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Relationship between accelerating seismicity and quiescence, two precursors to large earthquakes

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[1] The Non-Critical Precursory Accelerating Seismicity Theory (PAST) has been proposed recently to explain the formation of accelerating seismicity (increase of the *a*-value) observed before large earthquakes. In particular, it predicts that precursory accelerating seismicity should occur in the same spatiotemporal window as quiescence. In this first combined study we start by determining the spatiotemporal extent of quiescence observed prior to the 1997 Mw = 6 Umbria-Marche earthquake, Italy, using the RTL (Region-Time-Length) algorithm. We then show that background events located in that spatiotemporal window form a clear acceleration, as expected by the Non-Critical PAST. This result is a step forward in the understanding of precursory seismicity by relating two of the principal patterns that can precede large earthquakes.
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1. Introduction

[2] We investigate the spatiotemporal distribution of precursory accelerating seismicity by following the recently proposed Non-Critical Precursory Accelerating Seismicity Theory (PAST) [*Mignan*, 2008]. Contrary to a majority of studies that consider seismicity as a complex system where only a holistic approach to the problem of earthquake prediction can be proposed [e.g., *Tiampo and Anghel*, 2006; *Keilis-Borok*, 1999], the Non-Critical PAST is a reductionist approach, which allows us to study the behavior of precursory seismicity in a novel way.

[3] *Mignan et al.* [2007], who gave the mathematical background to the Non-Critical PAST, demonstrated that the cumulative number of events $\lambda(t)$, prior to a main shock, increases as a power-law through time because of an elastic rebound effect, as first proposed by *King and Bowman* [2003]. In that view, a critical point process [e.g., *Sammis and Sornette*, 2002; *Jaumé and Sykes*, 1999] is unnecessary to explain the power-law behavior, the acceleration being due to simple stress transfer and geometrical considerations.

[4] The power-law time-to-failure equation proposed by *Mignan et al.* [2007] is of the form

$$\lambda(t) \propto A - B(t_f - t)^m + Ct \qquad (1)$$

with A, B and C positive and the scaling exponent m is between 1/3 and 2/3. This formulation differs from previous ones proposed for Accelerating Moment Release (AMR) [e.g., *Bufe and Varnes*, 1993; *Ben-Zion and Lyakhovsky*, 2002; *Turcotte et al.*, 2003] by the fact that $\lambda(t)$ represents the cumulative number of events above the detection threshold instead of the cumulative Benioff strain through time. It means that the acceleration would correspond to an increase of the a-value, which is in agreement with recent observations [e.g., *Bowman and Sammis*, 2004; *Jimenez et al.*, 2006]. In the Non-Critical PAST, clusters, decrease of the *b*-value and periodic oscillations [e.g., *Sornette and Sammis*, 1995] are only fitting artifacts, not part of the theoretical accelerating pattern.

[5] *Mignan* [2008] proposed the use of synthetic seismicity catalogues based on concepts developed by *Mignan et al.* [2007] to test the reliability of earthquake forecasting algorithms under different seismicity behaviors. The power-law fit methodology [*Bowman et al.*, 1998] is the most common method employed to identify AMR and to subsequently forecast large events. *Mignan* [2008] showed that this method is weak, failing to determine the spatiotemporal extent of the precursory accelerating pattern, a priori a key parameter for earthquake prediction.

[6] The purpose of this study is to verify a prediction made by the Non-Critical PAST which is that precursory accelerating seismicity and quiescence should occur in the same spatiotemporal window. If an algorithm allows the determination of quiescent stages, it would help in theory identifying accelerating patterns as well. We apply here the RTL parameter [e.g., *Sobolev and Tyupkin*, 1999] to verify the quiescence/accelerating seismicity couple hypothesis, first on a synthetic seismicity catalogue based on the Non-Critical PAST, and then on seismicity prior to the 1997 Mw = 6 Umbria-Marche earthquake, before which quiescence is known to have occurred [*Console et al.*, 2000; *Di Giovambattista and Tyupkin*, 2000].

2. Data

[7] The analysis is based on data from the Instituto Nazionale di Geofisica (ING) earthquake catalogue for 1986–1998 [*Barba et al.*, 1995] with a magnitude cutoff M_{min} = 2.3 (level of completeness of the catalogue for Central Italy). Aftershocks are deleted from the catalogue by using the declustering method proposed by *Molchan and Dmitrieva* [1991].

[8] Figure 1 presents the plot of the RTL parameter (Appendix A) calculated at the epicenter of the September 26, 1997 Umbria-Marche main shock. The RTL parameter is estimated in the time window $[t - 2t_0, t]$ and cylindrical volume of radius $2r_0$ with t_0 = 1 year and r_0 = 50 km. A

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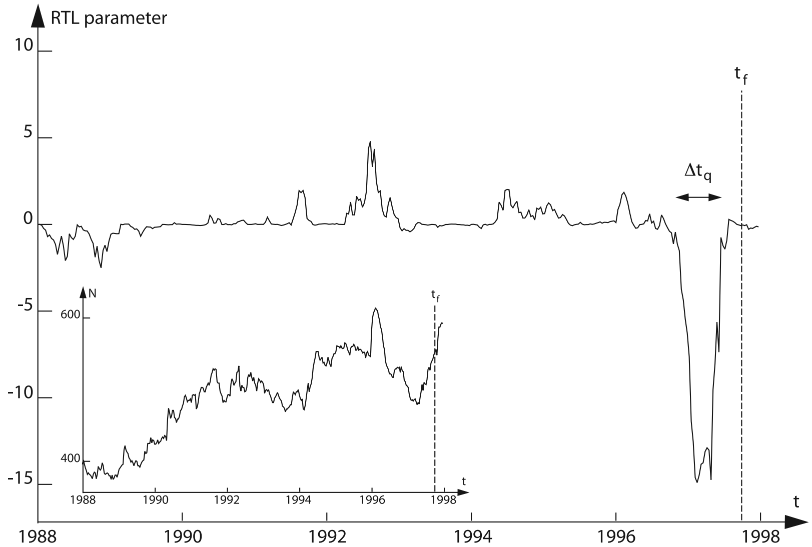

Figure 1. Plot of the RTL parameter calculated at the epicenter of the Umbria-Marche main shock. Δt_q corresponds to the period of precursory quiescence and t_f to the time of occurrence of the main shock. Inset: Number of events N used for estimation of the RTL parameter in the time window $[t - 2t_0, t]$ and cylindrical volume of radius $2r_0$ with t_0 = 1 year and r_0 = 50 km. Analysis reproduced from *Di Giovambattista and Tyupkin* [2000].

quiescent stage can be clearly observed over a period Δt_q, as already shown by *Di Giovambattista and Tyupkin* [2000].

3. The Non-Critical PAST

[9] The theoretical relationship between quiescence and accelerating seismicity is illustrated in Figure 2a, which represents the spatiotemporal evolution of background events in a synthetic catalogue based on the Non-Critical PAST (Appendix B). A quiescent stage is defined in the time period Δt_q and in the space interval $[0, r^*(t)]$ with $r^*(t)$ decreasing as a power-law through time [*Mignan et al.*, 2007]. The region of quiescence is defined as a stress shadow whose decrease in size is due to stress loading on the fault, located at r = 0, that will host the main shock at $t = t_f$. The density of background events is δ_b^- inside and δ_b^0 outside the region of quiescence, with $\delta_b^- < \delta_b^0$ (the noise ratio δ_b^-/δ_b^0 is fixed to 10% in this study to represent a case of clear quiescence - zero corresponds to perfect quiescence and one corresponds to no quiescence).

[10] Figure 2b presents a plot of the RTL parameter calculated at the epicenter of the main shock (center of the loaded fault) in the synthetic catalogue. The RTL parameter is estimated in the time window $[t - 2t_0, t]$ with $t_0 = 0.2\ \Delta t_q$ and cylindrical volume of radius $2r_0 \sim r^*_{max}$ (characteristic time-span t_0 and distance r_0 for an optimal result). A clear pattern of quiescence is observed (i.e. negative RTL), consistent with the time period Δt_q. The similarity between RTL curves in Figure 1 and Figure 2b suggests that the RTL algorithm behaves similarly in real catalogues and synthetic catalogues based on the Non-Critical PAST.

[11] As demonstrated analytically by *Mignan et al.* [2007] and verified with synthetic catalogues by *Mignan* [2008], the accelerating seismicity pattern is best defined in the time period Δt_q and in the space interval $[r = 0, r^*_{max}]$ with r^*_{max} the maximum spatial extent of the quiescent stage (Figure 2c). The degree of acceleration is quantified by using the curvature parameter C, or *c*-value, defined by *Bowman et al.* [1998] for AMR (C = power-law fit root-mean-square error/linear fit root-mean-square error) and is found to be ~0.3 in the synthetic catalogue where δ_b^-/δ_b^0 = 10%. A higher noise ratio would increase the weight of the linear trend Ct of equation (1), hiding part of the accelerating seismicity pattern and leading to a higher *c*-value [*Mignan et al.*, 2007]. The role of the density of background events and of the noise ratio on accelerating patterns is investigated in detail by *Mignan* [2008].

4. Results and Discussion

[12] If the Non-Critical PAST is correct, accelerating seismicity should be observed in the spatiotemporal window where quiescence is defined prior to the Umbria-Marche main shock. The time window is determined from the RTL analysis made at the epicenter of the main shock, found to be Δt_q = [1996.85, 1997.45] for RTL < −2 (Figure 1). To determine the spatial extent of the quiescent stage (i.e. r^*_{max}), a map of the Q parameter is computed for the period Δt_q using values t_0 = 1 year and r_0 = 50 km centered on each point, with Q being the mean RTL value for this period of time [*Huang et al.*, 2002]. Figure 3a represents the quiescent region, whose limit is fixed to RTL < −2. The cumulative number of background events located inside this region forms a clear acceleration with C ~ 0.3 (Figure 3b), like that predicted by the Non-Critical PAST (Figure 2c). For the same period of time Δt_q, regional seismicity is linearly increasing with C ~ 1.0 (inset Figure 3b).

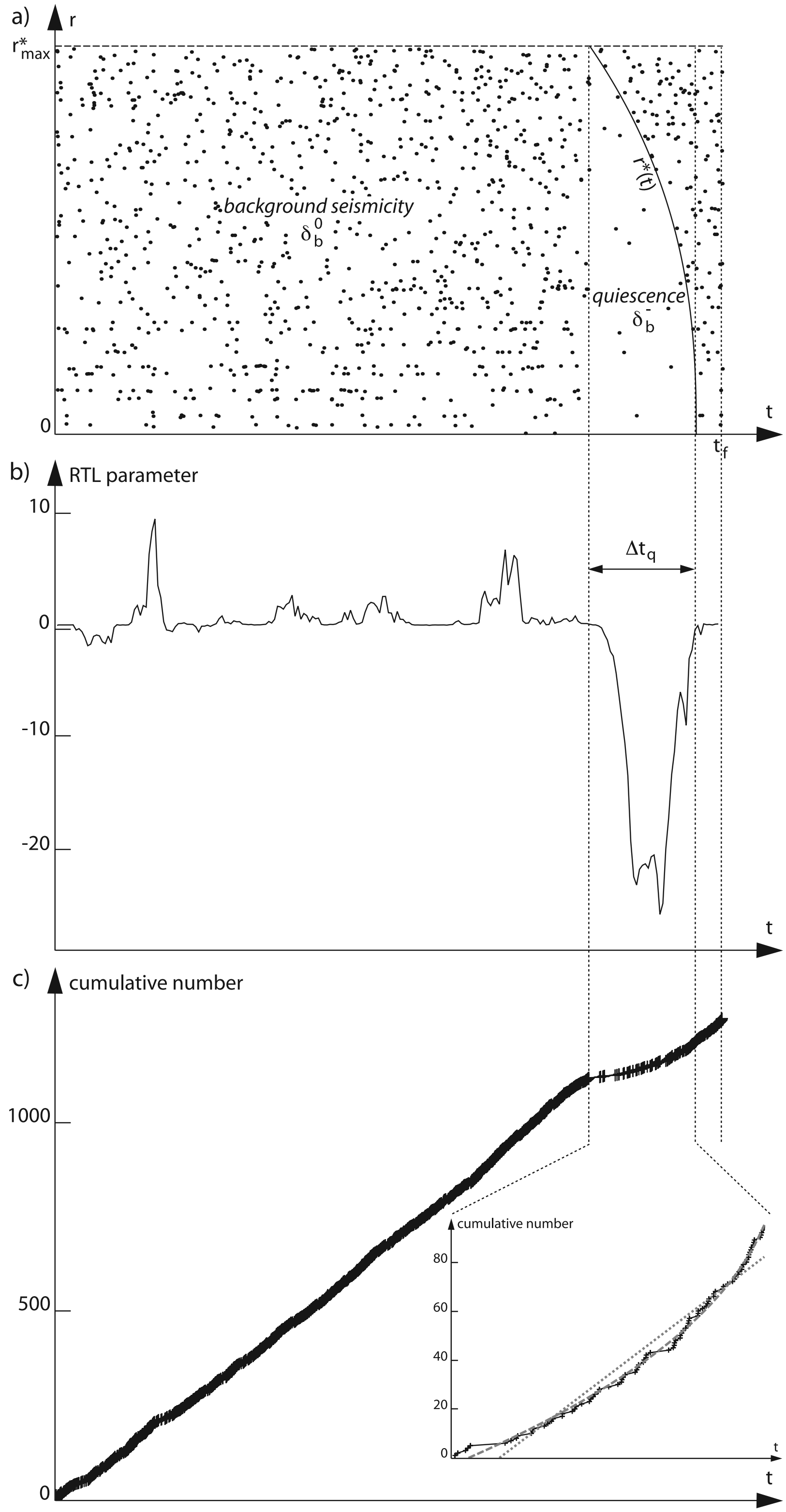

Figure 2. Quiescence/accelerating seismicity couple in the Non-Critical PAST. (a) Spatiotemporal evolution of background events (black dots) in a Non-Critical PAST synthetic catalogue. Main shock occurring at r = 0 and $t = t_f$; quiescence stage defined in the time period Δt_q and in the space interval [0, r*(t)] with r*(t) decreasing as a power-law through time [*Mignan et al.*, 2007]; density of background events δ_b^- inside and δ_b^0 outside the quiescence region, with $\delta_b^-/\delta_b^0 = 10\%$. (b) Plot of the RTL parameter calculated at the epicenter of the main shock. RTL parameter estimated in the time window $[t - 2t_0, t]$, with $t_0 = 0.2\Delta t_q$, and cylindrical volume of radius $2r_0 \sim r^*_{max}$. (c) Cumulative number of background events through time in the space interval $[0, r^*_{max}]$. A clear acceleration is observed in the time interval Δt_q, with C ~ 0.3 (power-law fit and linear fit represented respectively by the dashed curve and dotted line).

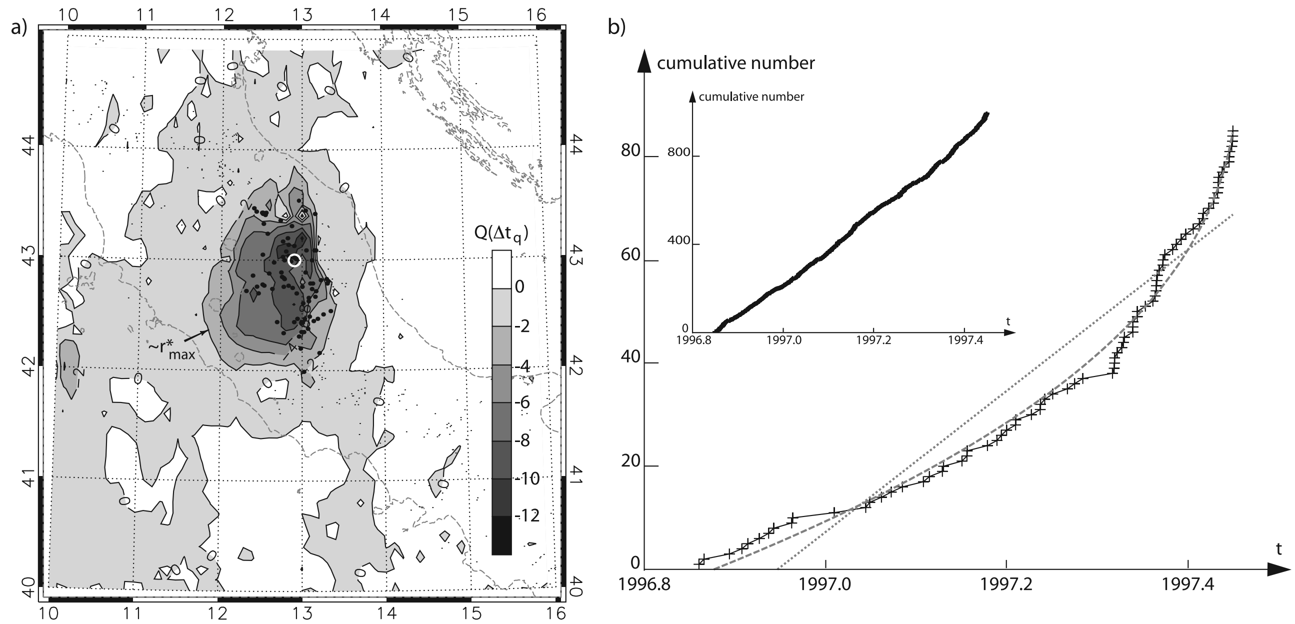

Figure 3. (a) Map of the parameter $Q(x,y,\Delta t_q)$, defined as the mean of RTL values for the time window Δt_q = [1996.85,1997.45] with value t_0 = 1 year and r_0 = 50 km. The Umbria-Marche main shock is represented by a white circle and events located in the quiescence region (where $Q(x,y,t) < -2$) by large black dots. (b) Cumulative number of events through time in the region of quiescence during Δt_q. A clear acceleration is observed with $C \sim 0.3$ (power-law fit and linear fit represented respectively by the dashed curve and dotted line). Inset: Regional seismicity in the time period Δt_q linearly increasing with $C \sim 1.0$.

[13] In space (during Δt_q), accelerating seismicity still persists when the size of the quiescent region is decreased to lower RTL values (down to RTL < −6) or when the quiescent region is approximated by a circle of radius $2r_0$ centered on the Umbria epicenter. In time (in the quiescent region where RTL < −2), seismicity is linearly increasing before and after Δt_q. A reliability test for the *c*-value [e.g., *Bowman et al.*, 1998] is not necessary here since no optimization procedure is used to improve the power-law fit. A reliability analysis method for the RTL algorithm is given by *Huang* [2006].

[14] The Non-Critical PAST appears to be a promising approach to better understand precursory seismicity. We have shown that (1) the RTL algorithm is reliable in synthetic catalogues (much as other forecasting techniques are, such as the power-law fit methodology [*Mignan*, 2008] or Pattern Informatics (A. Mignan and K. F. Tiampo, Testing the Pattern Informatics index on synthetic seismicity catalogues based on the Non-Critical PAST, manuscript in preparation, 2008)) and that (2) the theoretical prediction of a quiescence/accelerating seismicity couple is correct prior to the Umbria-Marche main shock.

[15] Although this result still needs to be confirmed by other natural examples, the Non-Critical PAST illustrates the efficiency of a reductionist approach to the problem of earthquake prediction.

Appendix A: RTL Algorithm

[16] The Region-Time-Length (RTL) algorithm [e.g., *Sobolev and Tyupkin*, 1999] is a statistical method for investigating quiescent and activation stages prior to large earthquakes. The RTL parameter is defined as the product of the following three functions:

$$R(x,t) = \left[\sum_{i=1}^{n} \exp(-r_i/r0)\right] - R_{bk}(x,t)$$

$$T(x,t) = \left[\sum_{i=1}^{n} \exp(-(t-t_i)/t0)\right] - T_{bk}(x,t)$$

$$L(x,t) = \left[\sum_{i=1}^{n} (l_i/r_i)\right] - L_{bk}(x,t)$$

where r_i is the distance from x, t_i the occurrence time and l_i the rupture dimension, function of magnitude M_i, of the ith event; n is the number of events satisfying $r_i \leq 2r_0$, $(t - t_i) \leq 2t_0$ and $M_{min} \leq M_i \leq M_{max}$; r_0 and t_0 are characteristic distance and time-span. $R_{bk}(x,t)$, $T_{bk}(x,t)$ and $L_{bk}(x,t)$ are background trends of R(x,t), T(x,t) and L(x,t), respectively. R(x,t), T(x,t) and L(x,t) are dimensionless functions further normalized by their standard deviations σ_R, σ_T and σ_L, respectively. The RTL parameter (in units of the product of the standard deviations $\sigma = \sigma_R\sigma_T\sigma_L$) describes the deviation from the background level of seismicity, a negative RTL being interpreted as quiescence and a positive RTL as activation (see review by *Huang* [2004]).

Appendix B: Synthetic Catalogues Based on the Non-Critical PAST

[17] Synthetic catalogues are implemented by following the method proposed by *Mignan* [2008] (a method taking into account clustering based on an Epidemic-Type Aftershock Sequence (ETAS) model is given by Mignan and Tiampo (manuscript in preparation, 2008)). Background events

(t,x,y) are random in time and space in respect to the density of events δ_b. Magnitudes (m) are also chosen randomly, according to the Gutenberg-Richter law (*b*-value = 1). A stress field $\sigma(t_i,x,y)$ is computed for a dip-slip fault for a displacement on the fault of $(i_{max} - i)\Delta D$, with $i\Delta D$ corresponding to the loading component (back-slip model). The density of events is δ_b^0 outside and δ_b^- inside the stress contour $\sigma^*(t_i,x,y)$ corresponding to the spatial limit of the stress shadow (i.e. region of quiescence). Since seismicity behavior is similar along any gradient in the stress field [*Mignan et al.*, 2007; *Mignan*, 2008], coordinates are switched from (x,y) to r, distance from the fault and proportional to $\sigma^{-1/3}$.

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