characterized by uncorrelated occurrence times, the power spectrum is flat, *i.e.* $\alpha \sim 0$, indicating a sort of equiprobability of occurrence of all the involved time scales. On the other hand, positive α is typical of those processes characterized by long-range correlations [8]. The more correlated the process, the higher the value of α [12].

Earthquakes are point processes that are temporally represented by a finite sum of Dirac's δ-functions centered on the occurrence times t_i [13]:

$$y(t) = \sum_{i=0}^{n} \delta(t - t_i). \tag{1}$$

Therefore, unlike time-continuous processes, for earthquake sequences the power spectrum cannot be calculated directly from the Fourier Transform (FT) [10]. Thus, the following procedure has to be performed. Dividing the time axis into equally spaced contiguous counting windows of duration τ, a sequence of counts $\{N_k(\tau)\}$, with $N_k(\tau)$ denoting the number of earthquakes in the k-th window, is produced [10]:

$$N_k(\tau) = \int_{t_{k-1}}^{t_k} \sum_{i=0}^{n} \delta(t - t_i) \mathrm{d}t. \tag{2}$$

The power spectrum, then, is estimated by means of the Count-Based Periodogram (CBP), which is obtained through the FT of the $N_k(\tau)$ [10].

Here we show scaling in the spectral behavior of 1999–2007 seismicity of Taiwan (fig. 1). The power spectrum (blue crosses in fig. 3) of the daily number of crustal earthquakes with magnitude larger than 2 occurred in the whole Taiwan region mainly reveals two scaling regions: at low frequencies (corresponding to long-term temporal

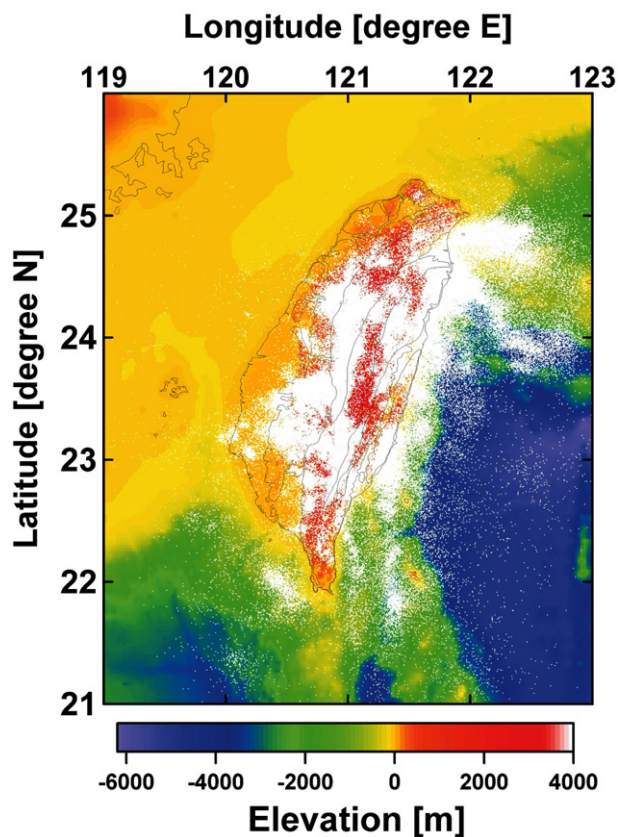(a)E-mail: luciano.telesca@imaa.cnr.it
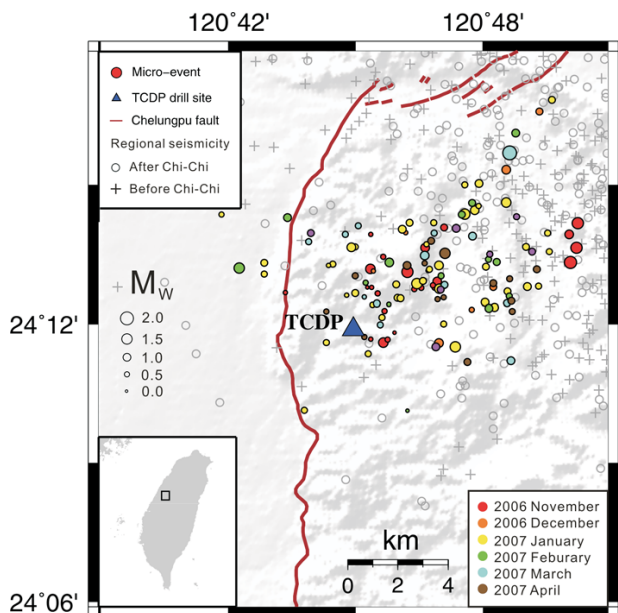
Fig. 1: (Colour on-line) Regional seismicity in Taiwan.

Fig. 2: (Colour on-line) Local micro-earthquakes registered by the TCDP borehole seismometers.
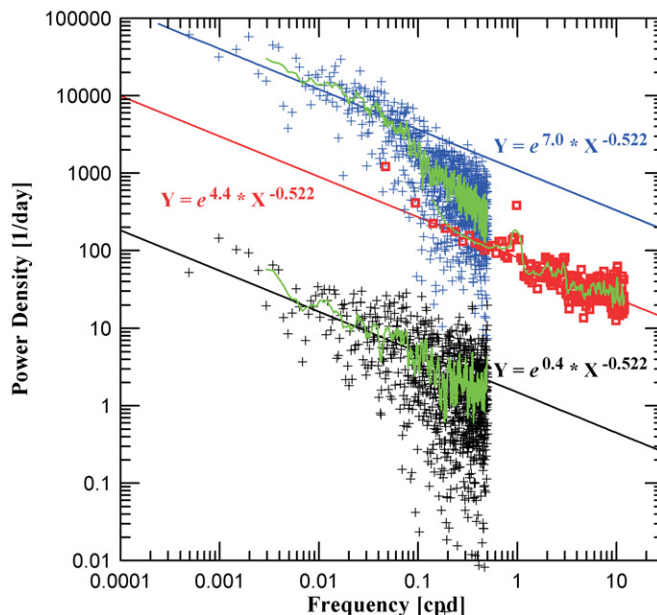

Fig. 3: (Colour on-line) Power spectra from time series of daily earthquake numbers (blue crosses), daily counts of declustered seismicity (black crosses) and hourly counts of micro-events (red squares). Three straight lines with same exponent of 0.522 were drawn to visually fit these power spectra. Green lines are the moving averages for each spectrum, plotted to better evidence the power law behavior. A temporal scaling behavior, with an exponent of around 0.52, universally holds in seismicity.

fluctuations) $\alpha \sim 0.52$, while at high frequencies (corresponding to short-term temporal fluctuations) $\alpha \sim 1.14$. In order to understand the presence of this double-scaling behavior in the power spectrum of Taiwanese seismicity, the aftershocks were removed, by using the method of spatiotemporal double-link cluster analysis. This method is similar to the single-link cluster analysis proposed by [14]. Given a magnitude threshold of main shocks, the declustering algorithm specifies two linking parameters in the time and space scales, 3 days and 5 km for example. An event would be identified as an aftershock when its epicenter and occurrence time lay within the prescribed spatiotemporal window of some main shock. Then, the procedure iteratively searches for secondary aftershocks, *i.e.* the aftershock of an earlier aftershock. The whole catalog turns out to be separated by many sequences of main shocks and aftershocks. By using the temporal and spatial linking parameters of 3 days and 5 km, the aftershock events generated from main shocks with magnitude larger than 4.5 were removed. Those linking parameters were usually used for declustering the Central Weather Bureau Seismic Network (CWBSN) catalog [15]. After removing the aftershocks the exponent α estimated from the power spectrum (black crosses in fig. 3) is around 0.52 over all the frequency bands. Thus, the lower value of α at lower frequencies characterizes the background seismicity of the Taiwan area while the higher α value at high frequencies describes the aftershock-related effect.

It is interesting to investigate the spectral properties of single-fault seismicity and evaluate weather the spectral behavior changes from a regional scale down to local

single-fault scale. Taiwan Chelungpu-fault Drilling Project (TCDP) had deployed a set of comprehensive 7-level borehole seismometers (BHS) after a successful 2-km-deep vertical hole drilling across the slip zone generated by the 1999 magnitude 7.6 Chi-Chi earthquake [16]. This TCDP BHS had capability to record micro-events down to magnitude 0.5. Several hundreds of micro-earthquakes with magnitude smaller than 2 were registered and located from November 2006 through April 2007 (fig. 2). Analyses elucidate that these micro-earthquakes are complete for recording and they are all located at a seismogenic layer around 10 km deep. The power spectrum (red squares in fig. 3) obtained from the hourly number of these micro-events, again, scales with the frequency with the same exponent $\alpha \sim 0.52$ as the regional earthquakes in Taiwan.

Strikingly, the micro-events registered by the TCDP BHS lead us to a common scaling in seismicity, which reveals an identical power law behavior from a local fault plane up to a large region and from large earthquakes down to micro-earthquakes as well.

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