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## **Radiated energy evolution during seismic sequences**

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**Abstract**

In this paper, I propose a new equation describing the evolution of seismic sequences, based on radiated energy. The evolution of radiated energy in time is described as function of the  $p$  and  $c$  parameters of the modified Omori law and of the energy radiated within a short time following the mainshock. By using the energy rather than the number of events in describing seismic sequences, I circumvent the problem of missing weak aftershocks close in time to the mainshock, because most of the total energy is contained in largest events. In addition, I propose an equation describing the difference in magnitude between the mainshock and the strongest aftershock as function of the energy radiated in a short time after the mainshock, of  $p$ ,  $c$ , and of the parameter  $b$  of the Gutenberg Richter equation. An application to California sequences shows values of  $p$  in the range [0.65, 1.5] and  $c$  in the range [0, 0.25] and no dependence of  $c$  on the difference between mainshock and cutoff magnitude.

## 49 ***1. Introduction***

50 Seismic sequences have been studied since the end of the 19<sup>th</sup> century to find general laws  
51 describing their time evolution and energy distribution. The so called “Båth law”, anticipated by  
52 Richter (1958) and then presented in larger detail by Båth (1965), states that the sample mean of the  
53 difference  $\Delta m$  between the mainshock and the strongest aftershock magnitudes is 1.2, for  
54 magnitudes based on surface wave scale. However, Båth (1965) itself provided examples in which  
55 the Båth law does not hold. Compatible results were found by Utsu (1957, 1961) on Japanese  
56 catalogue. This approach does not consider the different productivity and magnitude distribution  
57 from one sequence to the other and the temporal distribution of aftershocks.

58 In the same years, despite considerable statistical variability associated with seismicity, important  
59 general laws were observed for seismic sequences, like the Modified Omori Law (MOM – Utsu,  
60 1961) the frequency-magnitude scaling (Gutenberg and Richter, 1954) and, subsequently, the  
61 Reasenberg and Jones (1989, 1994) equation, that relates the event frequency to the magnitude  $M_m$   
62 of the main shock, the cutoff magnitude  $M_l$  and the time elapsed from the mainshock.

63 In this paper, I assume that the sequences can be approximated with Reasenberg and Jones  
64 equation, I apply the relation between energy and magnitude and I find analytically (see Section 2)  
65 an equation that describes the cumulative radiated energy as function of time. In the proposed law  
66 the aftershock radiated energy is expressed as a function of  $p$  and  $c$  parameters of the MOM, of the  
67 mainshock energy and of the energy radiated in a selected time period after the mainshock.

68 The description of seismic sequences in terms of energy or seismic moments has been already done  
69 in the other papers: Gentili and Bressan (2008) compared the radiated energy at short time after the  
70 mainshock with the one at the end of the sequence, Shcherbakov and Turcotte (2004) proposed a  
71 relation between the difference between the mainshock and the strongest aftershock magnitude and  
72 the sequence radiated energy, Kagan and Houston (2005) proposed a description of the sequence in  
73 terms of seismic moment, Zaliapin et al (2005) proposed a method for fitting cumulative moment.

74 An important feature of the approach proposed in this paper is that it allows to make an alternative  
75 evaluation of  $p$  and  $c$  parameters. Recently, the  $c$  parameter has been identified as related to the  
76 stress in the area, and is used for short term earthquake forecasting (EAST model - Shebalin et al.,  
77 2011). However, the value of  $c$  has been widely debated (Kagan and Houston, 2005, Lolli and  
78 Gasperini, 2006, Utsu et al., 1995, Shcherbakov et al., 2004, Kagan, 2004 and Lippiello et al.,  
79 2007). The origin of the debate is that the  $c$  term in the MOM is sensitive to the rate of seismicity  
80 for times close to the mainshock, i.e. when, due to the waveform superposition, it is more difficult  
81 to evaluate the seismicity rate, especially when small earthquakes are considered. The proposed  
82 approach overcomes this problem, because it is sensitive to strong magnitude earthquakes, i.e. the  
83 ones that are more easily detected.

84 A general law was proposed (see section 3) relating the energy radiated in a short time period after  
85 the mainshock and the difference in magnitude  $\Delta m$  between the mainshock and the strongest  
86 aftershock of the seismic sequence. The equations describing the radiated energy as function of time  
87 and the one on  $\Delta m$  were applied to 9 seismic sequences in California.

## 88 ***2. Temporal evolution of radiated seismic energy***

89 The aftershock temporal decay previously described by Omori law (1894) was improved by Utsu  
90 (1961) in the MOM, that relates the rate  $v$  of aftershocks with magnitude larger than  $M_I$  to the time  $t$   
91 elapsed after the main shock:

$$92 \quad v(t, M_I) = \frac{K(M_I)}{(t + c)^p} \quad (1)$$

93 where  $K(M_I)$  is related to the total number of earthquakes,  $c$  depends on the rate of activity in the  
94 earliest part of the sequence and  $p$  is related to the temporal decay of the aftershocks (Kisslinger and  
95 Jones, 1991). The Omori law was verified to have a good fit on hundreds of sequences (Utsu et al.  
96 1995). Two examples of alternative description of seismicity rates are the modified stretched  
97 exponential (Gross and Kisslinger 1994) and the Band Limited Power Law (Narteau et al. 2003).

98 Both laws are characterized by an exponential decay for long times after the mainshock. Lolli and  
 99 Gasperini (2006) and Gasperini and Lolli (2009) compared the quality of the fit of the three  
 100 different laws on real data by using the corrected Akaike Information Criteria (AICc) and the  
 101 Bayesian Information Criteria (BIC) and found that the exponential decay laws fit better the data if  
 102 a large time span after the mainshock is considered, while for shorter time span (Lolli and  
 103 Gasperini, 2006) the best fit is obtained by the MOM.

104 The energy distribution of the seismic sequence was described by the frequency-magnitude scaling  
 105 of Gutenberg and Richter (1954) that states that:

$$106 \quad \text{Log}_{10}(N(M_I)) = A - bM_I \quad (2)$$

107 where  $N(M_I)$  is the number of earthquakes with magnitude larger than  $M_I$ ,  $A$  is a measure of the  
 108 regional level of seismicity (Kagan, 2004), while  $b$  depends on the proportion of large and small  
 109 earthquakes (Gerstenberger et al, 2007).

110 It is debated if the Gutenberg and Richter (1954) law can be applied to the whole seismic sequence  
 111 or only to the aftershocks (see Utsu 1969, Helmstetter and Sornette 2003).

112 Combining equations (1) and (2) Reasenberg and Jones (1989, 1994) proposed an aftershock  
 113 occurrence model, which describes the rate of aftershocks with magnitude larger than  $M_I$  as a  
 114 function of time and of the main shock magnitude:

$$115 \quad \nu(t, M_I) = \frac{10^{a+b(M_m-M_I)}}{(t+c)^p} \quad (3)$$

116 where  $M_m$  is the magnitude of the main shock,  $c$  and  $p$  are the parameters of eq. (1),  $b$  is the  
 117 parameter of equation (2) and  $a$  is the “productivity” (Gasperini and Lolli, 2006), related to the  
 118 parameter  $A$  of equation (2) (Lolli and Gasperini, 2003):

$$119 \quad a = A - bM_m - \text{Log}_{10} \left[ \int \frac{1}{(t+c)^p} dt \right] \quad (4)$$

120 It was found that for some sequences equation (1) and therefore eq. (3) only approximately fits the  
 121 data, because not only the mainshock, but also the aftershock can trigger a seismic sequence.

122 Abrupt increases of seismicity following the strongest aftershocks have been observed. This  
 123 behavior is described by the ETAS (Epidemic Type Aftershock Sequences) law (Kagan and  
 124 Knopoff 1981, Ogata 1988) that is a generalization of eq. (3).

125 The magnitude of an earthquake is related with its radiated energy by the regression (Gutenberg and  
 126 Richter, 1956):

$$127 \log_{10} E(M) = \alpha M + \beta \quad (5)$$

128 where  $\alpha$  and  $\beta$  are constants and  $M$  is the magnitude. The parameters  $\alpha$  and  $\beta$  depend on the  
 129 magnitude scale adopted.

130 In this paper I study the evolution of the radiated seismic energy assuming that, during the seismic  
 131 sequence, the magnitude or energy distribution is independent on time. This assumption is  
 132 consequence of the Reasenberg and Jones equation (3).

133 The energy of the aftershocks  $E_{as}(t)$  of the sequence as function of time can be obtained by  
 134 integrating over the distribution of aftershocks magnitudes:

$$135 E_{as}(t) = \int_{M_c}^{M_m} E(m) \left( -\frac{dN(m,t)}{dm} \right) dm \quad (6)$$

136 where  $M_c$  is the completeness magnitude and  $N$  is the cumulative number of earthquakes with  
 137 magnitude greater than  $m$  at the time  $t$ , i.e.:

$$138 N(m,t) = \int_0^t \nu(\theta, m) d\theta \quad (7)$$

139 Substituting equation (3) into equation (7) and taking the derivative with respect to the magnitude  
 140  $m$ , I obtain:

$$141 \frac{dN(m,t)}{dm} = -b \ln(10) 10^{a+b(M_m-m)} \int_0^t \frac{d\theta}{(\theta+c)^p} \quad (8)$$

142 Substitution of equations (8) and (5) into equation (6) gives:

$$143 E_{as}(t) = \Lambda(a, b, \alpha, \beta, M_m, M_c) \int_0^t \frac{d\theta}{(\theta+c)^p} \quad (9)$$

144 Where  $\Lambda(a, b, \alpha, \beta, M_m, M_c)$  is:

$$145 \quad \Lambda = \frac{b}{\alpha - b} 10^{\alpha M_c + \beta} \cdot \left[ 10^{a + \alpha(M_m - M_c)} - 10^{a + b(M_m - M_c)} \right] \quad (10)$$

146 The derivative of eq. (9) with respect to time is the equivalent of the Reasenberg and Jones model  
 147 for radiated energy rather than for number of earthquakes. Bressan et al. (2007) define the  
 148 parameter  $R_{ES}$  as the ratio between the energy radiated by the mainshock and the summation of the  
 149 energies radiated by all the aftershocks of a seismic sequence. Let

$$150 \quad R_{ES}(t) = E_m / E_{as}(t) \quad (11)$$

151 where  $E_m$  is the radiated energy of the mainshock and  $E_{as}(t)$  is the summation of the energies  
 152 radiated by till the time  $t$  after the mainshock. From equation (9):

$$153 \quad \text{Log}(R_{ES}(t)) = \text{Log}(E_m) - \text{Log}(E_{as}(t)) = \text{Log}(E_m) - \text{Log}\left(\Lambda \int_0^t \frac{d\theta}{(\theta + c)^p}\right) \quad (12)$$

154 Let  $\tau$  be a generic time smaller than  $t$ ; from equation (12):

$$155 \quad \text{Log}(R_{ES}(t)) = \text{Log}(R_{ES}(\tau)) - \text{Log}\left(1 + \frac{\int_{\tau}^t \frac{d\theta}{(\theta + c)^p}}{\int_0^{\tau} \frac{d\theta}{(\theta + c)^p}}\right) = \text{Log}(R_{ES}(\tau)) - f(t, c, p, \tau) \quad (13)$$

156 with:

$$157 \quad f(t, c, p, \tau) = \begin{cases} \text{Log}\left[1 + \frac{(t + c)^{1-p} - (\tau + c)^{1-p}}{(\tau + c)^{1-p} - c^{1-p}}\right] & \text{for } p \neq 1 \\ \text{Log}\left[1 + \frac{\ln\left(\frac{t + c}{\tau + c}\right)}{\ln\left(\frac{\tau + c}{c}\right)}\right] & \text{for } p = 1 \end{cases} \quad (14)$$

158 Equation (13) states that the energy ratio evolution can be modeled using only the parameters  $c$  and  
 159  $p$  of the Modified Omori Model, and the selected time intervals  $(0, t)$  and  $(0, \tau)$ . In addition, it states  
 160 that the ratio of amounts of energy radiated within two different time intervals and the ratio of  
 161 number of aftershocks within the same time intervals are equal. This result is important for both  $c$



162 and  $p$  parameters evaluation. The Omori number-based approach treats all the events as having the  
 163 same weight, also the smaller ones, which are partially lost immediately after the mainshock. The  
 164 eq. (13) energy-based approach, vice-versa, gives a larger weight to larger earthquakes, that are the  
 165 ones recorded in the catalogue. For this reason, the less reliable data affect more the number-based  
 166 than the energy-based parameter estimation. Higher values of  $f$  mean that, after  $\tau$ , a great amount of  
 167 energy is radiated, decreasing the value of  $R_{ES}$ ;  $f$  close to 0, vice-versa, means that almost all the  
 168 energy of the sequence has been radiated within the time  $\tau$  and that the contribution to the  
 169 aftershock energy after the time  $\tau$  is negligible. Figure 1 shows an example with the trend of  $f$  for  
 170  $c=0.1$ ,  $\tau=1$  day and  $p=0.9$ , 1 and 1.1, respectively. For  $t \rightarrow \infty$ , finite values of  $\tau$  and  $p>1$ ,

$$171 \quad f(t, c, p, \tau) \rightarrow \text{Log} \left[ \frac{c^{1-p}}{c^{1-p} - (\tau + c)^{1-p}} \right] \text{ (see the asymptote of the curve for } p=1.1). \text{ If } \tau \rightarrow t, f \rightarrow 0;$$

172 if  $t < \tau$ ,  $f < 0$ .

173 <Insert Figure 1 here>

174 The equation (14) diverges for  $t \rightarrow \infty$  if  $p \leq 1$ . This is a well-known problem related to the  
 175 applicability of MOM (Utsu, 1961) and therefore Reasenberg and Jones (1989) equation for large  
 176 time after the mainshock. Gasperini and Lolli (2009) for a set of Italian and Californian sequences  
 177 with  $5.2 \leq M_m \leq 7.1$  have shown that, for a time period of the order of 4 years, equations with an  
 178 exponential decrease of the number of aftershock supply better results on real data than MOM.  
 179 However, for shorter time after the mainshock (1 year), the power law distribution holds (Lolli and  
 180 Gasperini, 2006). In this paper, I'll restrict the analysis to the domain of MOM applicability. In  
 181 order to have an estimate of the distribution of the fluctuation of the energy respect to its mean  
 182 value in time, I assumed that the ratio between energy and seismic moment is constant (e.g.  
 183 Kanamori 1977:  $E=M_0/2 \times 10^4$  erg). This relation assumes that the stress drop is constant and has  
 184 been debated in recent years. Recent papers (e.g. Malagnini et al. 2010, Gok et al 2009) show an  
 185 increase of stress drop with seismic moment, therefore Kanamori equation should be seen as a

186 simplified relation. If the Kanamori 1977 relation is wrong, the previous equations can be rewritten  
 187 in terms of seismic moment, where the term “energy” is substituted by “moment energy” defined as  
 188 the seismic moment divided by  $2 \times 10^4$ . For simplicity, in the following I will continue to refer it as  
 189 seismic energy. Using Kanamori 1977 equation, the summation of radiated energy is equivalent to  
 190 the summation of seismic moments. Zaliapin et al. (2005) showed that random fluctuations of the  
 191 sum of seismic moments are very large, because it is the sum of power law distributed variables, i.e.  
 192 heavy tailed random variables. A heavy tailed distribution is a distribution that assigns a non-  
 193 ignorable probability to extremely large observations. The approximation of the fluctuation of the  
 194 sum of seismic moments by a normal distribution is not justified (Zaliapin et al. 2005) and a large  
 195 number of summands are needed to yield reliable results (Kagan and Houston, 2005).  
 196 Kagan and Houston (2005) propose an equation for the seismic moment rate in the hypothesis that  
 197  $p=1$ :

$$198 \quad \dot{M} = \frac{k' \tau_{pk} \dot{M}_{pk}}{t + c'} \quad (15)$$

199 where  $c'$  is a coefficient similar to  $c$  but possibly with a different value,  $\dot{M}_{pk}$  is the peak moment  
 200 realize rate,  $\tau_{pk}$  is the time the peak occurs and  $k'$  is a constant. Assuming that the ratio between  
 201 energy and seismic moment is constant, equation (15) is compatible with (13) and (9) if  $c=c'$ .

202 Gentili and Bressan (2008), analyzing 8 seismic sequences in Northeastern Italy, found empirically  
 203 a linear relation between the value of  $\text{Log}_{10}(R_{ES})$  at the end of the seismic sequence ( $\text{Log}_{10}[R_{ES}(T)]$ )  
 204 and its value at a time  $\tau=24$  hours after the mainshock ( $\text{Log}_{10}[R_{ES}(24)]$ ). The relation holds also for  
 205 different time intervals after the mainshock; the time period of  $24^{\text{h}}$  was chosen as a compromise  
 206 between the stability of results (that needs large time intervals) and the need of an early estimate of  
 207  $R_{ES}$ . In particular, they found:

$$208 \quad \text{Log}_{10}[R_{ES}(T)] = D \cdot \text{Log}_{10}(R_{ES}(24)) - B \quad (16)$$

209 With  $D=0.78$ ,  $B=0.36$ ,  $\sigma(\text{Log}_{10}[R_{ES}(T)])=0.39$  and  $R^2=0.81$ . The error on the parameters  
210 (unpublished result) was high:  $\Delta D=\pm 0.4$  and  $\Delta B=\pm 1.1$ .

211 Comparing empirical equation (16) with analytical results of eq. (13), it can be seen that the  
212 parameter  $B$  it is not a constant, like in Gentili and Bressan paper, but it is a  $p$  and  $c$  dependent term.  
213 This caused the large uncertainty in  $B$  parameter estimation. A constant value of  $B$  could be possible  
214 if both  $p$  and  $c$  parameters were constant. The parameter  $p$  has been related with the surface heat  
215 flow (Mogi 1962, Kisslinger and Jones 1991, Marcellini 1995) or with the heterogeneity of the  
216 stress field (depending on the mainshock magnitude - Hainzl e Marsan 2008). The  $c$  parameter has  
217 been related to the magnitude of the static stress change after the mainshock (Dieterich 1994) or to  
218 the level of stress and seismogenic potential of the area (Shebalin et al 2011). A constant value of  $B$   
219 can be hypotized if the studied sequences are close enough in space, time and mainshock magnitude  
220 that the parameters are unchanged.

221 The equation proposed in this paper is therefore a refinement of Gentili and Bressan (2008)  
222 equation. The parameter  $D$  estimated by Gentili and Bressan as equal to  $0.8\pm 0.4$  is compatible with  
223 the value of 1 in eq. (13).

### 224 **3. Strongest aftershock magnitude**

225 Shcherbakov and Turcotte (2004) analyzed the partitioning of the released seismic energy between  
226 mainshock and aftershocks and its relation to  $\Delta m$ . They assumed that there is one only strongest  
227 aftershock in the seismic sequence and therefore the  $A$  and  $b$  parameters of the Gutenberg Richter  
228 equation are related one to the other:

$$229 \quad A=bM^* \tag{17}$$

230 where  $M^*$  is the magnitude of the strongest aftershock. With a method similar to the one used in  
231 this paper to obtain eq. (9), they found a relation between  $\Delta m$  and the ratio between the total energy  
232 radiated by the aftershocks  $E_{as}(T)$ , and the energy radiated by the mainshock  $E_m$ :

233 
$$\frac{E_{as}(T)}{E_m} = \frac{b}{\alpha - b} 10^{-\alpha \Delta m} \quad (18)$$

234 In particular, they obtained eq. (18) for  $\alpha=3/2$  in their paper. The equation was obtained considering  
 235 the whole real seismic sequence ( $m \leq M^*$ , completeness magnitude =  $-\infty$ ). If the completeness  
 236 magnitude is taken into account, equation (18) becomes:

237 
$$\frac{E_{as}(T)}{E_m} = \frac{b}{\alpha - b} 10^{-\alpha \Delta m} \left[ 1 - 10^{-(\alpha-b)(M^*-M_c)} \right] \quad (19)$$

238 That reduces to (18) for  $\alpha > b$  and  $M^* \gg M_c$ .

239 Gentili and Bressan (2008) rearranged the equation (18) in order to obtain a relation between of  $\Delta m$   
 240 and  $R_{ES}(T)$ :

241 
$$\Delta m = -\frac{1}{\alpha} \log_{10} \left[ \frac{E_{as}(T)}{E_m} \right] - \frac{1}{\alpha} \log_{10} \left( \frac{\alpha - b}{b} \right) = \frac{1}{\alpha} \log_{10} [R_{ES}(T)] + \frac{1}{\alpha} \log_{10} \left( \frac{b}{\alpha - b} \right) \quad (20)$$

242 The second addendum of the sum in equation (20) setting  $b \sim 1$  and  $\alpha=3/2$  (e.g. Utsu 2002) is  
 243 approximately 0.2. From eq. (20) it is possible to see that  $\Delta m$  decreases with increasing  $E_{as}/E_m$ , for  
 244  $b$ -term fixed, and decreasing  $b$ , if  $E_{as}/E_m$  is fixed.

245 Substituting eq. (13) into eq. (20) we have:

246 
$$\Delta m = \frac{1}{\alpha} \left[ \log_{10}(R_{ES}(\tau)) + \log_{10} \left( \frac{b}{\alpha - b} \right) - f(T, c, p, \tau) \right] \quad (21)$$

#### 247 ***4. Parameters dependence on the cutoff and mainshock magnitude***

248 The value of  $c$  parameter obtained by fitting MOM is widely debated. Kagan and Houston (2005)  
 249 proposed that  $c=0$  or negative, and that the measured  $c>0$  were due only to the underestimate of the  
 250 rate of the number of earthquakes immediately after the mainshock. This could be coherent with the  
 251 results of Lolli and Gasperini (2006) on 47 seismic sequences in Italy and California. They found  
 252 that, increasing the minimum magnitude considered,  $c$  tends to 0. However, detailed studies on the  
 253 seismicity after the mainshock (see e.g. Vidale et. al, 2003, Peng et al., 2007, Enescu et al., 2007)  
 254 could exclude this hypothesis at least for some sequences, also because if a value different from 0

255 was wrongly assigned to  $c$ , for  $t=c$  the percentage of lost event could be huge (e.g. 1/2 for  $p=1$ )  
256 (Utsu et al., 1995).

257 Shcherbakov et al. (2004) found a relation between  $c$  and the minimum considered magnitude  
258 (cutoff magnitude); a similar result was found by Kagan (2004) and Lippiello et al (2007).

259 All these papers agree on the fact that  $c$  evaluated from Omori law scales as:

$$260 \quad c = c_0 10^{\varphi(M_m - M_T)} \quad (22)$$

261 where  $\varphi$  is of the order of 1 and  $c_0$  is a constant or depends on the values of  $p$  and  $b$  of the sequence.

262 These results have been interpreted in different ways. Kagan claimed that the trend is an artifact due  
263 to the superposition of the waveforms for events close to the mainshock (the Short Term Aftershock  
264 Incompleteness hypothesis – Kagan, 2004). Gasperini and Lolli (2006) found a positive correlation  
265 between  $p$  and  $c$  for sequence analyses in Italy and New Zealand and imputed it to the under  
266 estimate of the number of earthquakes close to the mainshock. If, they say,  $c$  is overestimated due to  
267 lost earthquakes, this could slow the Omori law decay in the first times after the mainshock; to  
268 compensate this effect, the maximum likelihood test assigns a too high value of  $p$ .

269 On the other side, Nanjo et al. (2005, 2007) related it to a physical mechanism. In particular, in  
270 Nanjo et al. (2005) the trend of  $c$  has been explained in terms of damage mechanics; according with  
271 their paper,  $c$  is inversely proportional to the difference between the excess of stress induced by the  
272 mainshock and the yield stress, i.e. the stress above which the medium has no more an elastic  
273 behavior and there is a damage. Since it is reasonable that strongest aftershocks are connected with  
274 regions with higher stress variation,  $c$  should be inversely proportional to the aftershock magnitude.  
275 Lippiello et al (2007) evaluated the aftershock probability by a law that for long time after the  
276 mainshock coincides with Omori law, but that for short times has a logarithmic behavior, in which  $c$   
277 depends on the cutoff magnitude. They applied the law to the fit of a dataset proposed by Peng et al.  
278 2007, in which a careful high frequency filtering allowed the detection of a huge number of

279 aftershocks in Japan. The data appear to fit better this function than Omori law for short times after  
280 the mainshock.

281 Equation (22) has the important implication that for the same sequence, the choice of two different  
282 values of  $M_I$ ,  $M_{II}$  and  $M_{I2}$ , greatly affects the corresponding values  $c_1$  and  $c_2$  of  $c$ . Rearranging  
283 equation (22) I obtain:

$$284 \frac{c_1}{c_2} = 10^{\varphi(M_{I2}-M_{I1})} \quad (23)$$

285 This means, for example, that choosing  $M_{I2}=4$  instead of  $M_{II}=1$  we would obtain a  $\sim 1000$  times  
286 smaller value of  $c$ , if  $\varphi \sim 1$ .

287 The function  $f$  of equation (13) depends on the parameters  $t$ ,  $\tau$ ,  $c$  and  $p$ . While  $t$  and  $\tau$  terms are input  
288 terms of the fit, if the terms  $c$  and/or  $p$  depend on the selected cutoff magnitude, this causes a  
289 dependence also of  $f$  function and therefore of the radiated energy evolution. This means that the  
290 trend of the observed radiated energy during time depends on the selected cutoff magnitude.

291 Differently from  $c$ ,  $p$  was generally found to be independent on  $M_I$  (Utsu et al., 1995), which is  
292 equivalent to the fact that  $b$ -value of the Gutenberg and Richter law is constant throughout the  
293 aftershock activity (Utsu et al., 1995). On the other side, Ouillon and Sornette (2005) proposed a  
294 dependence of  $p$  on the mainshock magnitude  $M_m$  in their multifractal stress activation model. Their  
295 model is based on two hypotheses: rupture activation exponentially dependent by local stress and  
296 relaxation with long memory. They analyzed the California earthquake catalogue and stacked  
297 together sequences with mainshock within 0.5 magnitude units. They applied two different  
298 declustering approaches and found that  $p$  increases with magnitude by approximately 0.1-0.15 for  
299 each magnitude increase. The authors emphasize that this result can be obtained only by stacking  
300 together many sequences in order to average out the fluctuations. An analogous trend was found by  
301 Hainzl and Marsan (2008) applying many different declustering methods to the global earthquake  
302 catalog ISC. They explain this result in the framework of the rate and state friction model. The

303 values of  $p$  are occasionally significantly different between the two papers, probably due to the  
304 different catalogue and the different time intervals for fitting the decays (Hainzl and Marsan, 2008).

305

## 306 **5. Application to California**

307 The proposed method has been applied to a set of 9 Californian seismic sequences in the years  
308 1987-2003 with mainshock magnitude in the range [5.5, 7.3] (see Table 1).

309 <Insert Table 1 here>

310 The sequences were the same described in Shcherbakov and Turcotte (2004) with the exception of  
311 24 November 1987 Superstition Hills one, for which the presence of two closely spaced strong  
312 mainshocks, 12 hours one from the other, whose aftershocks are on different but close faults  
313 (Magistrale et al. 1989), causes problems in cluster definition.

314 For most aftershocks of the analyzed sequences neither the seismic moment nor the energy is  
315 determined, because they are too small. Therefore, I adopted the Southern California Seismic  
316 Network catalog ([http://www.data.scec.org/catalog\\_search/date\\_mag\\_loc.php](http://www.data.scec.org/catalog_search/date_mag_loc.php)) and the Northern  
317 California Seismic Network catalog (<http://www.ncedc.org/ncedc/catalog-search.html>) and,  
318 analogously to Kagan and Huston (2005) for smaller earthquakes, I assumed that the local  
319 magnitude in these catalogues is always equivalent to moment magnitude. Assuming that the ratio  
320 between seismic moment and energy is constant (or using “moment energy” instead of the real  
321 radiated energy – see section 2), I calculated the energy from eq. (5) with  $\alpha=3/2$ . The sequences  
322 have been selected using a space-time window. Similarly to Shcherbakov and Turcotte 2004, a  
323 circular space window has been chosen whose linear size  $L$  scales with the mainshock magnitude  
324  $M_m$ :  $L= 0.02 \times 10^{0.5 \cdot M_m}$  (Kagan, 2002) and a time window has been selected of 2 years for  $M < 7$   
325 mainshocks and of 3 years for larger Landers and Hector Mine earthquakes. The sequences were  
326 considered concluded at the end of the selected time interval because the contribution of eventual  
327 possible subsequent earthquakes was negligible respect to the overall aftershock energy. In addition,

328 an analysis on a too long time interval would exit from the domain of applicability of MOM  
329 equation and an exponential decrease of the number of earthquakes should have been taken into  
330 account (Lolli and Gasperini, 2006, Gasperini and Lolli, 2009). The completeness magnitude  $M_c$   
331 was obtained applying the EMR method (Woessner and Wiemer, 2005) by using Zmap (Wiemer,  
332 2001) software (see Table 1). It is important to remark that EMR method applied to the whole  
333 seismic sequence supplies an “overall sequence” completeness magnitude that does not take into  
334 account the fact that the completeness changes with time. Helmstetter et al. (2006) e.g., found the  
335 following relation for a set of California mainshocks:

$$336 \quad M_c(M_m, t) = M_m - 4.5 - 0.75 \text{Log}_{10}(t) \quad (24)$$

337 where  $t$  is the time (in days) after the mainshock. The change in completeness magnitude during  
338 time, accordingly with Kagan (2004), causes the change of the values of  $c$  obtained from Omori law  
339 fit.

340 In order to fit the data, a time  $\tau$  chosen for the analysis was 1 day, accordingly with Gentili and  
341 Bressan 2008.

342 Figure 2a-i shows the fit of the data using the new equation (eq. 13) proposed in this paper. For  
343 comparison, the curve obtained by using the parameters of the MOM fitting has been added (dotted  
344 lines).

345 <Insert Figure 2 here>

346 Thin continuous lines correspond to the real data; steps in the lines correspond to the large  
347 aftershocks that cause a sudden increase of the cumulative energy radiated by the aftershocks, and  
348 therefore a sudden decrease of  $R_{ES}(t)$ . Thick black lines correspond to the fit of the data. Deviations  
349 from the fit are due both to physical and computational causes. From the physical point of view, the  
350 inhomogeneity of the material in terms of rigidity, pre-existing fractures, stress distribution etc. can  
351 cause a delayed or advanced fracture of single patches. Brittle or fractured material is characterized  
352 by a smaller yield stress and fractures for smaller values of applied stress (e.g. Griffith, 1920); on



353 the other side, the stress itself is not homogeneous and some patches are characterized by higher  
 354 local stress. Das and Scholz (1981) proposed a model in which aftershock occur by static fatigue on  
 355 isolated locked fault patches, describing the evolution of earthquake nucleation in time as function  
 356 of both the medium characteristics and of the stress. From the computational point of view, the  
 357 assumptions of local magnitude equal to moment magnitude for all the earthquakes of the catalogue  
 358 and constant radiated energy/moment ratio (i.e. constant value of  $\alpha$ ) can cause over or under  
 359 estimates of the radiated energy. In addition, if the sum of seismic energy is considered equivalent  
 360 to the sum of seismic moments, large random fluctuations of this sum (see section 2) should be  
 361 considered.

362 The free parameters  $c$  and  $p$  are estimated using a maximum-likelihood estimate. One of the  
 363 problems in applying maximum likelihood method is defining the likelihood function to be  
 364 maximized. In particular, a model should be issued for the fluctuations of the independent variable.  
 365 The fluctuations of the cumulative energy are not normally distributed (see section 2). Zaliapin et al  
 366 (2005) propose the following pdf for the sum of seismic moments in the hypothesis that the  
 367 Gutenberg Richter parameter  $b \sim 1$ :

$$368 \quad g(x) = \frac{\sqrt{3}}{x\sqrt{\pi}} \exp\left(-\frac{16}{27x^2}\right) W_{\frac{1}{2}, \frac{1}{6}}\left(\frac{32}{27x^2}\right) \quad x > 0 \quad (25)$$

369 Where  $W$  is a Whittaker function (Abramowitz and Stegun, 1966), which can be calculated using  
 370 the confluent hypergeometric function  $U$  (Wolfram 1999):

$$371 \quad W_{\frac{1}{2}, \frac{1}{6}}(z) = \frac{z^{2/3} U\left(\frac{1}{6}, \frac{4}{3}, z\right)}{e^{z/2}}$$

372 In this paper, I assumed that the energy fluctuations pdf is the one of equation (25), that has a  
 373 maximum in  $x=1$ . The function to be maximized is therefore  $\text{Log}(g(X))$  with  $X = R_{ES} - f + 1$ .

374 The analysis has been performed for magnitude greater than the completeness magnitude shown in  
 375 Table 1. Table 2 shows the values of  $c$  and  $p$ , together with the values of  $R^2$  and RMSE for the fit of  
 376 the equation (13). I used a bootstrap method to calculate the uncertainties on  $p$  and  $c$  parameters.  
 377 Bootstrap sample radiated energy catalogues are generated by drawing with replacement an  
 378 equivalent amount of radiated energy from the original catalogue. For each of the bootstrap sample  
 379 energy catalogues,  $p$  and  $c$  are calculated. The standard deviation of the distributions of  $p$  and  $c$   
 380 values is defined as the uncertainty on the parameters. It is important to remark that this approach  
 381 does not take into account the fluctuations of  $R_{ES}(24)$ . It will be the topic of a future paper.

382 <Insert Table 2 here>

383 The value of  $c$  is always greater than 0 in all except one case. Most sequences show high value of  
 384  $R^2$  and small RMSE in the fit, confirming the good capability of eq. (13) in describing real data.

385 Figure 2j shows the values of  $f$  as a function of elapsed time from the mainshock at the  
 386 completeness magnitude. While most sequences are characterized by  $f$  ranging between 0.1 and 0.4,  
 387 in some cases  $f$  can reach larger values. Ridgecrest earthquake, e.g., shows a high value of  $f$  respect  
 388 to the other sequences, due to the small value of  $p$  (see eq. (14)). Such high value causes a strong  
 389 reduction of  $R_{ES}$  after the first day, i.e. a large relative productivity of aftershocks in terms both of  
 390 number of events and of radiated energy (see Section 2).

## 391 **5.1 Cutoff and mainshock magnitude dependence**

392 In order to understand if  $c$  dependence on  $M_m - M_I$  is the one of equation (23),  $M_I$  has been varied  
 393 between 1 and 5 for each sequence, with the constrain that at least 10 earthquakes were available for  
 394 the fit; the  $c$  value corresponding to the completeness magnitude,  $c_{M_c}$ , has been added to the data.

395 Setting  $M_{I2} = M_c$  and  $c_2 = c_{M_c}$ , equation (23) becomes:

$$396 \frac{c}{c_{M_c}} = 10^{\varphi(M_c - M_I)} \quad (26)$$

397 where  $c/c_{Mc}$  depends on the completeness magnitude of the analyzed sequence and on the cutoff  
398 magnitude adopted, while it does not depend neither on  $c_0$  nor on  $M_m$ . This allows to make a  
399 comparison also among different sequences. Figure 3a shows the values of  $c/c_{Mc}$  as a function of the  
400 difference between completeness the cutoff magnitude<sup>1</sup>. Different symbols correspond to different  
401 sequences.

402 <Insert Figure 3 here>

403 It is possible to see that choosing  $M_I$  within one magnitude unit from the completeness magnitude  
404 ( $M_c - M_I \in [-1, 1]$ ) the ratio  $c/c_{Mc}$  remains stable, close to 1. This result shows the robustness of  
405 the method, because the value of  $c$  remains stable also *below* the completeness magnitude.  
406 Therefore, possible fluctuations in completeness magnitude estimate due to different estimation  
407 method applied, do not affect the results. This is due to the low contribution of smaller earthquakes  
408 to the whole radiated energy. On the other side, increasing the cutoff magnitude ( $M_I > M_c + 1$  i.e.  $M_c -$   
409  $M_I < -1$ ),  $c$  increases, or decreases, or remains stable, depending on the sequence and does not have a  
410 defined trend; in particular,  $c$  ranges from 0 to 2.6 times the  $c_{Mc}$  at the completeness magnitude.

411 In order to understand a possible cause of the variability of  $c$  for  $M_c - M_I < -1$ , Fig. 3b shows  $c$  as a  
412 function of the number  $N$  of earthquakes considered for the fit. The  $N$  earthquakes used in the test  
413 are not chosen randomly, but are the ones corresponding to each cutoff magnitude of Fig. 3a. In this  
414 way, the smaller number of earthquakes is partially compensated by the fact that they are the larger,  
415 and therefore the more relevant for energy evaluation. The values of  $c$  are stable for  $N \geq 100$   
416 earthquakes ( $c/c_{Mc} \in [0.93, 1.15]$ ), while for smaller number of earthquakes the fluctuations are  
417 larger. In Fig. 3a the sequence symbols are marked in black if  $N \geq 100$ . I assume that  $c$  variability of  
418 Fig. 3a is not a physical effect, but it is due to large fluctuations in cumulative energy estimation  
419 previously described and to approximations due to the use of eq. (5). The values of  $c$  should be  
420 therefore independent on  $M_I$  and constant. In all except one case, the inferred  $c$  value is greater than

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<sup>1</sup> This approach cannot be applied for Baja California sequence for which  $c_{Mc}=0$ . However, since changing  $M_I$ , the value of  $c$  remains unchanged, for simplicity the ratio has been substituted by 1.

421 0, which confirms Utsu's thesis that at least in some cases,  $c$  value cannot be assumed always equal  
422 to 0.

423 In order to compare the previous results with classical parameter estimation methods, Figure 3c  
424 shows the value of  $c$  and  $p$  on the same sequences using the maximum likelihood procedure applied  
425 to the modified Omori formula as proposed by Ogata (1983) and implemented in Zmap software.  
426 The dispersion of  $c$  parameter is larger, ranging from  $10^{-3}$  to  $10^2$  times the value of  $c_{M_c}$ . Selecting  
427 only the cases in which  $M_I \geq M_c$  and  $N \geq 100$  (black symbols in Fig. 3c) a trend compatible with eq.  
428 (23) was found. In particular  $\phi=0.7$ . Figure 3d shows the normalized function  $c/[c_{M_c}10^{0.7(M_c-M_I)}]$ ,  
429 with the constrain  $M_I \geq M_c$ , as function of  $N$ . It can be seen that the MOM fit is extremely sensitive to  
430 the number of considered earthquakes, and if a small number of earthquakes is considered, the  
431 inferred values of the function range from  $10^{-1}$  to  $10^3$  times the values of the theoretical curve.  
432 Figure 3c shows that the method is sensitive also to the completeness magnitude, because below  
433  $M_c-M_I=0$  the data does not follow the straight line  $c/c_{M_c} = 10^{0.7(M_c-M_I)}$ .  
434 Accordingly with Kagan (2004) the dependence of  $c$  on  $M_I$  parameter is an artifact in Omori law  
435 fitting, due to the loose of data for times close to the mainshock (see eq. 24). The fact that a  
436 different approach to  $c$  value estimation finds constant values of  $c$  supports Kagan's thesis.  
437 Figure 4a and b show the normalized value of  $p$  as a function of  $M_c-M_I$  and of  $N$ , respectively,  
438 applying the method proposed in this paper.

439 <Insert Figure 4 here>

440 Also in this case, no relation was found between the parameter and  $M_c-M_I$ . An instability of the  
441 results was detected for  $N < 100$ . In this case, however, the result is much more stable;  $p$  ranges from  
442 0.8 to 1.2 times the value of  $p$  at the completeness magnitude ( $p_{M_c}$ ), while if only the cases  $N \geq 100$  is  
443 considered, it ranges between 0.99 and 1.04  $p_{M_c}$ . Figure 4c and d show the normalized value of  $p$  as  
444 a function of  $M_c-M_I$  and of  $N$ , respectively, applying the modified Omori formula as proposed by  
445 Ogata (1983) and implemented in Zmap software. It can be seen that the range of variation of  $p$  is

446 larger than in the energy-based evaluation, ranging from 0.6 to 3.2 times the value at the  
 447 completeness magnitude if all values of  $N$  and  $M_I$  are considered, that reduces to [0.9-1.8]  $p_{M_c}$  if  
 448 only  $M_I \geq M_c$  and  $N > 100$  is considered. The approach proposed in this paper for  $p$  value estimation is  
 449 therefore more stable. It is important to remark that while the method is more stable for a single  
 450 sequence, it is however dependent also on the fluctuations of the energy of the strongest  
 451 earthquakes before  $\tau$ , that affect  $R_{ES}(\tau)$ , especially if  $\tau$  is small; it is therefore not necessary more  
 452 stable for multiple repeats of the same sequence. This problem could be solved by a smoothing of  
 453 the data and will be topic of a future paper.

454 In order to investigate the stability of the parameters using energy based approach for different  
 455 values of  $\tau$ , Figure 5 shows the comparison among the values of  $c/c_{M_c}$  and  $p/p_{M_c}$  for  $\tau$  equal to 12,  
 456 24 and 48 hours, as function of  $N$ .

457 <Insert Figure 5 here>

458 From the figure it can be seen that the parameters remain stable in all the cases for  $N \geq 100$ , while for  
 459  $N < 100$  larger values of  $\tau$  supply more stable results. The quality of the fit generally decreases, with  
 460 decreasing of the time  $\tau$ . For  $\tau$  equal 1 hour, for example, the quality of the fit is so poor that  $R^2$  is  
 461 close to 0 for most sequences. This is probably related to fact that the cumulative energy is less  
 462 smoothed when a smaller number of events is involved. Abrupt changes of radiated energy,  
 463 corresponding to larger aftershocks immediately after the mainshock, cause large fluctuations of  
 464  $R_{ES}(\tau)$  if  $\tau$  is small. In order to state that the variables  $\log_{10}(c/c_{M_c})$  calculated with energy-based  
 465 approach (Fig. 3a) and  $M_c - M_I$  are uncorrelated, I computed the linear correlation coefficient  $R$  and  
 466 estimated its statistical significance (see e.g. Davis, 1986). I used only the data with  $N \geq 100$  and  
 467  $c_{M_c} \neq 0$ . The null hypothesis  $H_0$  is that  $R=0$ , the alternative is that  $R \neq 0$ . I compared the two  
 468 hypotheses by using the Student-t statistics:

$$469 \quad t = \sqrt{\frac{R^2 (n-2)}{1-R^2}} \quad (27)$$

470 Where  $n$  is the number of samples. If  $t$  is greater than a threshold (available on statistical tables),  
471 corresponding to a significance level of 0.05 for degrees of freedom  $n-2$ , the existence of correlation  
472 can be asserted at a significance level of 0.05; conversely, for smaller values of  $t$ , the hypothesis  $H_0$   
473 cannot be rejected, and the two variables are uncorrelated at a significance level of 0.05. Table 3  
474 shows the values of  $R$  and  $t$  for the two variables.

475 <Insert Table 3 here>

476 From Student-t test the two variables result uncorrelated. Since eq. (26) fails in describing the real  
477 data, when the influence of artifacts due to the loss of small magnitude aftershocks is reduced, this  
478 implies a failure also of equations (22) and (23), of which eq. (26) is a consequence.

479 Table 3 shows the correlation coefficient  $R$  and the value of  $t$  for  $p/p_{Mc}$  vs.  $M_c-M_I$  too. From  
480 Student-t test the two variables appear uncorrelated.

481 The independence of  $c$  and  $p$  on  $M_I$  implies that also  $f$  is independent. Figure 2j should be regarded  
482 as the real value of  $f$ , regardless of the cutoff magnitude applied.  $R_{ES}$  depends on both  $R_{ES}(\tau)$  and  $f$ .  
483  $R_{ES}(\tau)$  increases with increasing cutoff magnitude  $M_I$ , because  $E_m$  remains unchanged, while  $E_{as}$   
484 decreases, if smaller earthquakes are eliminated. The trend of  $\text{Log}(R_{ES}(t))$  is however independent  
485 on  $M_I$ , except for a shift, which depends on  $\text{Log}(R_{ES}(\tau))$  value. This result is unsurprising, since for  
486 the Gutenberg Richter equation the trend of radiated energy should be independent (except for a  
487 shift) on the selected cutoff magnitude.

488 In order to analyze the  $p$  parameter dependence on  $M_m$ , I divided the classes of seismicity at steps of  
489 0.5 magnitude units and I calculated the mean and the standard deviation of the value of  $p$  inferred  
490 with the method proposed in this paper. Figure 6 shows the results together with their fit. For  
491 comparison, the fit for one declustering technique of Ouillon and Sornette (2005) and one of Hainzl  
492 and Marsan (2008) data has been added.

493 <Insert Figure 6 here>

494 Accordingly with this paper data,  $p$  increases with magnitude by 0.20 for each magnitude increase,  
495 and the value of  $R^2$  is 0.73. The results can be compared only qualitatively, due to the poor statistics  
496 of this paper results for  $M > 6$ . The analysis by using the Student-t statistics confirms a positive  
497 correlation of the two variables with a significance level of 0.05 (see Table 3). A direct analysis  
498 using the  $p$  values of all the sequences, without supplying a mean value, gives a positive correlation  
499 only increasing the significance level to 0.15. This confirms, in the limits of the small statistics used,  
500 the assertion of Ouillon and Sornette (2005) that the correlation can be found considering together  
501 several sequences, while it is generally not true for the single sequence.

502 The  $c$  parameter shows a not relevant dependence on  $M_m$ , with a large scatter of the parameter (see  
503 Table 3).

504 A last test has been done to verify if the positive correlation between  $p$  and  $c$  parameters found by  
505 Gasperini and Lolli (2006) for Italy and New Zealand could be found also applying energy based  
506 method. The values of  $R$  and  $t$  are shown in Table 3. The two variables are not correlated, because  
507 of the different method adopted in their estimation. This supports Gasperini and Lolli (2006) thesis  
508 that the correlation was due to the wrong estimate of  $c$ .

## 509 **5.2 Strongest aftershock magnitude estimation**

510 Table 4 shows the values of the 3 terms of equation (21) for the analyzed sequences for  $M_I = M_c$ . For  
511 comparison, also the value of  $\text{Log}_{10}[R_{ES}(T)]$  at the end of the sequence has been added in the last  
512 column. The  $b$ -dependent term has been calculated setting  $\alpha = 3/2$  (Gutenberg and Richter, 1956) and  
513 using  $b$  values listed Shcherbakov and Turcotte (2004), with the exception of San Simeon value  
514 ( $b = 1.17 \pm 0.09$ ), that was calculated manually using Zmap software, because in Shcherbakov and  
515 Turcotte (2004) paper only 100 days of the sequence were available. The last rows show the mean  
516 and the standard deviation of each column. The 6<sup>th</sup> column shows the value of  $\Delta m$  (theoretical)  
517 deduced applying equation (21).

518 <Insert Table 4 here>

519 The mean theoretical and the real value of  $\Delta m$  are similar and close to the value of 1.2 of the Båth  
520 law and the standard deviation is 0.4. The mean of the difference between the true value of  $\Delta m$  and  
521 the theoretical one (obtained from eq. 21) is 0.1 and its standard deviation is 0.1, compatible with a  
522 magnitude assessment accuracy of 0.1. The mean value of  $f$  and its standard deviation,  $0.37 \pm 0.37$ , is  
523 similar to the result found by Gentili and Bressan (2008) ( $B=0.36 \pm 1.1$ ), with a smaller standard  
524 deviation.

525 <Insert Figure 7 here>

526 The reason why Gentili and Bressan (2008) found a good correlation between  $\text{Log}_{10}[R_{ES}(T)]$  and  
527  $\text{Log}_{10}[R_{ES}(24)]$ , even if the  $c$  and  $p$  parameters changed from one sequence to the other, is that  $f$  is  
528 generally lower than  $\text{Log}_{10}[R_{ES}(24)]$  (see Table 4), or, in other words, that most of the sequence  
529 energy is radiated in the first 24 hours. Making the same fit of Gentili and Bressan (2008) on  
530 Californian data (see Fig. 7) I found  $D=1.0 \pm 0.4$  and  $B=-0.2 \pm 0.7$ , compatible with both Gentili and  
531 Bressan result and the value of  $f$  found in this paper. Even if the value of  $R^2$  is high, Whittier  
532 Narrows and Ridgecrest sequences (shown by an arrow in Fig. 7), have values of  $R_{ES}(T)$   
533 anomalously low respect to the best fit line. This anomaly is due to the high value of  $f$  that in these  
534 cases reaches the 50% and the 70% of the value of  $\text{Log}_{10}[R_{ES}(24)]$ , respectively (see Table 4). This  
535 is due to two different reasons: Whittier Narrows is characterized by a high value of  $c$ ; this means  
536 that the onset of the power law decay is later than in other sequences and therefore there is a high  
537 frequency of earthquakes (high radiated energy) also after the first day. Ridgecrest, vice-versa, is  
538 characterized by a very low value of  $p$ . This means that the frequency of the earthquakes (radiated  
539 energy) decreases slowly and therefore it is still high after the first day.

540 <Insert Figure 8 here>

541 Figure 8a-c shows the ratio between of each term of eq. (21) and their sum. Note that, since  $f$  is  
542 positive (see Fig 3j), the term  $-f$  is negative and therefore the ratio can be greater than 1 and smaller  
543 than -1. Figure 8a shows the ratio for the  $R_{ES}(24)$  dependent term. The ratio is generally close to 1



544 (mean 1.18, standard deviation 0.51) except in the cases of the abovementioned sequences 1 and 6  
545 (Whittier Narrows and Ridgecrest), corresponding to high negative values of  $-f$  term (see Fig. 8b);  
546 the  $-f$  term has a generally smaller ratio (mean -0.37, standard deviation 0.54); the  $b$ -dependent term  
547 (see Fig. 8c) has less variable ratio (mean 0.19, standard deviation 0.12).

548 Figure 8d shows, for each sequence, the absolute value of the 3 terms of eq. (21) divided by the sum  
549  $\Sigma$  of their absolute values. From the figure, it is possible to see that the energy dependent term  
550 absolute value is preponderant being always greater than 50% with mean approximately the 70%;  
551 this is true both for the sequences in which the strongest aftershock is within the first 24<sup>h</sup>, and for  
552 the ones (Whittier Narrows, Ridgecrest and Baja California) for which the strongest aftershock  
553 occurs later. The  $b$  and  $f$  dependent terms have similar contributions, with high variability from one  
554 sequence to the other, with a slightly larger contribution of  $f$ . In Table 4, it is interesting to notice  
555 also the differences between Ridgecrest and Hector Mine sequences. The two sequences have  
556 similar values of both the energy and the  $b$  dependent terms (see Table 4). The differences of  $\Delta m$   
557 are due to the  $f$  term. The huge value of  $f$  (Table 4, 7<sup>th</sup> row) of the Ridgecrest sequence respect to the  
558 other is due to a small value of  $p$  (Table 2 row 7 and discussion in section 2). It is therefore a  
559 difference in  $p$  and not in  $b$  that drives a large difference in  $\Delta m$ .

## 560 **6. Conclusions**

561 In this paper, a new temporal description of seismic sequences in terms of  $R_{ES}(t)$  ratio has been  
562 shown. In particular, the analytical description of  $R_{ES}(t)$  as function of  $R_{ES}(\tau)$  with  $\tau < t$  and of  
563  $f(t, c, p, \tau)$  (equation 13) has been proposed.

564 In the following, the main results obtained in this paper are listed and described.

565 1. **Real data description.** The equation (13) has been applied to 9 seismic sequences in  
566 California. Real data are characterized by sudden steps in  $R_{ES}(t)$ , which cause deviations  
567 from the fit line and are due both to physical and to computational causes (see section 5).

568 However, most sequences show high value of  $R^2$  and small RMSE in the fit, confirming the  
569 good capability of eq. (13) in describing real data.

570 2. **Comparison with relations in literature.** The data are generally compatible with an  
571 empirical relation proposed by Gentili and Bressan (2008) relating  $R_{ES}(T)$  and  $R_{ES}(\tau)$  where  
572  $T$  is the time of the end of the sequence and  $\tau = 24^h$ . However, the proposed equation (13)  
573 should be considered an improvement in radiated energy trend description, because a  
574 constant term in Gentili and Bressan (2008) equation is replaced by a  $p$  and  $c$  dependent  
575 one, that explains deviations from the fit of Gentili and Bressan (2008) equation (see Fig. 7).  
576 In addition, eq. (13) is compatible with Kagan and Houston (2005) equation for seismic  
577 moment rate (eq. (16) in this paper) if  $c=c'$ .

578 3. **Parameter estimation:  $c$ .** The description of  $f$  in terms of  $c$  and  $p$  allows to perform an  
579 estimate of the two parameters that is alternative to the MOM fitting. The problem of  $c$   
580 estimation arises from the fact that the frequency of earthquakes in the MOM depends on  $c$   
581 only for short times after the mainshock, when it is more difficult detecting the earthquakes;  
582 therefore the inferred  $c$  is often interpreted, at least partially, as an artifact (Kagan, 2004,  
583 Lolli and Gasperini, 2006, Utsu et al 1995), due to the fitting of incomplete data for times  
584 close to the mainshock. Equation (13) of this paper allows to circumvent the problems  
585 connected with MOM fitting, because this approach is less sensitive to variation in  
586 completeness magnitude (strongest earthquakes influence more the overall radiated energy  
587 than the smaller ones) and  $f$  is sensitive to the value of  $c$  for longer times. The values of  $c$   
588 obtained by applying equation (13) to 9 Californian sequences, show no dependence on the  
589 cutoff magnitude  $M_I$ , confirming the Kagan (2004) thesis that the dependence of  $c$  on  $M_I$   
590 ( $c = c_0 10^{\varphi(M_m - M_I)}$ ) is an artifact. On the other side, in all except one case, the inferred  $c$   
591 value is greater than 0, in accordance with Utsu et al. (1995). If these results will be  
592 confirmed on a larger database, they will invalidate the Nanjo et al. (2005) thesis that the  $c$

593 parameter varies in space and is proportional to the local difference between yield stress and  
594 excess stress induced by the mainshock. The obtained values of  $c \geq 0$  are compatible with  
595 both the Dieterich (2004) physical model, that predicts an initially constant aftershock rate  
596 before the rate begins to decay as a power law with time, and with Shebalin (2011) model,  
597 that inversely relates the  $c$  value and the seismogenic potential of the area.

598 4. **Parameters estimation:  $p$ .** An increase of  $p$  with  $M_m$  have been found by binning the  
599 magnitude  $M_m$  axis and evaluating the mean of  $p$ ; in particular, a positive correlation has  
600 been observed at a significance level of 0.05. This is compatible both with Ouillon and  
601 Sornette (2005) multifractal activation model and with Hainzl and Marsan (2008) treatment,  
602 based on rate and state model. No correlation was found between  $p$  and  $c$  parameters. This is  
603 unsurprising, because accordingly with Gasperini and Lolli (2006) it was an artifact, due to  
604 the wrong fitting of the  $c$  parameter of using MOM.

605 5. **New relation for  $\Delta m$ .** A new equation (eq. 21) has been proposed, that describes the  
606 difference  $\Delta m$  between the mainshock and the strongest aftershock earthquake energy as  
607 function the sum of three terms: one depending on  $R_{ES}(\tau)$ , one on the  $b$  parameter of the  
608 Gutenberg Richter equation and one on  $f(\tau)$ . The mean estimated values of  $\Delta m$  using  
609 equation (21) and the real one are similar and close to the value of 1.2 of the Båth law. An  
610 analysis has been performed to understand which term of equation (21) is the more relevant  
611 for the value of  $\Delta m$  if  $\tau=1$  day. It emerges that the contribution of the energy dependent term  
612 is preponderant, being always greater than 50% of the sum of the tree terms absolute values,  
613 with mean approximately the 70%; this is true both for the sequences in which the strongest  
614 aftershock is within the first 24<sup>h</sup>, and for the ones (Whittier Narrows, Ridgecrest and Baja  
615 California) for which the strongest aftershock is after.

616

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620

621 ***References***

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623 Standards Applied Mathematics Series 55). National Bureau of Standards, Washington, D.C..

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734 **Figure captions**

735 **Figure 1:** The trend of  $f$  for  $c=0.1$ ,  $\tau=1$  day and  $p=1.1$ ,  $p=0.9$ ,  $p=1$ . The asymptote for  $p=1.1$  is also  
736 shown.

737

738 **Figure 2:** (a-i)  $R_{ES}(t)$  vs. time (in days) for 9 Californian seismic sequences: (a) Whittier Narrows,  
739 (b) Upland (c) Sierra Madre (d) Landers (e) Northridge (f) Ridgecrest (g) Hector Mine (h) Baja  
740 California (g) San Simeon. Thin line: real data. Thick line: maximum likelihood fit. Dotted line:  
741 Parameters from MOM fit. (j)  $f$  as a function of time for the seismic sequences.

742

743 **Figure 3:** (a)  $c/c_{Mc}$ , calculated by using the energy based approach, as a function of  $M_c-M_I$ ; the  
744 symbols marked in black correspond to  $N \geq 100$ . (b)  $c/c_{Mc}$ , calculated by using the energy based  
745 approach, as a function of the number  $N$  of earthquakes. (c)  $c/c_{Mc}$ , calculated by using Omori law, as  
746 a function of  $M_c-M_I$ ; the symbols marked in black correspond to  $N \geq 100$  and  $M_I \geq M_c$ . (d)  
747  $c/[c_{Mc}10^{0.7(M_c-M_I)}]$  calculated by using Omori law, with the constrain  $M_I \geq M_c$ , as a function of the  
748 number of earthquakes.

749

750 **Figure 4:** (a)  $p/p_{Mc}$ , calculated by using the energy based approach, as a function of  $M_c-M_I$ ; the  
751 symbols marked in black correspond to  $N \geq 100$ . (b)  $p/p_{Mc}$ , calculated by using the energy based  
752 approach, as a function of the number of earthquakes. (c)  $p/p_{Mc}$ , calculated by using Omori law, as a  
753 function of  $M_c-M_I$ ; the symbols marked in black correspond to  $N \geq 100$  and  $M_I \geq M_c$ . (d)  $p/p_{Mc}$ ,  
754 calculated by using Omori law, with the constrain  $M_I \geq M_c$ , as a function of the number of  
755 earthquakes.

756

757 **Figure 5:**  $c/c_{Mc}$  as function of  $N$  using different values of  $\tau$ . Circles:  $\tau=1$  day. Squares:  $\tau=0.5$  days.  
758 Diamonds:  $\tau=2$  days.

759

760 **Figure 6:** Mean of  $p$  as function of  $M_m$ . Thick dashed line corresponds to the minimum squares fit  
761 of the data. Two of the fitting line proposed by Ouillon and Sornette (2005) (O&S – dotted line) and  
762 Hainzl and Marsan (2008) (H&M – dot-dashed line) are shown.

763

764 **Figure 7:**  $\text{Log}_{10}[R_{ES}(T)]$  vs.  $\text{Log}_{10}[R_{ES}(24)]$  for the 9 sequence analyzed. Sequences with  
765  $\text{Log}_{10}[R_{ES}(T)]$  far from the fit line are shown with an arrow.

766

767 **Figure 8:** (a-c) Ratio between of each term of eq. (21) and their sum. (d) Absolute value of the 3  
768 terms of eq. (21) divided by the sum of their absolute values. Each number corresponds to a  
769 different sequence as listed in Table 1.

770 **Table captions**

771 **Table 1:** Main characteristics of the analyzed sequences.  $N$ : sequence number; *Main date*:  
772 mainshock date (UTC). *Lat* and *Lon*: north latitude and east longitude of the main shock (degrees);  
773  $M_m$ : mainshock local magnitude;  $M_c$ : sequence completeness magnitude;  $M_a$ : strongest aftershock  
774 local magnitude; *Aft date*: strongest aftershock date (UTC).

775

776 **Table 2:** Parameters of the analyzed sequences.  $N$ : sequence number;  $p$  and  $c$ :  $p$  and  $c$  parameters of  
777 the Modified Omori Law; RMSE: Root Mean Square Error of the fit;  $R^2$ : coefficient of  
778 determination.

779

780 **Table 3:** Correlation analysis between different parameters.  $R$ : correlation coefficient;  $t$ : value of t-  
781 Student statistics for the null hypothesis of no correlation.  $p$ ,  $M_m$  (3 points): correlation obtained  
782 between  $p$  mediated over all sequences with mainshock magnitude  $M_m$  inside 0.5 magnitude bin and  
783  $M_m$ ; (9 points): correlation between  $p$  and  $M_m$ .

784

785 **Table 4:** Equations (13) and (21) parameters.  $N$ : sequence number; Theoretical  $\Delta m$ : difference  
786 between mainshock and strongest aftershock magnitude obtained applying evaluated parameters to  
787 equation (21). Real  $\Delta m$ : real difference.

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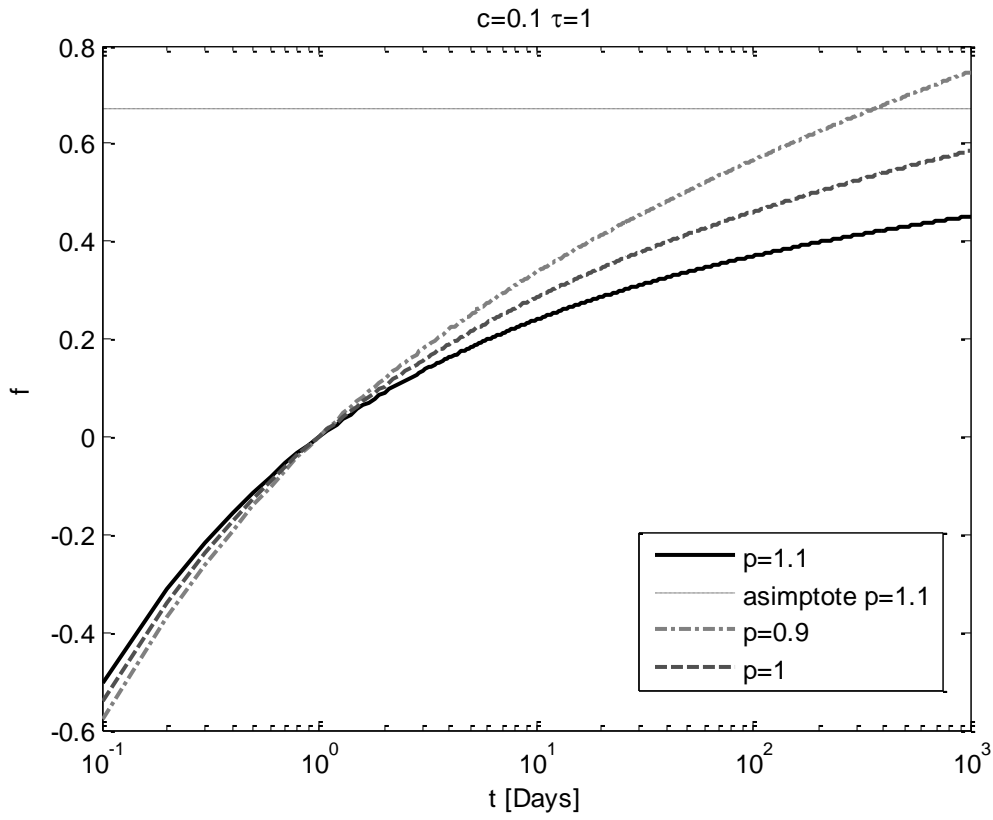
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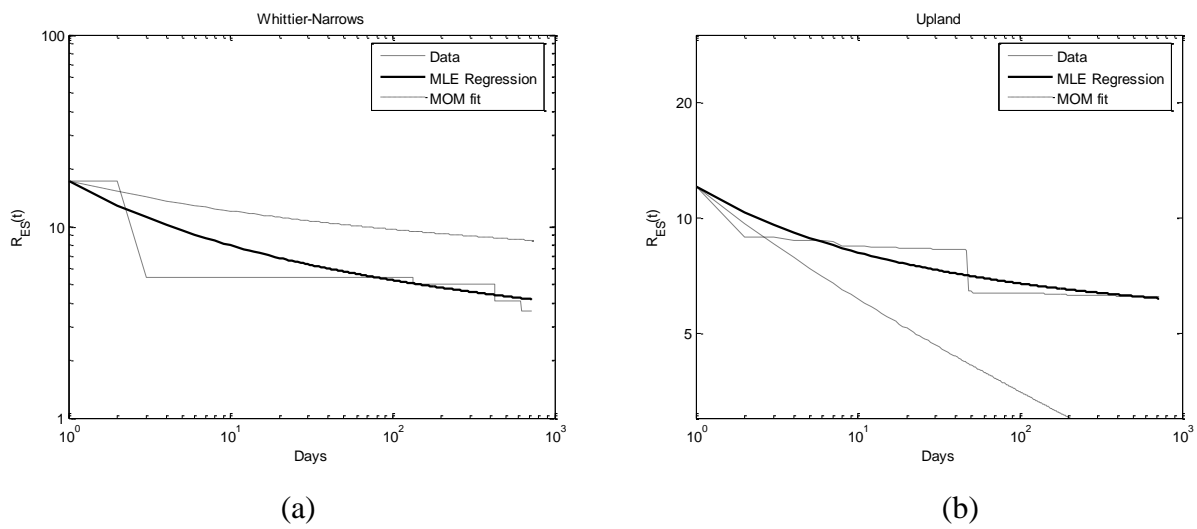
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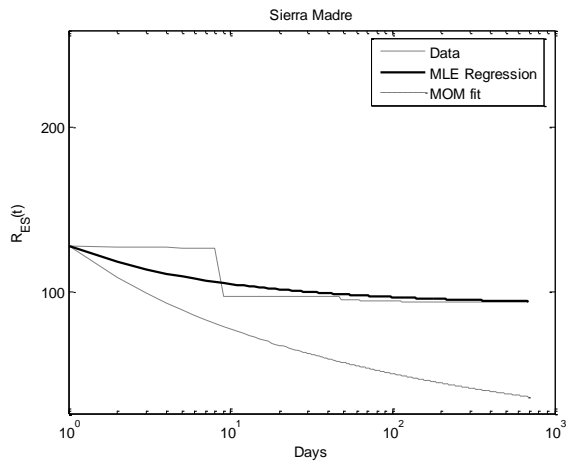


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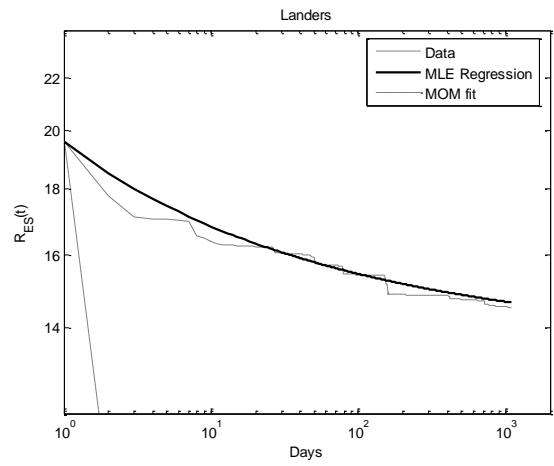
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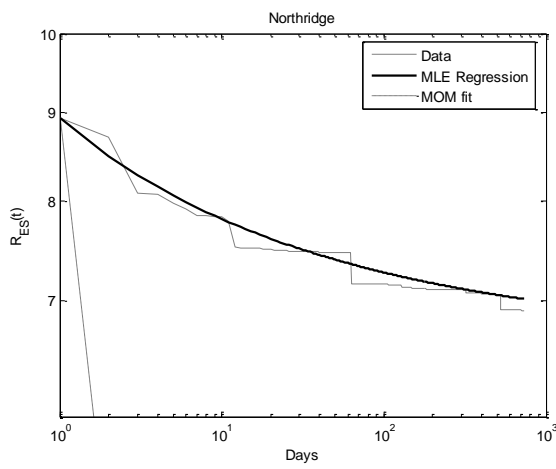
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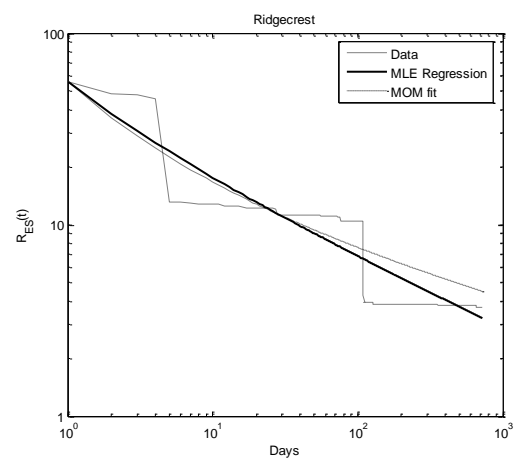
(c)



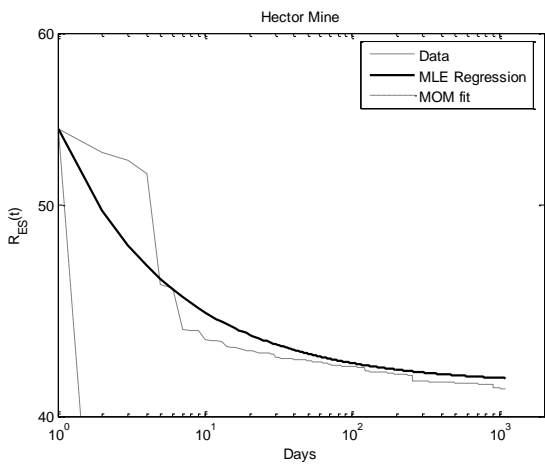
(d)



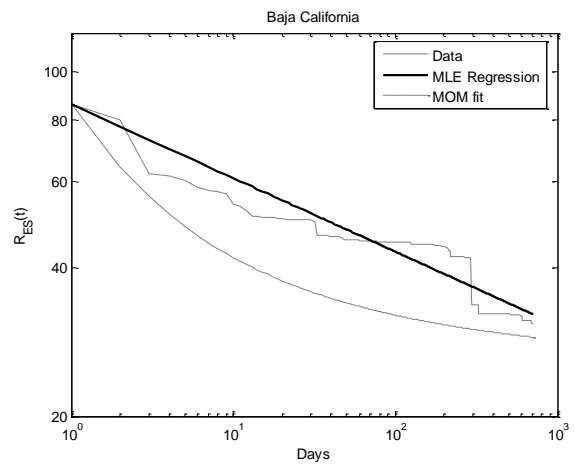
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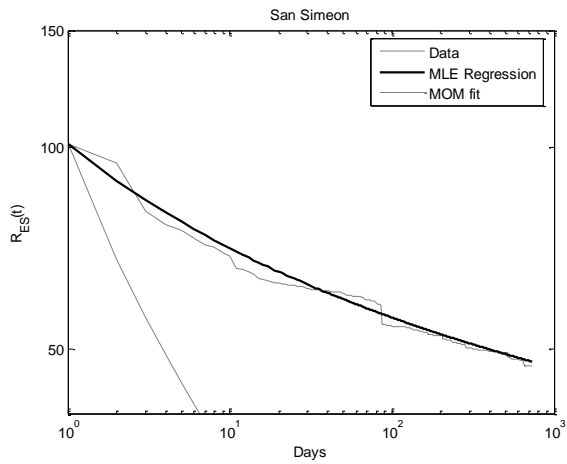
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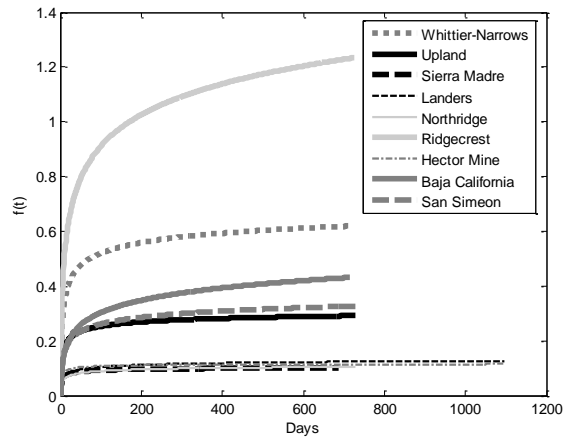
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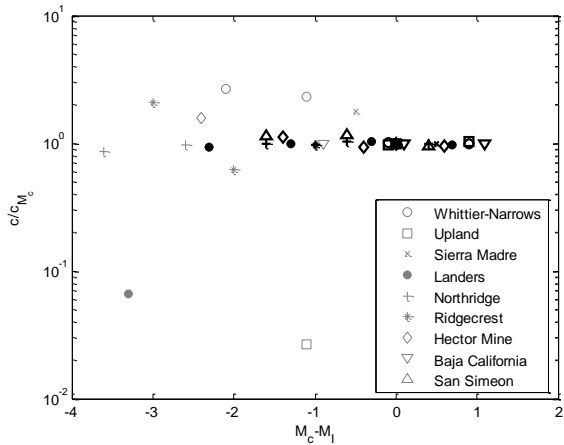


(i)

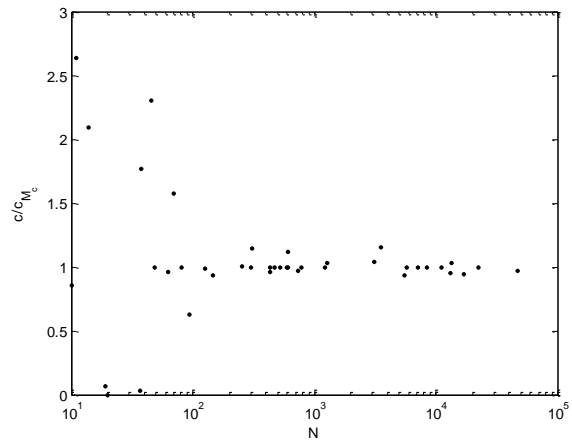


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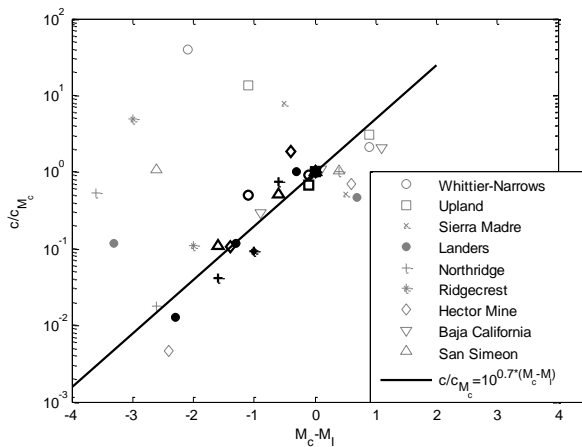
Fig. 2



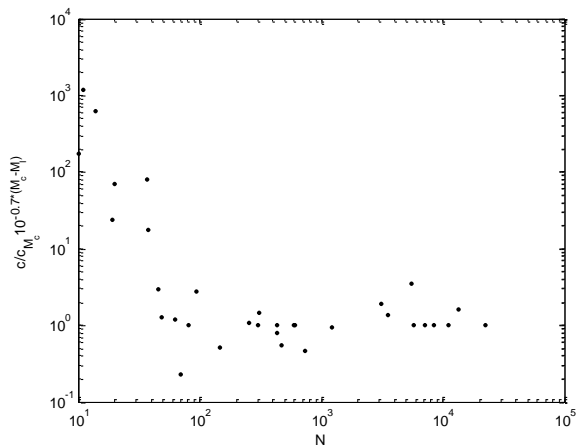
(a)



(b)



(c)



(d)

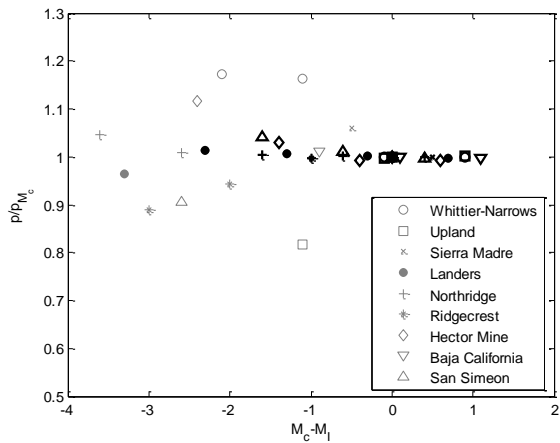
Fig. 3

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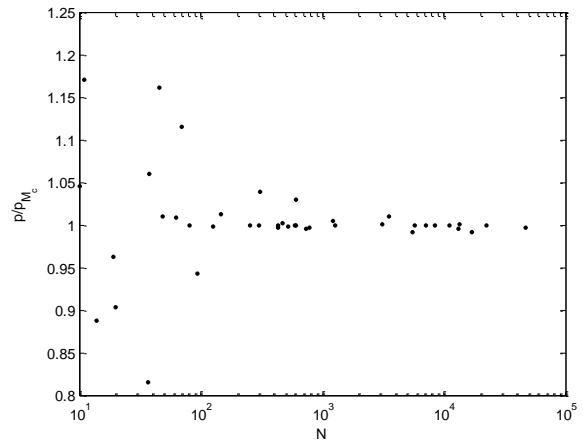
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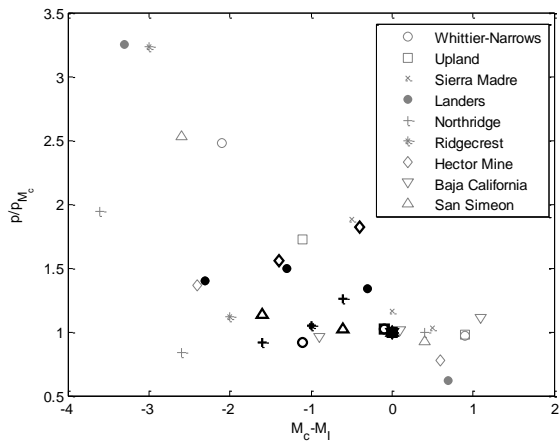
(a)



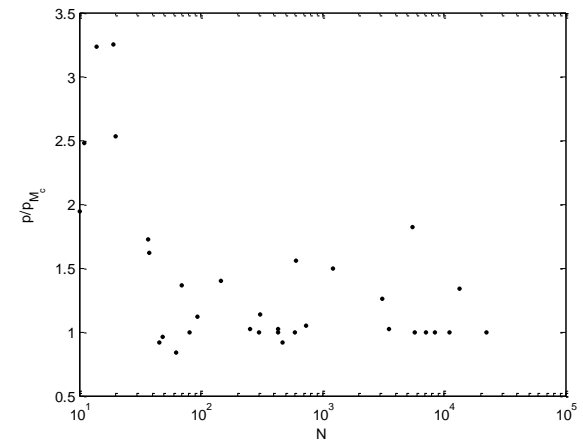
(b)

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(d)

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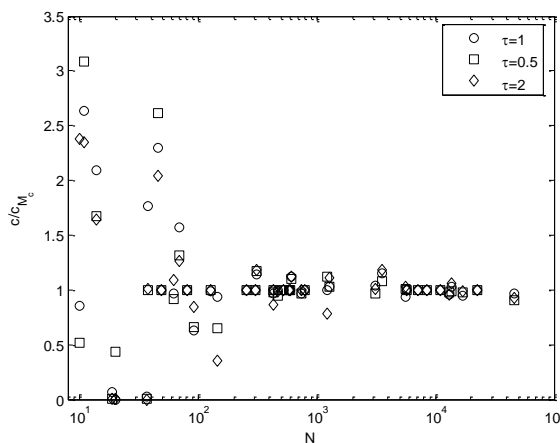
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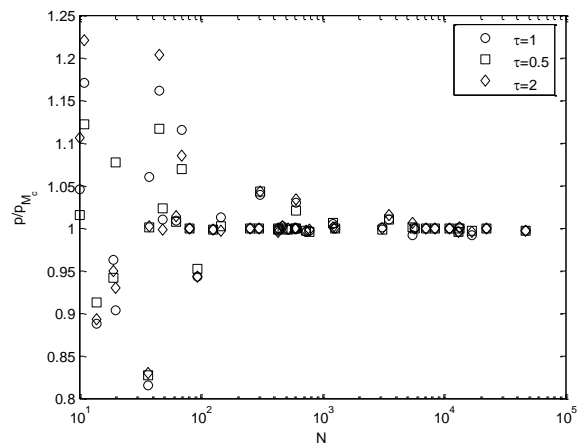
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Fig. 4



(a)



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Fig. 5

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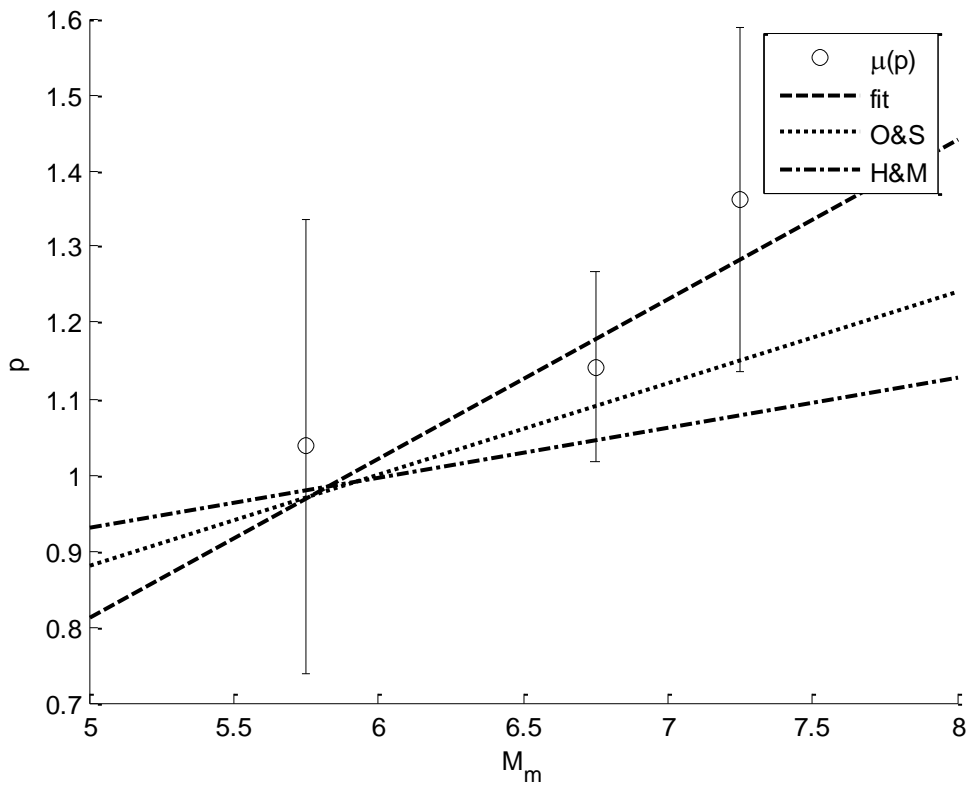


Fig. 6

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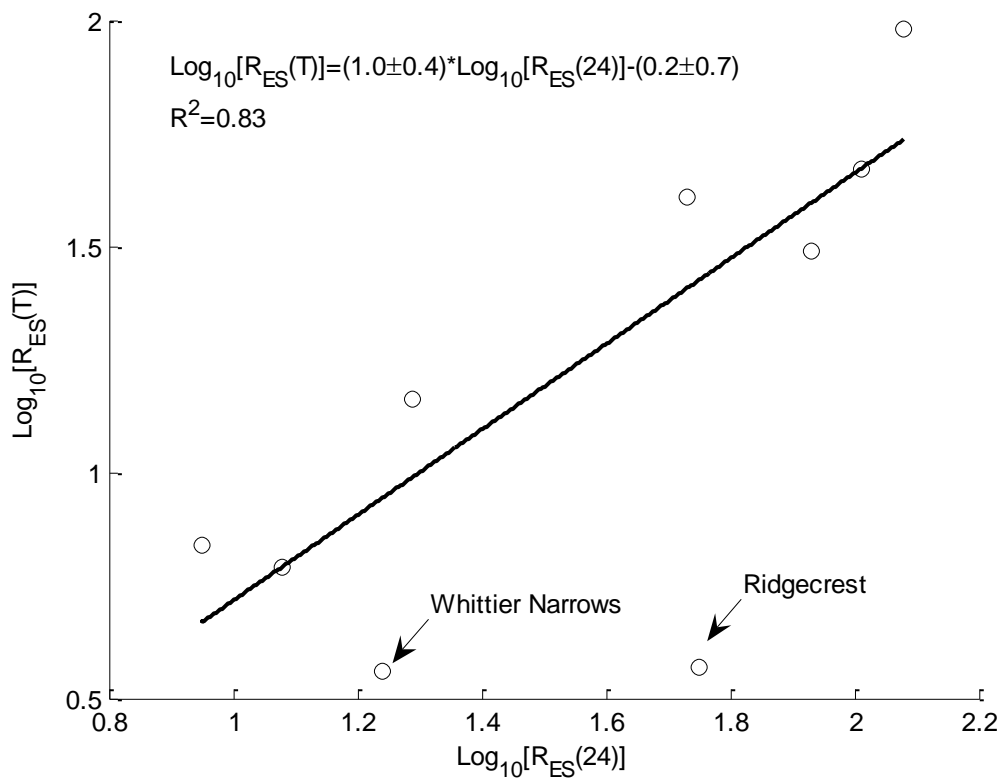
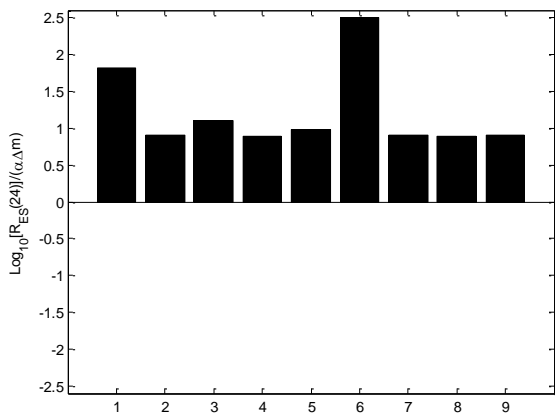
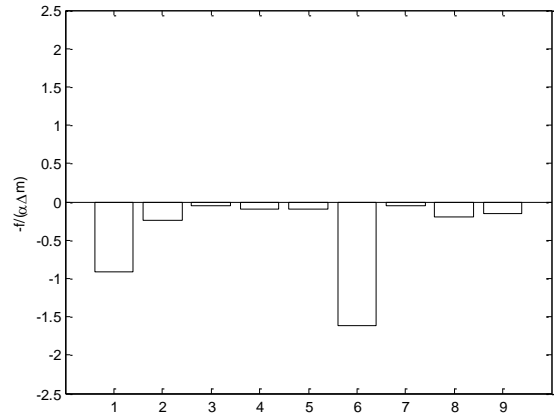


Fig. 7

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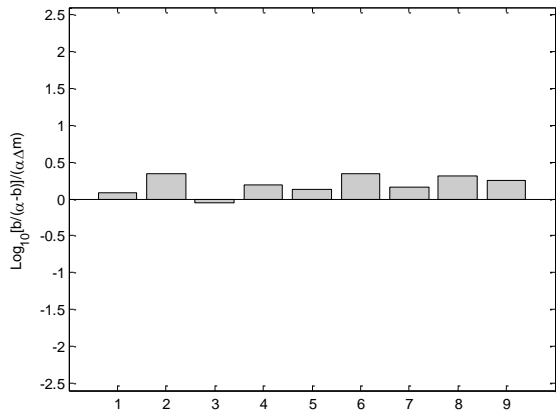


(a)

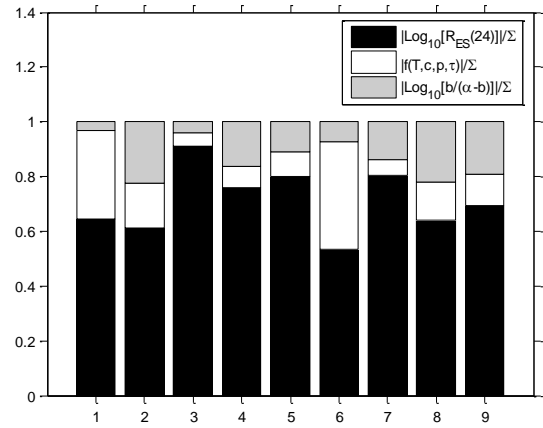


(b)

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(c)



(d)

Fig. 8

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**Tables**

N	Sequence	Main date yyyy/mm/dd	Lat	Lon	M <sub>m</sub>	M <sub>c</sub>	M <sub>a</sub>	Aft date yyyy/mm/dd
1	Whittier Narrows	1987/10/01	34.061	-118.079	5.9	1.9±0.1	5.3	1987/10/04
2	Upland	1990/02/28	34.144	-117.697	5.5	1.9±0.08	4.7	1990/03/01
3	Sierra Madre	1991/06/28	34.270	-117.993	5.8	1.5±0.3	4.3	1991/06/28
4	Landers	1992/06/28	34.200	-116.437	7.3	1.7±0.06	6.3	1992/06/28
5	Northridge	1994/01/17	34.213	-118.537	6.7	1.4±0.1	5.9	1994/01/17
6	Ridgecrest	1995/09/20	35.761	-117.638	5.8	1.00±0.05	5.2	1996/01/07
7	Hector Mine	1999/10/16	34.594	-116.271	7.1	1.6±0.11	5.8	1999/10/16
8	Baja California	2002/02/22	32.319	-115.322	5.7	2.1±0.1	4.2	2002/12/12
9	San Simeon	2003/12/22	35.709	-121.104	6.5	1.4±0.03	4.7	2003/12/22

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Table 1

N	Sequence	p	c	R <sup>2</sup>	RMSE
1	Whittier Narrows	1.06±0.03	0.26±0.05	0.5056	0.0476
2	Upland	1.2±0.2	0.07±0.06	0.7110	0.0175
3	Sierra Madre	1.41± 0.05	0.03± 0.01	0.5737	0.0071
4	Landers	1.202± 0.002	0.00300±0.00002	0.8581	0.0046
5	Northridge	1.231± 0.009	0.0028±0.0002	0.7934	0.0051
6	Ridgecrest	0.65±0.02	0.13± 0.06	0.7280	0.0948
7	Hector Mine	1.52± 0.05	0.07± 0.01	0.6914	0.0042
8	Baja California	0.851± 0.005	0.0000±0.0000	0.8025	0.0341
9	San Simeon	1.05± 0.01	0.012±0.004	0.9676	0.0068

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Table 2

parameters	R	t	Correlation s.l. 0.05
Log <sub>10</sub> (c/c <sub>M<sub>c</sub></sub> ), M <sub>c</sub> -M <sub>I</sub>	-0.0999	0.3478	No correlation
p/pM <sub>c</sub> , M <sub>c</sub> -M <sub>I</sub>	-0.0322	0.1116	No correlation
p, M <sub>m</sub> (3 points)	0.9243	2.4217	Positive correlation
(9 points)	0.4529	1.3440	No correlation (positive with s.l. 0.15)
c, M <sub>m</sub>	-0.3329	0.9340	No correlation (negative with s.l. 0.20)
p, c	-0.2314	0.6293	No correlation

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Table 3

N	Sequence	Log <sub>10</sub> [R <sub>ES</sub> (24)]	f	Log <sub>10</sub> [b/(α-b)]	Theoretical Δm	Real Δm	Log <sub>10</sub> [R <sub>ES</sub> (T)]
1	Whittier Narrows	1.24	0.62	0.06	0.5	0.6	0.56
2	Upland	1.08	0.29	0.40	0.8	0.8	0.79
3	Sierra Madre	2.08	0.10	-0.09	1.3	1.5	1.98
4	Landers	1.29	0.13	0.28	1.0	1.0	1.16
5	Northridge	0.95	0.10	0.13	0.6	0.8	0.84
6	Ridgecrest	1.75	1.23	0.24	0.5	0.6	0.57
7	Hector Mine	1.73	0.11	0.30	1.3	1.3	1.61
8	Baja California	1.93	0.42	0.66	1.4	1.5	1.49
9	San Simeon	2.01	0.33	0.55	1.5	1.8	1.67
	Mean	1.56	0.37	0.28	1.0	1.1	1.18
	std	0.43	0.37	0.23	0.4	0.4	0.52

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Table 4

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