Earthquake Interevent Time Distribution for Induced Micro-, Nano-, and Picoseismicity

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We examine the temporal statistics of micro-, nano-, and picoseismicity induced by mining as well as by long-term fluid injection. Specifically, we analyze catalogs of seismic events recorded at the Mponeng deep gold mine, South Africa, and at the German deep drilling site. We show that the distribution of time intervals between successive earthquakes is form invariant between the different catalogs. In particular, the distribution can be described by the same scaling function recently established for tectonic seismicity and acoustic emissions from laboratory rock fracture. Thus, our findings bridge the energy gap between those two cases and provide clear evidence that these temporal features of seismicity are independent of the energy scales of the events and whether they are of tectonic or induced origin.

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One of the main features of seismicity is its energy-scale invariance as documented by the empirical Gutenberg-Richter (GR) law [1]. It states that the frequency-magnitude distribution of earthquakes decays as 10^{-bm} with an exponent $b \approx 1$. Since the magnitude m is a logarithmic measure of the energy of an earthquake [2], this corresponds to a power law in terms of the energies which is a typical sign of scale invariance. Moreover, the b value seems to be independent of the specific geographic area as long as one considers sufficiently large areas over sufficiently long time intervals [3,4]. Recently, it has been shown that the GR law even holds down to magnitudes $M_W = -4.4$ [5,6]; i.e., it also holds at the scale of picoseismicity [7]. This indicates that the dynamic rupture processes of these tiny earthquakes is similar to those of larger earthquakes supporting similar conclusions for microseismicity based on static stress drops [8,9]. In addition, it has been shown that the GR law can also be observed in acoustic emissions (AE) from rock fracture [10] and from microcracking in polyurethane foams [11], and even in fracturing of single crystals [12]. This supports its scale-free nature down to atomic scales.

In contrast to the GR law, much less is known about the scale (in)dependence of other empirical features of seismicity. This includes the distribution of time intervals between successive earthquakes in a recorded catalog, which has been the focus of much research over the past decade (see, e.g., Refs. [13–18], and references therein). In Refs. [13,15] it was shown that the probability density function (PDF) of these time intervals or interevent times can be described by a unique scaling function if time is rescaled with the mean rate of seismic occurrence. It was shown in particular that this observation holds from worldwide to local scales, for quite different tectonic environments and for all considered magnitude ranges above 2.0. This is even true if the seismic rate is highly nonstationary as during aftershock sequences when the rate decays according to the Omori-Utsu law [19]. In these cases, the interevent times have to be rescaled by the instantaneous rate instead [13,20].

Further evidence that the distribution of interevent times is indeed independent of time, space, and energy scales comes from the analysis of AE time series measured for laboratory rock fracture [10] and from the heat signal generated by fracturing single crystals [12]. In both cases, it was found that the PDF of the interevent times follows the same unique scaling function as in the case of tectonic seismicity. For the case of rock fracture, this is true for a large variety of materials and very different experiments [10,22]. Yet, there is a difference of many orders of magnitude in energy scales between rock fracture experiments on one hand and the tectonic seismicity studied in Ref. [13] on the other hand. This makes it necessary to explicitly test the hypothesis of scale invariance of the distribution of interevent times for earthquakes in the energy range between the two extreme cases. Here, we do exactly that by considering micro-, nano-, and picoseismicity. We find that the PDF of the interevent times is indeed scale independent and also independent of the specific origin of the seismic activity, i.e., whether it is tectonic or induced seismicity.

We consider seismic catalogs from two different locations. The first one is the Mponeng deep gold mine in South Africa where nano- and picoearthquakes were recorded as part of the JApanese-German Underground Acoustic emission Research in South Africa (JAGUARS) project [5,23]. The highly sensitive seismic network composed of accelerometer and acoustic emission sensors allowed us to record extremely small earthquakes with magnitudes M_W

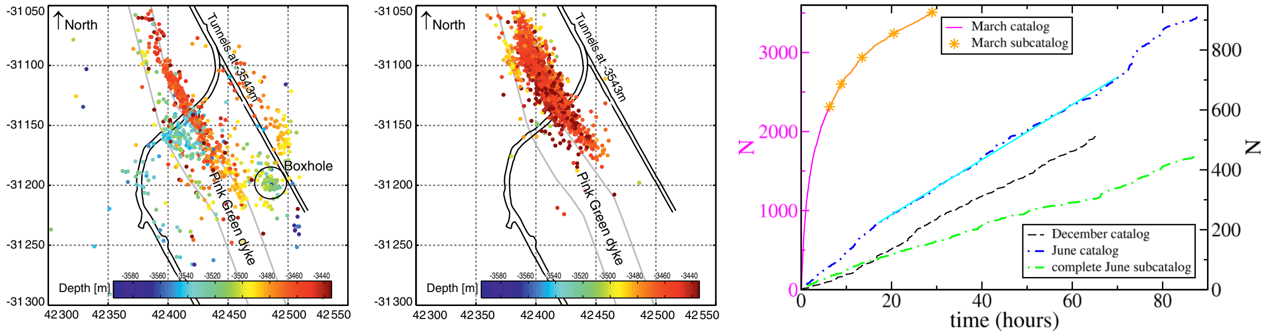

FIG. 1 (color online). Left and middle: Two of the catalogs of nano- and picoseismicity recorded at the Mponeng gold mine, June 2008 dataset (left) and March 2008 postblasting data set (middle). The location of the boxhole is marked by a circle (see text for details). Right: The cumulative number of earthquakes as a function of time for the different catalogs and subcatalogs from the Mponeng mine. The straight line indicates approximately stationary seismic activity and corresponds to the restricted June catalog (see text for details).

between -5.0 and -0.8 [5,24]. We analyze three catalogs from this location shown in Fig. 1. The first one contains $N = 513$ seismic events recorded over a continuous period of 4 days (December 24–27, 2007). The catalog is free from manmade noises and induced seismicity due to the Christmas vacation period (see Ref. [25] for a detailed overview of the recording conditions). The second catalog is recorded over another continuous 4 day period (June 14–17, 2008) and contains $N = 913$ seismic events. The initial part of the catalog exhibits some induced seismic activity leading to a higher seismicity rate which is clearly visible in Fig. 1. This is the response of the rocks to production blastings performed at 7:00 pm the day before. Since the catalog starts at midnight on June 14, postblasting activity contributes to the seismicity in the direct neighborhood of the blasting area for more than 12 h after the blasting, similar to what was observed in Ref. [25]. In Fig. 1, a higher rate of activity can also be observed around hour 72 after the beginning of the catalog. Further inspection shows that this is due to the onset of seismic activity at the location of the boxhole indicated by the encircled area in Fig. 1. This activity is induced by workers shoveling blasted material through the boxhole. In order to check whether such weak nonstationarities and/or the induced origin of the seismic activity affect the overall interevent time distribution, we also consider a restricted version of the June 2008 catalog that excludes the initial and final periods contaminated by human mining activity ($N = 531$ events). To test the influence of catalog incompleteness on our findings, we further study a *complete* subcatalog which contains all events ($N = 450$) above $M_c = -3.5$ that occurred within 150 m from the network [26].

The third catalog contains seismic events induced by earlier strong production blasting. Over the recorded period of about 30 h between March 29–30, 2008, the activity displays strong nonstationary behavior shown in Fig. 1. Because of restrictions in the time resolution, we focus on events occurring after about 6 h (see Fig. 1 for details), giving $N = 1194$. This catalog allows us to investigate directly whether induced activity is significantly different from natural seismicity in terms of the interevent time distribution.

The second location we consider is the German deep drilling site (KTB) where microseismicity has been recorded [27]. The seismicity was induced by long-term fluid injection into a continental crustal fault. The inset of Fig. 3 shows the cumulative number of earthquakes, N_c, as a function of time during the longest *continuous* recording period of the 2004/2005 injection experiment at KTB (February 9–April 12, 2005); see also Fig. 3 in Ref. [27]. This is the catalog we focus on here.

For each given (sub-)catalog, we extract the ordered times of occurrence of the events, t_i. The interevent times are defined as $T_i = t_{i+1} - t_i$ and their corresponding PDF is denoted by $P_C(T)$ for the given (sub-)catalog C. Figure 2 shows the PDF of the normalized interevent times $\theta = T/\langle T\rangle_C$ for the different catalogs from the Mponeng mine. Here, $\langle T\rangle_C$ is the respective mean interevent time defined as $\langle T\rangle_C = (t_N - t_1)/(N-1)$. To compensate for the strong nonstationarities in the March catalog, we perform the normalization with the "instantaneous" mean interevent time computed over windows of 200 events instead. The excellent data collapse implies that $P(T/\langle T\rangle)$ does not depend on the particular catalog and that we can write

$$P_C(T) = P(T/\langle T\rangle_C)/\langle T\rangle_C. \quad (1)$$

Thus, for a given catalog C, $P_C(T)$ is determined by $\langle T\rangle_C$—or equivalently the mean rate $R_C = \langle T\rangle_C^{-1}$—and the scaling function $P(\theta)$. As indicated in Fig. 2, the latter can be well approximated by a Gamma distribution

$$P(\theta) \propto \theta^{-(1-\gamma)} \exp(-\theta/B). \quad (2)$$

Using a standard maximum likelihood estimator for the Gamma distribution [28], we obtain $\gamma = 0.74 \pm 0.02$ and

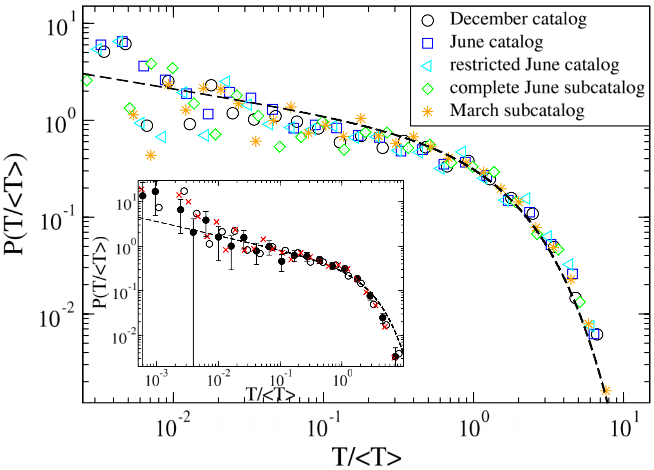

FIG. 2 (color online). Probability density function of the time intervals T between successive events for the different catalogs discussed in Fig. 1. The time intervals have been rescaled by the respective mean $\langle T \rangle$. All distributions collapse onto the same curve, which can be well described by a Gamma distribution. This is indicated by the dashed black line. Inset: December catalog split into subcatalogs. Circles correspond to conditioning on the directly preceding T using $T > T_{\text{median}}$ (solid circles) and $T < T_{\text{median}}$ (open circles). $\langle T \rangle$ is larger by more than 10% in the former case. Crosses correspond to conditioning on the magnitude of the first event—see text for details. For better readability, 1σ error bars are only shown for one of the data sets.

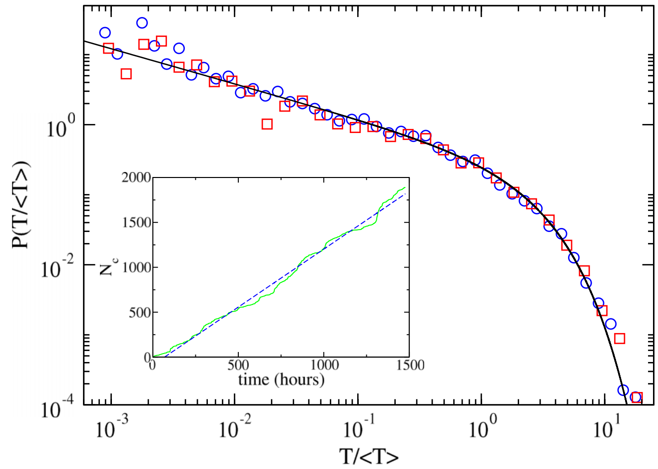

FIG. 3 (color online). Probability density function of the time intervals T between successive events for the KTB catalog (blue circles) and a shorter subcatalog (February 17—March 29, 2005; red squares). The time intervals have been rescaled by the respective mean $\langle T \rangle$. Both distributions collapse onto the same curve, which closely follows the functional form given in Eq. (2) with $\gamma = 0.5 \pm 0.05$ and $B = 2.2 \pm 0.2$. This is indicated by the solid black line. Inset: Cumulative number of earthquakes, N_c, in the KTB subcatalog as a function of time. The approximate linear increase as highlighted by the dashed curve indicates that the overall seismic activity does not show pronounced nonstationary behavior.

$B^{-1} = 0.74 \pm 0.03$ for the combined data sets where the error bars correspond to one standard deviation [29]. Individual data sets give very similar results. Note that the prefactor is fixed by normalization. Therefore, we have essentially a decreasing power law with exponent ≈ 0.3 up to the largest values of the argument, $\theta = T/\langle T \rangle$ close to 1, where the exponential factor comes into play. This is statistically indistinguishable from the results for tectonic earthquakes given in Ref. [13], namely, $\gamma = 0.67 \pm 0.05$ and $B = 1.58 \pm 0.15$. For the data from the KTB experiment, we obtain similar results. Figure 3 shows that Eq. (2) is also a very good description in this case. The slightly different values of γ and B could be due to systematic uncertainties.

While the functional form of Eq. (2) seems to be universal, other temporal features of seismicity are *not*. Specifically, we find that $P(\theta)$ does not change significantly if we consider only those interevent times that are preceded by an interevent time larger (or alternatively smaller) than the median interevent time for a given catalog as shown in the inset of Fig. 2 for one of the catalogs. While this agrees with results for rock fracture [10], it is in sharp contrast to findings for tectonic earthquakes on much larger energy scales for which such a conditional $P(\theta)$ has significantly different values of γ [30]. The variations in γ can be understood as a consequence of aftershock sequences, which—if considered in isolation—typically exhibit $1 - \gamma = 2 - 1/p \approx 1$, where p corresponds to the exponent in the Omori-Utsu law [19]. This has led to theoretical explanations of Eq. (2) for tectonic earthquakes based on aftershock sequences [18,31].

There are a number of potential explanations for the absence of any significant variations in $P(\theta)$ for our catalogs of micro-, nano-, and picoseismicity. For example, the observed variations in γ for tectonic earthquakes could be predominantly due to catalog incompleteness rather than the dynamics of aftershock sequences. While this seems very unlikely given the robustness of the findings in Ref. [30] with respect to variations in the magnitude thresholds and consequently the number of events, an alternative explanation is that aftershocks are just less common in our catalogs of micro-, nano-, and picoseismicity—similar to rock fracture in the lab [32]. This explanation is supported by the observation that $P(\theta)$ also does not change significantly if we consider only those interevent times for which the magnitude of the first event is larger than the median (see inset of Fig. 2). Such a conditioning should lead to a preferred selection of interevent times arising from aftershock sequences similar to the conditioning on short preceding interevent times. This is confirmed by the fact that $\langle T \rangle_{\text{conditional}}$ is shorter than $\langle T \rangle$, similar to what we observe if we condition on the previous interevent time. Note that these variations in the mean interevent time also argue against the possibility that the conditioning is ineffective due to severely overlapping aftershock sequences. Hence, aftershocks are certainly not absent from the catalogs studied here but they play a lesser role than for tectonic seismicity on much larger energy scales. This is supported by a more in-depth analysis of triggering relationships [33] and also other studies of fluid induced microseismicity [34].

To summarize, our findings show that the distribution of interevent times is form invariant between the different catalogs of micro-, nano-, and picoseismicity. This is not only regardless of the energy scale but also independent of the physical origin of the seismicity (blasting, fluid injection, or natural seismicity) and whether weak nonstationarities are present. Moreover, the catalog incompleteness does not affect the functional form either which can be well approximated by a Gamma distribution. Such a broad distribution is very different from an exponential distribution expected for simple random Poisson processes. Since the same distribution has been observed for tectonic seismicity at much larger spatial and energy scales, it is truly scale invariant [35]. Yet, its general origin seems rather unclear and remains to be understood. While aftershocks are present in the catalogs studied here, they do not seem to significantly influence the shape of the observed distribution. This behavior discounts aftershock-based explanations of this distribution originally proposed for tectonic seismicity and suggests some other mechanism, at least for micro-, nano-, and picoseismicity. Our findings for fluid induced seismicity suggest that pore pressure could play an important role [36,37], though there are some arguments against it [34]. Hence, this hypothesis should be further tested over a diverse set of seismic catalogs as, for example, those reported in Refs. [38–42].

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[1] B. Gutenberg and C. Richter, *Seismicity of the Earth* (Princeton University, Princeton, NJ, 1949).
[2] D. L. Turcotte, *Fractals and Chaos in Geology and Geophysics* (Cambridge University Press, Cambridge, England, 1997), 2nd ed.
[3] H. Kanamori and E. E. Brodsky, Rep. Prog. Phys. **67**, 1429 (2004).
[4] L. Gulia and S. Wiemer, Geophys. Res. Lett. **37**, L10305 (2010).
[5] G. Kwiatek, K. Plenkers, M. Nakatani, Y. Yabe, G. Dresen (JAGUARS-Group), Bull. Seismol. Soc. Am. **100**, 1165 (2010).
[6] M. S. Boettcher, A. McGarr, and M. Johnston, Geophys. Res. Lett. **36**, L10307 (2009).
[7] M. Bohnhoff, G. Dresen, W. Ellsworth, and H. Ito, in *New Frontiers in Integrated Solid Earth Sciences*, edited by S. Cloetingh and J. Negendank (Springer, the Netherlands, 2010), p. 261.
[8] T. Yamada, J. J. Mori, S. Ide, R. E. Abercrombie, H. Kawakata, M. Nakatani, Y. Iio, and H. Ogasawara, J. Geophys. Res. **112**, B03305 (2007).
[9] A. Baltay, S. Ide, G. Prieto, and G. Beroza, Geophys. Res. Lett. **38**, L06303 (2011).
[10] J. Davidsen, S. Stanchits, and G. Dresen, Phys. Rev. Lett. **98**, 125502 (2007).
[11] S. Deschanel, L. Vanel, G. Vigier, N. Godin, and S. Ciliberto, Int. J. Fract. **140**, 87 (2006).
[12] J. Åström *et al.*, Phys. Lett. A **356**, 262 (2006).
[13] A. Corral, Phys. Rev. Lett. **92**, 108501 (2004).
[14] J. Davidsen and C. Goltz, Geophys. Res. Lett. **31**, L21612 (2004).
[15] A. Corral, Int. J. Mod. Phys. B **23**, 5570 (2009).
[16] P. Traversa and J.-R. Grasso, Bull. Seismol. Soc. Am. **100**, 1755 (2010).
[17] M. Bottiglieri, L. de Arcangelis, C. Godano, and E. Lippiello, Phys. Rev. Lett. **104**, 158501 (2010).
[18] S. Touati, M. Naylor, I. G. Main, and M. Christie, J. Geophys. Res. **116**, B03304 (2011).
[19] T. Utsu, Y. Ogata, and R. S. Matsu'ura, J. Phys. Earth **43**, 1 (1995).
[20] Note that if this is not taken into account, significant variations can be encountered as in Ref. [21].
[21] X. Zhao, T. Omi, N. Matsuno, and S. Shinomoto, New J. Phys. **12**, 063010 (2010).
[22] G. Niccolini, F. Bosia, A. Carpinteri, G. Lacidogna, A. Manuello, and N. Pugno, Phys. Rev. E **80**, 026101 (2009).
[23] M. Nakatani, Y. Yabe, J. Philipp, G. Morema, G. Stanchits, and G. Dresen, Seismol. Res. Lett. **79**, 311 (2008).
[24] G. Kwiatek, K. Plenkers, and G. Dresen, Bull. Seismol. Soc. Am. **101**, 2592 (2011).
[25] K. Plenkers, G. Kwiatek, M. Nakatani, G. Dresen (JAGUARS Research Group), Seismol. Res. Lett. **81**, 467 (2010).
[26] This subcatalog does not contain any events arising from the mentioned manmade activities. See Ref. [5] for a discussion of the magnitude of completeness.
[27] S. A. Shapiro, J. Kummerow, C. Dinske, G. Asch, E. Rothert, J. Erzinger, H.-J. Kümpel, and R. Kind, Geophys. Res. Lett. **33**, L01309 (2006).
[28] R Manual, http://stat.ethz.ch/R-manual/R-patched/library/stats/html/GammaDist.html.
[29] Note that $B^{-1} = \gamma$ since $\langle\theta\rangle = 1$.
[30] V. N. Livina, S. Havlin, and A. Bunde, Phys. Rev. Lett. **95**, 208501 (2005).
[31] A. Saichev and D. Sornette, Phys. Rev. Lett. **97**, 078501 (2006).
[32] I. Main, Geophys. J. Int. **142**, 151 (2000).
[33] J. Moradpour, G. Kwiatek, and J. Davidsen (to be published).
[34] C. Langenbruch, C. Dinske, and S. A. Shapiro, Geophys. Res. Lett. **38**, L21302 (2011).
[35] Note that this does not apply to volcanic seismicity [16].
[36] E. Rothert and S. A. Shapiro, J. Geophys. Res. **112**, B04309 (2007).

[37] T. Jahr, G. Jentzsch, A. Gebauer, and T. Lau, J. Geophys. Res. **113**, B11410 (2008).
[38] A. M. Smith, Geophys. Res. Lett. **33**, L24501 (2006).
[39] L. Jenatton, R. Guiguet, F. Thouvenot, and N. Daix, J. Geophys. Res. **112**, B11304 (2007).
[40] S. Michelet and M. Nafi Toksöz, J. Geophys. Res. **112**, B07315 (2007).
[41] D. R. Bohnenstiehl, F. Waldhauser, and M. Tolstoy, Geochem. Geophys. Geosyst. **9**, Q10T03 (2008).
[42] R. P. Young and D. S. Collins, Int. J. Rock Mech. Min. Sci. **38**, 787 (2001).