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The unusual case of the ultra-deep 2015 Ogasawara earthquake $(M_W7.9)$: Natural time analysis

P. A. VAROTSOS^{1(a)}, N. V. SARLIS¹, E. S. SKORDAS¹, TOSHIYASU NAGAO² and MASASHI KAMOGAWA³

 ¹ Section of Condensed Matter Physics and Solid Earth Physics Institute, Physics Department, National and Kapodistrian University of Athens - Panepistimiopolis, Zografos 157 84, Athens, Greece, EU
 ² Division for Earthquake Prediction, Tsunami and Volcano Research, Institute of Oceanic Research and Development, Tokai University - Shizuoka 424-0902, Japan

³ Division for Earthquake Prediction Research, Global Center for Asian and Regional Research, University of Shizuoka 3-6-1, Takajo, Aoi-Ku, Shizuoka-City, Shizuoka Prefecture, 420-0839, Japan

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Abstract – On 30 May 2015, a powerful earthquake (EQ) (M_W 7.9, Japan Meteorological Agency reported magnitude M8.1) struck west of Japan's remote Ogasawara (Bonin) island chain, which lies more than 800 km south of Tokyo. It occurred at 680 km depth in an area without any known historical seismicity. It was the first EQ felt in every Japanese prefecture since intensity observations began in 1884. Here, by applying natural time analysis, which unveils hidden properties in complex time series, we find that almost three and a half months before this powerful EQ, which is the strongest one after the $M_W 9.0$ Tohoku EQ on 11 March 2011, the fluctuations of the order parameter of seismicity were minimized around 17 February 2015. Remarkably, such a behavior has been also observed 1–3 months before all shallow EQs in Japan of magnitude M7.6 or larger that occurred since 1984 until the $M_W 9.0$ Tohoku EQ. We also find that upon the Ogasawara EQ occurrence the change of the entropy of Japanese seismicity upon changing the direction of the time arrow (*i.e.*, under time reversal) exhibited a minimum. This minimum, which may appear when a system approaches a dynamic phase transition, is not equally deep with that observed on 22 December 2010 along with the occurrence of a M7.8 EQ in Bonin islands. The fact that the latter EQ was followed almost 3 months later by the appreciably stronger Tohoku EQ, while the Ogasawara EQ did not, is discussed in the frame of the Lifshitz-Slyozov-Wagner theory of phase transitions and subsequent work by Penrose and coworkers.

This paper is dedicated to Professor Seiya Uyeda on the occasion of his 90th birthday.

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A M_W 7.9 earthquake (EQ) occurred beneath the Ogasawara (Bonin) Islands on 30 May 2015 at 680 km depth (D) in an area without any known historical seismicity and caused significant shaking over a broad area of Japan at epicentral distances in the range 1000–2000 km. In particular, the maximum shaking intensity was reached at both Hahajima Island above the hypocenter and Kanagawa (near Tokyo) located over 800 km from the hypocenter. The extraordinary spread of the felt (intensity ≥ 1 , JMA scale) area over all 47 prefectures of the Japanese Islands is the first [1] since intensity observations began in 1884. Concerning the peculiar ground motion associated with this deepest major EQ in the seismological record [2] the results seem to indicate that it was due to its great

source depth as well as its location outside the subducting slab. The occurrence of this EQ is still puzzling, not only for its great depth but also because its epicenter lies more than 100 km away from the ordinary seismicity in the vicinity (see ref. [1] and references therein). Very recently, Gardonio et al. [3] explored the EQ productivity in the hypocentral surroundings and detected 49 not previously identified EQs, 28 of which occurred during an accelerating preseismic phase that started almost 3 months prior to the main shock (restricting ourselves to EQs of magnitude 4 or larger, the first ones occurred on 10 February 2015 and 19 March 2015). This is the first time that such foreshock activity has been observed for a deep EQ. According to Gardonio et al., this preseismic and postseismic activity suggests transformational faulting within a metastable olivine wedge inside the slab at depth as the

 $^{{}^{(}a)}{\operatorname{E-mail:}}\ {\tt pvaro@otenet.gr}$ (corresponding author)

triggering principal mechanism for this deep EQ sequence, the seismicity starting where the backward bending of the subducting Pacific plate is maximum.

In view of the above and the fact that the occurrence of the Ogasawara EQ has been characterized as curious case [2], unusual [1] as well as a surprise to scientists [3], it is the scope of this paper to study this case by applying to Japanese seismicity natural time analysis. The latter unveils hidden properties in complex time series [4] such as EQs which exhibit complex correlations in time, space and magnitude that have been studied by several authors, e.g., see refs. [5-10]. Natural time has recently been also used by Turcotte, Rundle and coworkers as basis of a new methodology to estimate the current seismic risk level, e.q., see refs. [11–14]. We consider that the observed EQ scaling laws point to [4,15,16] the existence of phenomena closely associated with the proximity of the system to a critical point (the mainshock is the new phase [4,17]) and that natural time analysis can identify the approach of the dynamical system to the critical point.

Natural time analysis. Background. – In a time series comprising N EQs, the natural time χ_k for the occurrence of the k-th EQ of energy Q_k is defined as $\chi_k = k/N$, *i.e.*, we ignore the time intervals between consecutive events, but preserve their order as well as their energy Q_k . In natural time analysis, the evolution of the pair (χ_k, p_k) is studied, where $p_k = Q_k / \sum_{n=1}^N Q_n$ is the normalized energy and Q_k is estimated by means of the relation [18] $Q_k \propto 10^{1.5M_k}$, where M_k stands for the EQ magnitude. It has been shown [19] that the quantity $\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2$ of natural time χ weighted by p_k , namely

$$\kappa_1 = \sum_{k=1}^N p_k(\chi_k)^2 - \left(\sum_{k=1}^N p_k \chi_k\right)^2,$$
 (1)

may serve as an order parameter of seismicity. To compute κ_1 fluctuations, or simply β_W , we follow the procedure described in detail in refs. [20,21] by using a sliding natural time window of constant length, *i.e.*, comprising a number W of EQs that would occur on average within the crucial scale [22] of a few months, or so, which is the average lead time of seismic electric signals (SES) activities. These are series of low-frequency transient changes of the electric field of the Earth [23,24] detected before major EQs (both in Japan [25] and Greece [26–28]). We then compute the average value $\mu(\kappa_1)$ and the standard deviation $\sigma(\kappa_1)$ of the ensemble of κ_1 obtained from subexcerpts of the W consecutive EQs. The quantity

$$\beta_W \equiv \sigma(\kappa_1) / \mu(\kappa_1) \tag{2}$$

is termed [4,29] variability of κ_1 . To obtain this variability of κ_1 , we need many values of κ_1 for each target EQ. For this purpose, we first take an excerpt comprised of Wsuccessive EQs just before a target EQ from the seismic catalog. The number W was chosen to cover a period of a few months, as mentioned. For this excerpt, we form its



Fig. 1: Epicenters (stars) of all shallow major EQs in Japan since 1 January 1984 with magnitude 7.6 or larger within the large area N_{25}^{46} E_{125}^{148} (black rectangle) together with the epicenter of the ultra-deep M_W 7.9 (or M8.1 according to JMA) Ogasawara EQ in 2015 (solid red circle). The smaller area N_{25}^{46} E_{125}^{146} (yellow rectangle) is also shown.

subexcerpts $E_j = \{Q_{j+k-1}\}_{k=1,2,...N}$ of consecutive N = 6 EQs (since at least six EQs are needed [19] for obtaining reliable κ_1). Further, $p_k = Q_{j+k-1} / \sum_{l=1}^{N} Q_{j+l-1}$, and by sliding E_j over the excerpt of W EQs, $j = 1, 2, \ldots, W$ – N+1 = (W-5), we calculate κ_1 using eq. (1) for each j. We repeat this calculation for $N = 7, 8, \ldots, W$, thus obtaining an ensemble of $(W-4)(W-5)/2(=1+2+\ldots+$ W-5) κ_1 values. We then calculate the average $\mu(\kappa_1)$ and the standard deviation $\sigma(\kappa_1)$ of the thus obtained ensemble of $(W-4)(W-5)/2 \kappa_1$ values. The variability β_W of κ_1 for this excerpt W is defined according to eq. (2) and is assigned to the (W + 1)-th EQ of the EQ catalog, *i.e.*, the target EQ. The time evolution of the β_W value can be pursued by sliding the natural time window of Wconsecutive EQs, event by event, through the EQ catalog and assigning to its value the occurrence time of the EQ which follows the last EQ of the window in the EQ catalog. The corresponding minimum value is labeled $\beta_{W,min}$.

A minimum has been observed 1–3 months before all six shallow $M \ge 7.6$ EQs in Japan (fig. 1) during the period 1 January 1984–11 March 2011 [20]. These distinct minima are observed simultaneously (see, *e.g.*, appendix A of ref. [21]) at β_{200} and β_{300} having a ratio $\beta_{300,min}/\beta_{200,min}$ in the range 0.95 to 1.08 and $\beta_{200,min} \le 0.295$ (see table 1 of ref. [20]). The deepest minimum was observed around 5 January 2011, being almost simultaneous with the detection of anomalous magnetic field fluctuations on the z-component which is characteristic of an intense SES activity [30].

The entropy S defined [31] in natural time is

$$S = \langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle, \qquad (3)$$

where $\langle f(\chi) \rangle = \sum_{k=1}^{N} p_k f(\chi_k)$ denotes the average value of $f(\chi)$ weighted by p_k , *i.e.*, $\langle \chi \ln \chi \rangle = \sum_{k=1}^{N} p_k(k/N) \ln(k/N)$ and $\langle \chi \rangle = \sum_{k=1}^{N} p_k(k/N)$. The entropy obtained by eq. (3) upon considering [4,32] the time-reversal \hat{T} , *i.e.*, $\hat{T}p_k = p_{N-k+1}$, is labelled by S_- :

$$S_{-} = \sum_{k=1}^{N} p_{N-k+1} \frac{k}{N} \ln\left(\frac{k}{N}\right)$$
$$-\left(\sum_{k=1}^{N} p_{N-k+1} \frac{k}{N}\right) \ln\left(\sum_{k=1}^{N} p_{N-k+1} \frac{k}{N}\right). \quad (4)$$

The quantity S_{-} is different from S, thus there exists a change $\Delta S \equiv S - S_{-}$ in natural time under time reversal. Hence, S does satisfy the condition to be time-reversal asymmetric [4,32,33]. The quantity ΔS is of key importance to identify when a system approaches a dynamic phase transition.

The ΔS calculation is carried out by means of a natural time window length i (=number of successive events), sliding each time by one event, through the whole time series. The entropies S and S_- , and therefrom their difference ΔS_i , are calculated each time. Thus, we form a new time series comprising successive ΔS_i values. Computing the standard deviation $\sigma(\Delta S_i)$ of the time series of $\Delta S_i \equiv S_i - (S_-)_i$, the complexity measure Λ_i is defined by [4,34]

$$\Lambda_i = \frac{\sigma(\Delta S_i)}{\sigma(\Delta S_{100})},\tag{5}$$

where the denominator stands for the standard deviation $\sigma(\Delta S_{100})$ of the time series of ΔS_i of i = 100 events. In simple words, Λ_i quantifies how the statistics of ΔS_i time series varies upon changing the natural time window length (or simply scale) from 100 to another scale *i*, and is of profound importance to study the dynamical evolution of a complex system (see p. 159 of ref. [4]).

Data analyzed. – The Japan Meteorological Agency (JMA) seismic catalog was used (*e.g.*, see [20,35]) and the magnitudes reported are simply labeled M. We considered all $M \geq 3.5$ EQs (to assure data completeness of JMA catalog) from 1 January 2011 until 1 January 2019 within the area $N_{25}^{46} E_{125}^{146}$ (yellow rectangle in fig. 1). The calculation was repeated also for a second larger area N_{25}^{46} E_{125}^{148} (black rectangle in fig. 1) in order to avoid boundary effects and assure that the results do not depend on the selection of the area studied [21]. The energy Q_k of each EQ was obtained from M after converting [36] to the moment magnitude M_W [37]. Since 47204 EQs occurred in a period of about 326 months, from 1 January 1984 to the $M_W 9.0$ Tohoku EQ occurrence on 11 March 2011, within the area $N_{25}^{46} E_{125}^{148}$, we have on average an order of 10^2 EQs per month, thus we choose the natural time window lengths W = 200 and 300 for the calculation of β_W that would correspond on average to a few months period in accordance with the SES activities observations, as already mentioned. In order to judge when the seismicity rate returned to its normal value after the $M_W 9.0$ Tohoku EQ occurrence, we consider the time-dependent seismicity rate $(\lambda(t) - \mu)/K_0 = \sum_{t_i < t} \exp [\alpha(M_i - M_c)] / (t - t_i + c)^p$ of the temporal epidemic-type aftershock sequence (ETAS) model [38–40], according to eq. (1) of Ogata *et al.* [41]. (The ETAS model parameters (α, p, c) are the same as those presented in fig. 2(a) of ref. [41]). This happened approximately around the end of 2013.

Results. – In fig. 2 we plot, for the larger area N_{25}^{46} E_{125}^{148} , the variability β_W for W = 200 (red) and 300 (blue) events vs. the conventional time. In fig. 2(a) we present the results for the whole eight year period from 1 January 2011 until the end of 2018, while in fig. 2(b) and in order to better visualize what happened close to the Ogasawara EQ, an excerpt of fourteen month duration, i.e., from 1 May 2014 until 1 July 2015, is depicted. A careful inspection of the latter figure reveals that a broad β_W minimum is observed, for both natural time window lengths W = 200 and 300 events, around 17 February 2015 shown by a green arrow preceding the Ogasawara EQ almost by $3\frac{1}{2}$ months. (This date, quite interestingly, is compatible with what was mentioned by Gardonio et al. [3] that an accelerating preseismic phase started almost 3 months prior to the mainshock.) The ratio $\beta_{300,min}/\beta_{200,min}$ actually lies in the range 0.95 to 1.08 and in addition $\beta_{200,min} \leq 0.295$ as found in ref. [20] for the precursory β_W minima 1–3 months before all shallow EQs of magnitude 7.6 or larger in Japan during the period from 1 January 1984 until the M9 Tohoku EQ in 2011. Practically the same results —as far as the existence of the aforementioned precursory β_W broad minimum is concerned— are obtained, see fig. 3, if we repeat the above β_W computation for the smaller area N⁴⁶₂₅ E¹⁴⁶₁₂₅.

We now turn to the ΔS investigation for several natural time window lengths from 10^3 to 8×10^3 events. The selection of the minimum length of around 10^3 events was made as follows: It has been found [21] that there exists a significant change in the temporal correlations between EQ magnitudes when comparing the two stages that correspond to the periods before and just after the initiation of an SES activity. This change is likely to be captured by the time evolution of ΔS_i , thus we start our study in the larger area from the scale of $i \sim 10^3$ events, which corresponds to the number of seismic events M > 3.5 that occur during a period exceeding the maximum lead time of the observed SES activities (that is around $5\frac{1}{2}$ months). The detailed investigation in the range $10^3 - 8 \times 10^3$ events showed that in the longer window lengths the following behavior emerged: In fig. 4(a)–(d), we plot the ΔS_i values



Fig. 2: The variability β_W for W = 200 (red) and 300 (blue) vs. the conventional time for the larger area N₂₅⁴⁶ E₁₂₅¹⁴⁸ since 1 January 1984 until 1 January 2019 (a), or since 1 May 2014 until 1 July 2015 (b). In the lower panel of (a) and (b) we plot the time-dependent seismicity rate $(\lambda(t) - \mu)/K_0$ —described in the text— vs. the conventional time together with the seismicity (black vertical lines ending at circles corresponding to EQs whose magnitudes can be read in the right scale). The horizontal line corresponds to $\beta_{200,min}$ observed before the M9.0 Tohoku EQ which is the global minimum and has been drawn as a guide to the eye.



Fig. 3: The same as fig. 2 but for the smaller area $N_{25}^{46} E_{125}^{146}$.

vs. the conventional time upon analyzing all $M \geq 3.5$ seismic events in the larger area N⁴⁶₂₅ E¹⁴⁸₁₂₅ for the lengths i= 5000 to 8000 events. An inspection of this figure reveals that, upon the occurrence of the Ogasawara EQ, ΔS_i exhibit the minimum value during the study period (until the



Fig. 4: Plot of ΔS_i values vs. the conventional time. Panels (a), (b), (c) and (d) correspond to the scales $i = 5 \times 10^3$, and 6×10^3 , and 7×10^3 and 8×10^3 events, respectively, when analysing all EQs with $M \geq 3.5$ within the larger area N_{25}^{46} E_{125}^{148} shown by the black rectangle in fig. 1 during the period from 1 January 2010 until 1 January 2019. The vertical lines ending at circles depict the EQs of magnitude $M \geq 7$ read in the right scale.

end of 2018) after the end of 2013 when —as mentioned the seismicity rate returned to its value before the $M_W 9.0$ Tohoku EQ in 2011. Interestingly, this minimum is less deep than that preceding the $M_W 9.0$ Tohoku EQ which appeared on 22 December 2010.

In order to better visualize the change of the ΔS_i values when we approach the Ogasawara EQ occurrence, we also give in fig. 5(a), (b), (c), and (d) excerpts of fig. 4 but in expanded horizontal time scale during an almost six month period from 1 January 2015 until 1 July 2015. Two shallower ΔS_i minima appeared on 17 February 2015 and 13 May 2015 upon the occurrence of two EQs of magnitude M6.9 and M6.8, respectively with epicenters 39.87° N 143.19°E (D = 12.72 km) and 38.86° N 142.15°E (D = 46.24 km) (the latter being closer to Tohoku EQ). Comparing these two ΔS_i minima we find that the former, *i.e.*, the one of 17 February 2015 is deeper preceding the Ogasawara EQ. This is consistent with our earlier finding that upon analyzing in natural time the Olami-Feder-Christensen model for EQs [42], it was observed (see fig. 8.12, p. 361 of ref. [4]) that the value of ΔS_i exhibits a clear minimum [4] (or maximum if we define



Fig. 5: Excerpt of fig. 4 during the six month period from 1 January 2015 until 1 July 2015. The vertical line ending at a circle corresponds to the Ogasawara EQ of magnitude M = 8.1 (read on the right scale) that occurred on 30 May 2015.

as in ref. [43] $\Delta S \equiv S_{-}S$, instead of $\Delta S \equiv S - S_{-}$) before large avalanches. To highlight the broad interest of the extrema of ΔS_i to identify when a system approaches a dynamic phase transition, the electrocardiograms of 18 sudden cardiac death individuals (the data of which are described in ref. [33]) were analysed in natural time at proper scales. We consider that, physiologically, the origin of the complex dynamics of heart rate has been attributed to antagonistic activity of the branches of the autonomic nervous system, *i.e.*, the parasympathetic and the sympathetic nervous systems, respectively, decreasing and increasing heart rate (see ref. [33] and references therein). Focusing on the low-frequency (LF) range (i.e., around0.1 Hz) in heart rate and blood pressure with autonomic involvement and selecting the scale i = 13 heartbeats, we find that a minimum of ΔS_{13} is observed and ventricular fibrillation starts (signalling the impending sudden cardiac death, which remains a major cause of death in industrialized countries) within approximately 3 hours in the vast majority, and specifically in 15 out of 18 individuals (*i.e.*, except for the individuals numbered 32, 44 and 45 in fig. 2(b) of ref. [33]). In other words, from a physical point of view, the following happens: The LF range is usually described as corresponding to [44] "the process of slow regulation of blood pressure and heart rate" or it is said that [45] "it reflects modulation of sympathetic





Fig. 6: Plot of the quantity β_W (quantifying the fluctuations of the order parameter of seismicity) vs. the conventional time just after the occurrence of the M7.8 Chichijima-Kankai shallow EQ (a) and the M8.1 Ogasawara EQ on 30 May 2015 (b). In the lower panel (c) we plot the corresponding increase $\Delta\beta_W$ of β_W after the occurrence of each of these two EQs vs. the logarithm of the natural time window length W.

or parasympathetic activity by baroflex mechanisms" due to [46] the emergence of a limit cycle caused by the vascular sympathetic delay (its exact explanation, however, is strongly debated [47]). Thus, the appearance of the minimum of ΔS_{13} probably marks that the slow regulation of blood pressure and heart rate is "disorganized".

Repeating the study for ΔS in the smaller area N⁴⁶₂₅ E¹⁴⁶₁₂₅, we find similar results as in figs. 4 and 5.

Discussion. – The Ogasawara EQ has not been followed yet by an appreciably stronger EQ in contrast to the M7.8 Chichijima-Kinkai shallow EQ which occurred also at Bonin islands at 27.05°N 143.94°E almost three months before the super-giant $M_W9.0$ Tohoku EQ on 11 March 2011. This could be understood in the following context: Upon the occurrence of the Chichijima-Kinkai EQ the following facts have been observed: First, according to ref. [48] the complexity measures Λ_{2000} , Λ_{3000} and Λ_{4000} , *i.e.*, the Λ_i values at the natural time window lengths (scales) i= 2000, 3000 and 4000 events, respectively, show in fig. 2 of ref. [48] a strong abrupt increase

 $\Delta \Lambda_i$ on 22 December 2010 and after the EQ occurrence exhibit a scaling behavior of the form $\Delta \Lambda_i = A(t-t_0)^c$ where the exponent c is independent of i with a value very close to 1/3, while the pre-factors A are proportional to i (see fig. 3 of ref. [48]) and t_0 is approximately 0.2 days after the M7.8 EQ occurrence. This equation conforms to the seminal work by Lifshitz and Slyozov [49] and independently by Wagner [50] (LSW) on phase transitions which shows that the characteristic size of the minority phase droplets exhibits a scaling behavior in which time growth varies with time as $t^{1/3}$ (a behavior reminiscent of eqs. (100.14) and (100.23) in the chapter entitled "Kinetics of Phase Transitions" of ref. [51]). Second, the order parameter fluctuations exhibited a unique change [52], *i.e.*, an increase $\Delta \beta_W$ which exhibits a functional form consistent with the LSW theory and the subsequent work of Penrose et al. [53]. In particular, $\Delta \beta_W$ obeys the interrelation $\Delta \beta_W = 0.5 \ln(W/114.3)$, see fig. 2(g) and (h) of ref. [52] (for a similar example, but in California, see ref. [54]). It has a functional form strikingly reminiscent of the one discussed by Penrose et al. [53] in computer simulations of phase separation kinetics using the ideas of Lifshitz and Slyozov [49], see their eq. (33) which is also due to Lifshitz and Slyozov. Such a behavior has not been observed along with the occurrence of either the Ogasawara EQ (see the blue part of fig. 6(c)) or all other shallow EQs in Japan of magnitude 7.6 or larger during the period from 1 January 1984 to the time of the M9 Tohoku EQ [52]. As an outlook for the future, it would be of interest to study whether such a behavior is obeyed prior to extreme events like magnetic storms [55,56], etc.

Main conclusions. – Analysing the seismicity all over Japan in natural time, we find the following during the study period from the end of 2013 until the end of 2018:

1) The fluctuations of the order parameter of seismicity exhibit a broad minimum around $3\frac{1}{2}$ months before the Ogasawara EQ around 17 February 2015.

2) Upon the occurrence of the Ogasawara EQ, the entropy change of seismicity under time reversal was minimized. This, for the longer scales, is the deepest minimum after the $M_W 9.0$ Tohoku EQ occurrence.

3) The increase of the fluctuations of the order parameter of seismicity just after the Ogasawara EQ occurrence did not follow the Lifshitz-Slyozov-Wagner theory of phase transitions and the subsequent work by Penrose and coworkers. This is consistent with the fact that Ogasawara EQ has not been followed by an appreciably stronger EQ, in contrast to the case of the M7.8 EQ on 22 December 2010 (that also occurred in the Bonin islands) which conformed to this theory and was followed by the super-giant $M_W 9.0$ Tohoku EQ almost three months later.

REFERENCES

 FURUMURA T. and KENNETT B. L. N., J. Geophys. Res.: Solid Earth, 122 (2017) 8143.

- [2] COOK T., Eos **98** (2017).
- [3] GARDONIO B., SCHUBNEL A., DAS S., LYON-CAEN H., MARSAN D., BOUCHON M. and KATO A., *Geophys. Res.* Lett., 47 (2020) e2019GL085589.
- [4] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., Natural Time Analysis: The new view of time. Precursory Seismic Electric Signals, Earthquakes and other Complex Time-Series (Springer-Verlag, Berlin Heidelberg) 2011.
- [5] HUANG Q., Geophys. Res. Lett., 35 (2008) L23308.
- [6] LENNARTZ S., LIVINA V. N., BUNDE A. and HAVLIN S., EPL, 81 (2008) 69001.
- [7] TELESCA L., Tectonophysics, **494** (2010) 155.
- [8] HUANG Q. and DING X., Bull. Seismol. Soc. Am., 102 (2012) 1878.
- [9] HUANG Q., Proc. Natl. Acad. Sci. U.S.A., 112 (2015) 944.
- [10] YANG S.-S., POTIRAKIS S. M., SASMAL S. and HAYAKAWA M., Entropy 22 (2020).
- [11] LUGINBUHL M., RUNDLE J. B., HAWKINS A. and TUR-COTTE D. L., Pure Appl. Geophys., 175 (2018) 49.
- [12] LUGINBUHL M., RUNDLE J. B. and TURCOTTE D. L., Pure Appl. Geophys., 175 (2018) 661.
- [13] LUGINBUHL M., RUNDLE J. B. and TURCOTTE D. L., *Philos. Trans. R. Soc. A*, **377** (2018) 20170397.
- [14] LUGINBUHL M., RUNDLE J. B. and TURCOTTE D. L., *Geophys. J. Int.*, **215** (2018) 753.
- [15] CARLSON J. M., LANGER J. S. and SHAW B. E., *Rev. Mod. Phys.*, 66 (1994) 657.
- [16] HOLLIDAY J. R., RUNDLE J. B., TURCOTTE D. L., KLEIN W., TIAMPO K. F. and DONNELLAN A., *Phys. Rev. Lett.*, 97 (2006) 238501.
- [17] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., Pract. Athens Acad., 76 (2001) 294.
- [18] KANAMORI H., Nature, **271** (1978) 411.
- [19] VAROTSOS P. A., SARLIS N. V., TANAKA H. K. and SKORDAS E. S., *Phys. Rev. E*, **72** (2005) 041103.
- [20] SARLIS N. V., SKORDAS E. S., VAROTSOS P. A., NAGAO T., KAMOGAWA M., TANAKA H. and UYEDA S., Proc. Natl. Acad. Sci. U.S.A., 110 (2013) 13734.
- [21] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., J. Geophys. Res.: Space Phys., 119 (2014) 9192.
- [22] VAROTSOS P., SARLIS N. and SKORDAS E., EPL, 96 (2011) 59002.
- [23] VAROTSOS P. and ALEXOPOULOS K., Tectonophysics, 110 (1984) 73.
- [24] VAROTSOS P., ALEXOPOULOS K., NOMICOS K. and LAZARIDOU M., Nature (London), 322 (1986) 120.
- [25] UYEDA S., KAMOGAWA M. and TANAKA H., J. Geophys. Res., 114 (2009) B02310.
- [26] VAROTSOS P. and LAZARIDOU M., Tectonophysics, 188 (1991) 321.
- [27] VAROTSOS P., ALEXOPOULOS K. and LAZARIDOU M., *Tectonophysics*, **224** (1993) 1.
- [28] SARLIS N. V., SKORDAS E. S., LAZARIDOU M. S. and VAROTSOS P. A., *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci.*, 84 (2008) 331.
- [29] SARLIS N. V., SKORDAS E. S. and VAROTSOS P. A., *EPL*, 91 (2010) 59001.
- [30] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., Ann. Geophys., 37 (2019) 315.
- [31] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., *Phys. Rev. E*, 68 (2003) 031106.

- [32] VAROTSOS P. A., SARLIS N. V., TANAKA H. K. and SKORDAS E. S., *Phys. Rev. E*, **71** (2005) 032102.
- [33] VAROTSOS P. A., SARLIS N. V., SKORDAS E. S. and LAZARIDOU M. S., Appl. Phys. Lett., 91 (2007) 064106.
- [34] SARLIS N. V., CHRISTOPOULOS S.-R. G. and BEMPLI-DAKI M. M., *EPL*, **109** (2015) 18002.
- [35] SARLIS N. V., SKORDAS E. S., VAROTSOS P. A., NAGAO T., KAMOGAWA M. and UYEDA S., *Proc. Natl. Acad. Sci.* U.S.A., **112** (2015) 986.
- [36] TANAKA H. K., VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., Proc. Jpn. Acad. Ser. B Phys. Biol. Sci., 80 (2004) 283.
- [37] HANKS T. C. and KANAMORI H., J. Geophys. Res., 84 (1979) 2348.
- [38] OGATA Y., Research Memorandum (Technical report), No. 288 (1985), see https://www.ism.ac.jp/editsec/resmemo-j.html; also in SAITO M. (Editor), Suri-Zisin Gaku (Mathematical Seismology), Vol. 1, Cooperative Research Report (The Institute of Statistical Mathematics, Tokyo) March 1986 (in Japanese).
- [39] OGATA Y., J. Am. Stat. Assoc., 83 (1988) 9.
- [40] OGATA Y., Tectonophysics, **169** (1989) 159.
- [41] OGATA Y., KATSURA K., TSURUOKA H. and HIRATA N., Earth Planets Space, 71 (2019) 113.
- [42] OLAMI Z., FEDER H. J. S. and CHRISTENSEN K., Phys. Rev. Lett., 68 (1992) 1244.
- [43] SARLIS N., SKORDAS E. and VAROTSOS P., Tectonophysics, 513 (2011) 49.
- [44] PROKHOROV M. D., PONOMARENKO V. I., GRIDNEV
 V. I., BODROV M. B. and BESPYATOV A. B., *Phys. Rev.* E, 68 (2003) 041913.

- [45] BIGGER, J. THOMAS J., FLEISS J. L., STEINMAN R. C., ROLNITZKY L. M., SCHNEIDER W. J. and STEIN P. K., *Circulation*, **91** (1995) 1936.
- [46] KOTANI K., STRUZIK Z. R., TAKAMASU K., STANLEY H. E. and YAMAMOTO Y., *Phys. Rev. E*, **72** (2005) 041904.
- [47] MCSHARRY P. E., CLIFFORD G. D., TARASSENKO L. and SMITH L. A., *IEEE Trans. Biomed. Eng.* 550 (2003) 289.
- [48] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., *Entropy*, **20** (2018) 757.
- [49] LIFSHITZ I. and SLYOZOV V., J. Phys. Chem. Solids, 19 (1961) 35.
- [50] WAGNER C., Z. Elektrochem. Ber. Bunsenges. Phys. Chem., 65 (1961) 581.
- [51] PITAEVSKII L. and LIFSHITZ E., Course of Theoretical Physics, Vol. 10, Physical Kinetics (Pergamon Press Ltd., Oxford, England) 1993.
- [52] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., *EPL*, 125 (2019) 69001.
- [53] PENROSE O., LEBOWITZ J. L., MARRO J., KALOS M. H. and SUR A., J. Stat. Phys., 19 (1978) 243.
- [54] VAROTSOS P. A., SARLIS N. V. and SKORDAS E. S., *EPL*, 132 (2020) 29001.
- [55] BALASIS G., PAPADIMITRIOU C., BOUTSI A. Z., DAGLIS I. A., GIANNAKIS O., ANASTASIADIS A., MICHE-LIS P. D. and CONSOLINI G., *EPL* 131 (2020) 69001.
- [56] PAPADIMITRIOU C., BALASIS G., BOUTSI A. Z., DAGLIS I. A., GIANNAKIS O., ANASTASIADIS A., MICHELIS P. D. and CONSOLINI G., *Entropy*, **22** (2020) 574.