LONGER AFTERSHOCKS DURATION IN EXTENSIONAL TECTONIC SETTINGS

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Every day, moderate to large magnitude earthquakes release seismic energy stored within the Earth’s crust. This energy is accumulated for tens or thousands of years, during the interseismic phase, and released instantaneously (i.e., seconds) through an earthquake (i.e., the mainshock) during the co-seismic phase (e.g., Kanamori and Bordsky, 2004). After the mainshock, the energy release continues (for months to years) during the post-seismic phase with aftershocks generally characterized by magnitudes smaller than the mainshock. Few studies were dedicated to the control of tectonic setting on the duration of aftershock sequences, although a better understanding of aftershocks decay with time is fundamental to better constrain seismic hazard during ongoing seismic sequences by predicting their duration. Typically, seismological observations indicate that, within a seismic sequence, the aftershocks decay in time follows the Omori-Utsu law (e.g., Omori, 1894; Utsu, 1961) and depends on several parameters peculiar of each seismogenic region, such as the tectonic setting (i.e., extensional, strike-slip, contractional regimes), stress changes along fault, structural heterogeneities, crustal rheology. However, the geological and seismotectonic parameters that control the aftershocks decay during seismic sequences are still unclear (e.g., Utsu and Ogata, 1995). In this work, we focus on the tectonic setting control on the aftershocks decay within seismic sequences. In particular, using data from international catalogues and proposing and comparing two different methods, we analysed the aftershocks sequences following five extensional settings earthquakes and five contractional settings earthquakes. In particular, we show that within extensional tectonic settings the average duration of aftershock sequences is longer and the number of events is larger than in contractional tectonic settings. We propose an interpretation of these different behaviours in terms of different type of energy involved during earthquake nucleation processes.
We employed the following two innovative approaches to determine the duration and the number of events of the selected aftershock sequences:

1) Tangents method. We adopted a completeness (threshold) magnitude (Mc) of 2.5 as, below this threshold, the number of recorded seismic events strongly depends on the sensitivity of the seismic network, which varies from place to place. The adoption of a completeness magnitude allowed us to remove the seismic noise. Our methodology is based on the build-up of cumulative curves for each seismic sequence, reporting the days elapsed from the mainshock on the x-axis versus the cumulative number of earthquakes on the y-axis. We distinguish two different parts in the graphs: one indicates a non-linear increase of the cumulative number and the other one a linear increment. The first non-linear trend suggests that the seismic sequence related to the mainshock event is still active, whereas the linear increment represents the ground seismicity that affect an active seismic region. We consider the point where the tangent to the linear increment departs from the cumulative curve as indicative of the end of the aftershock sequence.

2) Mandelbrot method. We examined faulting and fragmentation processes using the fractals theory (e.g. Turcotte, 1986; Mandelbrot, 1989). The fractal geometries are related to fragmentation processes caused by earthquake nucleation and, therefore, the variation of fractal parameters can be indicative of the evolutions of the fragmentation processes along a fault system in time and space. We analysed the seismological data, fit the same data with a linear regression and obtained the fractal dimension and the related coefficient of determination (i.e., R squared). This method allows the representation of the magnitude-frequency distribution of earthquakes. In particular, we realized semi-logarithmic graphs for each seismic sequences, in which we compared the number of earthquakes occurred in certain magnitude ranges. The fitting straight line represents a simple linear regression according to the following equation, which also define a fractal set: $N_i = Cry^{-D}$ where $N_i$ is the number of objects with a characteristic linear dimension $r$, $C$ is a constant of proportionality, and $D$ is the fractal dimension. The fractal dimension value represents the level of irregularity of the selected fractal set (e.g., Turcotte, 1997) and is indicative of the fragmentation process occurred during the mainshock and the following aftershocks. If $D=0$, it represents the classical Euclidean dimension of a point; if $D=1$, it represents the dimension of a line segment; if $D=2$, it represents the dimension of a surface and, finally, if $D=3$, it represents the dimension of a volume.

According to the here proposed Tangents method, the average duration of aftershocks sequences within extensional tectonic settings is about 390 days, i.e. about 270 days longer than the duration (about 120 days) of aftershocks sequences within contractional tectonic settings. Furthermore, aftershock sequences within extensional tectonic settings are characterized by a larger number of seismic events (1045 aftershocks on average) than those within contractional earthquakes (790 aftershocks on average).

According to the Mandelbrot method, the average duration of aftershocks sequences within extensional tectonic settings is about 430 days, which is about 295 days longer than that of aftershocks sequences within contractional tectonic settings (about 135 days). Furthermore, aftershock sequences within extensional tectonic settings are characterized by a larger number of seismic events (1056 aftershocks on average) than those within contractional earthquakes (795 aftershocks on average).

The fractal dimension ($D$) values calculated for extensional and contractional seismic sequences are also different. For extensional earthquakes, the fractal dimension varies from ca. 2 to ca. 3. Conversely, for contractional earthquakes, the fractal dimension varies from 1 to ca. 2. The fractal dimension is indicative of the geometrical fragmentation process. Therefore, the analysis of the fractal dimension shows that extensional seismic sequences tend to occupy a volume with time; on the other hand, contractional seismic sequences tend to develop along a surface with time.

Our analyses strongly support the conclusion that, irrespective of the magnitude of the mainshocks, extensional seismic sequences are longer than compressional sequences. We
propose that the different duration of seismic sequences is controlled by the type of energy released during the earthquakes, which is, in turn, related to the tectonic setting. Doglioni et al. (2015) proposed that extensional earthquakes are characterized by dissipation of gravitational energy, stored during the interseismic phase within a hangingwall volume confined by the main normal fault and an antithetic fractured dilated zone. When the stresses related to this gravitational energy exceed the strength of the dilated zone and of the main normal fault, the rock volume collapses slipping along the main fault, generating the earthquake. The downward hangingwall block movement happens in favour of gravity (e.g., Petricca et al., 2015). The aftershock sequences can be interpreted as related to the rock wedge settlement due to the closure of fractures and to the complete dissipation of gravitational energy within the dilated antithetic zone. On the contrary, thrust-related earthquakes are characterized by dissipation of elastic energy, which is stored both within the rock volume above the thrust fault (i.e., the hangingwall block) and along the thrust fault itself during the pre-seismic period (e.g., Doglioni et al., 2015). When the elastic energy exceeds the fault resistance, the hangingwall block moves upward along the fault against gravity, thus generating the earthquake; the elastic energy dissipation is buffered by the gravitational force. Finally, this comparative analysis of aftershock seismic sequences may be useful for seismic hazard assessment and, consequently, for the full understanding of long-term behaviour of an ongoing seismic sequence within different tectonic settings.

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